Review of High Frequency Conducted Susceptibility Limits

Assessment of CS114 Test Limits in TR-102323

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Executive Summary

This report documents a review of the bases for the high-frequency conducted emission susceptibility (CS) test limits recommended in EPRI Report TR-102323, Revisions 0-2 for testing and qualifying equipment to be installed in nuclear power plants. The primary purpose of the investigation was to provide additional information to support EMI Working Group discussions of the problems that are consistently experienced with this part of EMI qualification testing. The report provides recommendations on potential ways to develop additional bases for revising the current recommended limits for this testing.

MIL-STD-461E test CS114 is the method recommended by TR-102323 for high-frequency conducted emission susceptibility testing. 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. Below 200 kHz, the TR-102323 test levels for CS114 are significantly higher than those invoked by the U.S. military and similar commercial standards. Questions have been raised as to whether such high levels are actually warranted for nuclear plant applications. Additionally, this review raises some questions regarding the approach used to establish the existing TR-102323 levels for CS114. Based on this experience and the new evidence discussed in this report, it is recommended that existing CS114 test levels included in TR-102323 be reconsidered and new test levels be developed.

The TR-102323 test levels for CS114 were based on conducted emissions (CE03 and CE102) data collected at nuclear plants in the 1993-94 time frame. These data, along with the procedures by which they were collected and reduced, were examined as part of this review. The 1993-94 data were used to reconstruct parts of the emissions spectra that were used in TR-102323 Revisions 1 and 2 to establish the recommended CS114 test limits. Additionally, members of the EPRI EMI Working Group and other personnel at electromagnetic compatibility (EMC) test laboratories were contacted to discuss their experience with conducted susceptibility testing of new equipment per CS114, results of electromagnetic interference mapping surveys, and the methods used for measuring high-frequency conducted emissions per CE102. The CS114 test basis and procedure were compared to the CE03 and CE102 test procedures to better understand the relationships between data measured by CE03 and CE102 and the susceptibility levels established by CS114.

The activities described above revealed several technical factors, including inappropriate methods for collecting and analyzing test data, that appear to have contributed in varying degrees to the adoption of overly conservative high-frequency conducted susceptibility test levels in TR-102323 (and Regulatory Guide 1.180). This investigation also generated several suggestions for tasks that should be considered as part of an effort to develop a technical basis for test levels that are more appropriate. Some combination of these tasks may constitute the most effective approach. In no particular order, they are:

1. **Develop more appropriate CS114 test levels based on MIL-STD-461E.** MIL-STD-461E explains that CS114 was intended to examine susceptibility to radiated emissions being picked up on signal and power cables in aircraft. The TR-102323 recommended limits, in contrast, are based on CE03 and CE102 data that include noise introduced to the cables through both radiation and conduction. The impact of the conducted emission contribution is potentially amplified by impedance differences between the test equipment and plant systems (see item 5). Development of a new basis for CS114 test levels might be approached by analytically adjusting the MIL-STD-461E curves to reflect cable lengths more characteristic of power plants, or through collection of new power plant data using a test setup similar to that used to establish MIL-STD-461E CS114 limits, but with conditions based on representative power plant cable configurations. This approach would result in test levels that roll off at the low frequency end (like the CS114 curves in MIL-STD-461E), reflecting the resonance behavior of radiated coupling onto a cable of a fixed length and characteristic impedance, and would more accurately reflect the expected operating environment for the equipment.

2. **Develop new baseline for conducted emissions data using up-to-date test procedures.** This primarily addresses differences between the CE03 procedure that was used to develop most of the TR-102323 conducted emissions data for determining the CS114 test levels and the more up-to-date CE102 procedure. Measurements of conducted emissions in a plant would be taken using procedure CE102, modified to more closely resemble the conditions of test CS114. The modifications of CE102 would include reduced input bandwidth and the use of average rather than peak voltage measurements (see item 3). Preliminary indications are that adopting the updated CE102 procedure would lead to an 8-10 dBμA decrease in the test levels recommended in TR-102323 CS114 for power cables. Rather than taking new data, it may be possible to obtain existing MIL-STD-461E/CE102 data from EPRI member utilities for this. The emissions data would be separated according to whether the measurements were taken on power or signal cables. This body of new conducted emissions data would then be used to produce new composite emissions envelopes on which to base revised CS114 test limits.

3. **Justify using average emissions rather than peak to determine CS114 test levels.** At present, peak emissions levels from measurements per CE03 and CE102 are applied in CS114 as continuous wave emissions on cabling to the equipment under test. The average measurement of conducted emissions in a plant may provide a more technically appropriate measurement of the environment that could serve as a basis for the CS114 test levels. This task would look at the validity of using average voltage detector settings for EMI analyzers to measure continuous emissions and reject transient conducted emissions. If successful, this effort would lead to development of a recommended procedure that measures only continuous conducted emissions, which are the type of interference to which test CS114 determines the susceptibility of equipment. Separate EMC testing is already performed to ensure equipment is not susceptible to transient emissions.

4. **Develop separate CS114 test levels for signal and power cables.** Conducted emissions envelopes for signal and power cables would be established where the conducted emissions data measured using CE03 or CE102 can be separated into measurements from signal cables

and measurements from power cables. The resulting signal cable conducted emissions envelope would be used to support lower CS114 test levels for signal cables, as recommended in TR-102323 Revision 2. This action has been effectively taken by this report and TR-102323 Revision 2. Completion should only require inclusion of the analysis in this report into a future Revision 3 to TR-102323..

5. **Develop correction factor approach for loop impedance effects.** The effects of the difference between the loop impedance of installed power and signal wiring and the loop impedance of the CS114 test configuration should be investigated. This task could verify that the required CS114 test levels are overly conservative when used for qualifying safety-related equipment, even if a generic correction factor cannot be developed, and could also confirm the anecdotal evidence that the power levels applied to equipment under test in the laboratory are more conservative than those the equipment will encounter in its installed application.

1 Introduction

1.1 Background

Nuclear utilities are now replacing and upgrading aging and obsolete instrumentation and control systems. Most of these replacements involve transitions from analog to digital technology. Before installing new equipment, the owner/operator must establish reasonable assurance that the device will not be adversely affected by electromagnetic interference (EMI) and that it will not adversely affect other equipment that is important to safety.

EPRI has been working with industry and the NRC for several years to establish an approach and technical basis for assessing the electromagnetic compatibility (EMC) of digital equipment. The current approach is documented in EPRI Report TR-102323, Revisions 0-2. The NRC issued a Safety Evaluation Report dated April 17, 1996, that assessed Revision 0 of TR-102323 as an acceptable method of addressing issues of EMC for safety-related digital I&C systems. In January 2000, the NRC issued Regulatory Guide 1.180 "Guidelines for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related Instrumentation and Control Systems" (Reference 9).

Revision 2 of TR-102323 was issued in November, 2000 (Reference 6). This revision aligned the recommendations of TR-102323 with the methods of MIL-STD-461E, issued in 1999 (Reference 3), and with NRC Regulatory Guide 1.180, Revision 0. Revision 2 of TR-102323 also endorsed some tests of the International Electrotechnical Commission (IEC) as alternatives to MIL-STD-461E tests for certain applications, such as IEC test 61000-4-6 for high-frequency conducted susceptibility and test 61000-4-13 for low-frequency conducted susceptibility. Revision 2 recommended separate test requirements for high-frequency conducted susceptibility for signal and power cables, using the requirements of MIL-STD-461E test CS114 Curves #3 and #4 as the recommended test level for signal cables until more evidence is accumulated to support using the lower test level of CS114 Curve #2. The recommended test level for power cables was changed from 103 dBµA over the entire frequency range to a level following the MIL-STD-461E Curve #4 from 200 MHz to 1 MHz, then remaining at 97 dBµA from 1 MHz to 10 kHz. This change was based on accepting a margin of 6 dBµA rather than 8 dBµA to the highest plant composite measured conducted emissions envelope.

The NRC recently issued Regulatory Guide 1.180 Revision 1 (Reference 11). Regulatory Guide 1.180 Revision 1 (RG 1.180 Rev. 1) adopted the test levels recommended in NUREG/CR-6431, "Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants" (Reference 15) and is not consistent with several recommendations of TR-102323 Revision 2. Specifically in TR-102323 Revision 2 the requirements for signal cables have been adjusted to correspond to MIL-STD-461E test CS114. However, the CS114 test levels recommended in RG 1.180 Rev. 1 for both signal and power cables are higher than those recommended in TR-102323 Revision 2. One reason for this is to maintain a safety margin above the conducted emissions environment at frequencies below 200 kHz documented by TR-102323 and in NUREG/CR-6436, "Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants," (Reference 16). The EPRI EMI Working Group is discussing proposed revisions to TR-102323 Revision 2 that will incorporate the most up-to-date data available.

Of particular interest is the high-frequency conducted susceptibility test (CS114), for which it appears the currently recommended test levels are overly conservative. These test levels were established based on conducted emissions test data collected on selected cables in several nuclear power plants. It appears that the CE03 plant emissions data was misapplied to the CS114 equipment susceptibility test in a way that results in overly conservative test levels. These test levels have proven problematic during qualification testing of new equipment. The specific area of interest is the frequency range below 200 kHz, where the TR-102323 test levels were considerably higher than those of corresponding military and commercial standards (see Figure 1-1 for graphs comparing various requirements related to power cables and Figure 1-2 for signal cables). Note that the IEC Standard 61000-4-6 high-frequency conducted susceptibility test does not extend to frequencies below 150 kHz.

There is now a need to revisit the technical basis for the existing conducted susceptibility test levels in TR-102323, and if appropriate, propose an updated basis and determine what additional analysis and testing might be needed to defend it. The primary objective of this report is to recommend a means to develop an improved technical basis for updating the MIL-STD-461E CS114 test levels in the EPRI guidelines on EMI testing (TR-102323) to reduce over-conservative requirements and if possible, align the guideline with the corresponding existing military and/or commercial standards. Results of this effort would then be used in a subsequent project to update the TR-102323 guidelines.

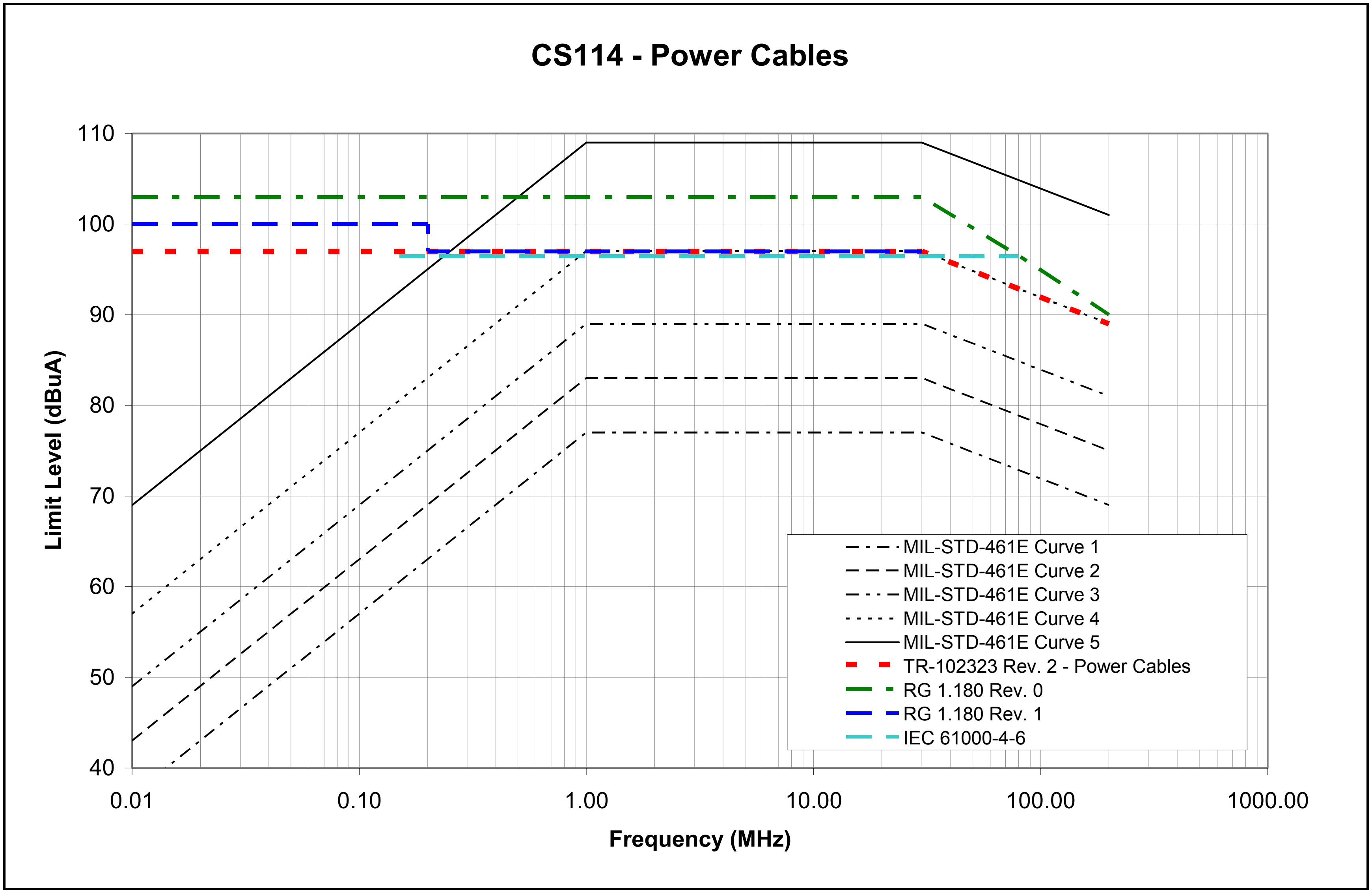

Figure 1-1. Comparison of Conducted Susceptibility Requirements for Power Cables

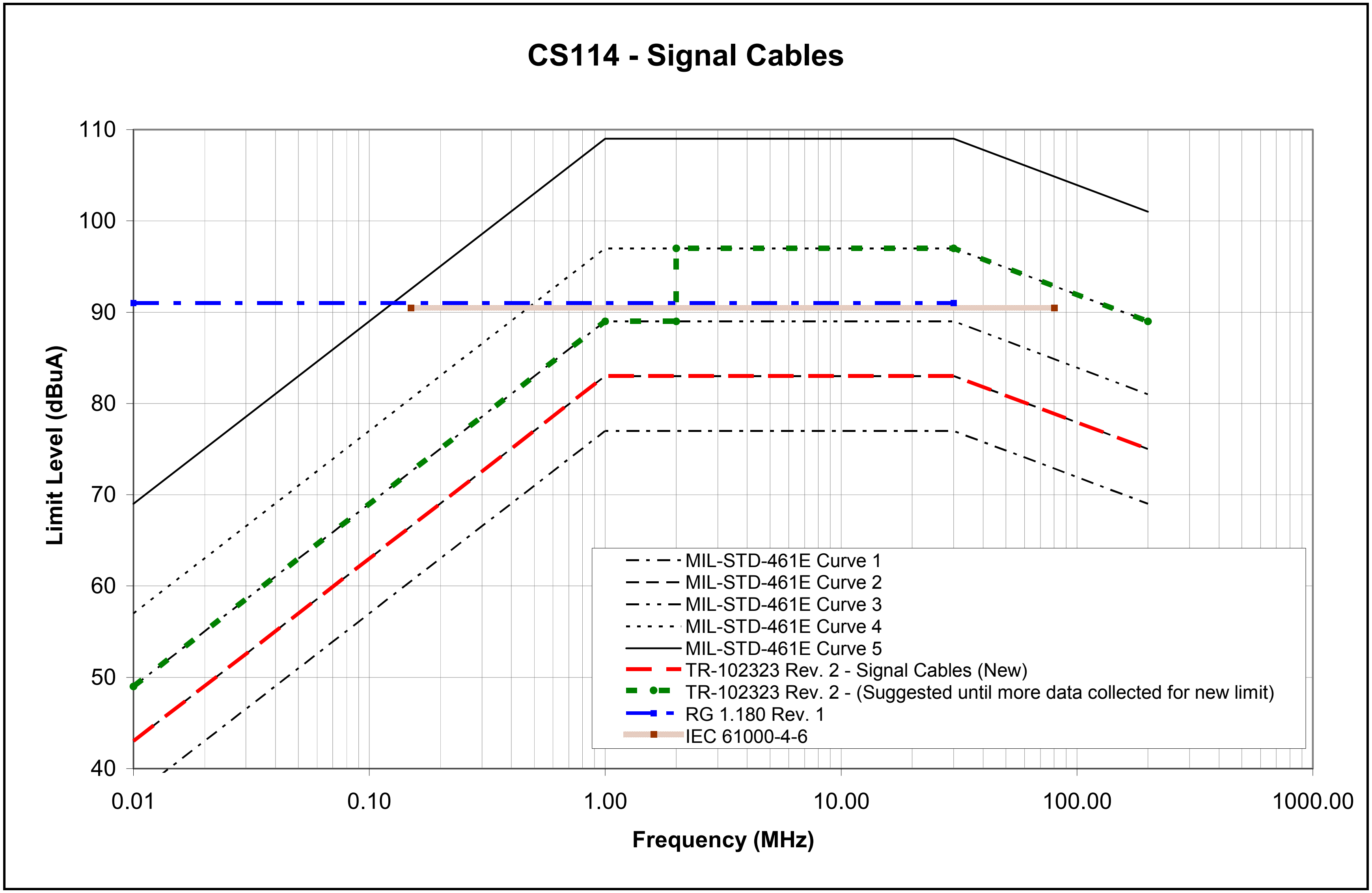

Figure 1-2. Comparison of Conducted Susceptibility Requirements for Signal Cables

1.2 PURPOSE/SCOPE

The purpose of this review is to investigate the technical basis for the high-frequency conducted emission susceptibility (CS) test limits recommended in EPRI Report TR-102323, Revisions 0-2 for testing equipment to be installed in nuclear power plants. The results of the investigation provide additional information to support EMI Working Group discussions of the problems that are consistently experienced with this part of EMI qualification testing. This report includes the results of the review and recommendations on potential ways to establish a technical basis for revising the currently recommended limits for this test, which is test CS114 of MIL-STD-461E. The CS114 test limits recommended in TR-102323 have proven to be problematic, even for components that have been tested to commercial standards and demonstrated reliable performance in industrial applications. For frequencies below 200 kHz, The TR-102323 test levels are significantly higher than those in MIL-STD-461E and in similar commercial standards. Questions have been raised as to whether such high levels are actually warranted for nuclear plant applications. Additionally, this review examines some questions regarding the approach used to establish the existing TR-102323 levels for the CS114 test. The combination of this experience and the new evidence prompted this review of the technical bases for the recommended limits in TR-102323.

1.3 APPROACH

The TR-102323 test levels for CS114 were based on conducted emissions (CE03 and CE102) data collected at nuclear plants in the 1993-94 time frame. These data, along with the procedures by which they were collected and reduced, were examined as part of this investigation. The 1993-94 data were used to reconstruct parts of the emissions spectra that were used in TR-102323 Revisions 1 and 2 to establish the recommended CS114 test limits. The purpose, method, and requirements for CS114 were also reviewed.

To better understand the methods by which the conducted emissions data were collected, the requirements for measuring high-frequency conducted emissions from 15 kHz to 50 MHz per MIL-STD-461C test CE03 were compared to the requirements of MIL-STD-461E test CE102, which superceded test CE03. The revisions to the MIL-STD-461 measurement procedure were reviewed to determine the effect of the changes on the measured emissions.

Members of the EPRI EMI Working Group and personnel at electromagnetic compatibility (EMC) test laboratories were contacted to discuss their experience with conducted susceptibility testing of new equipment per CS114, results of electromagnetic interference mapping surveys, and the methods for measuring high-frequency conducted emissions per CE102. The CS114 test basis and procedure were compared to the CE03 and CE102 test procedures to better understand the relationships between data measured using CE03 and CE102 and the susceptibility levels established by CS114.

2 Investigations/Evaluations

2.1 EMC Testing and Qualification Approach Used by TR-102323

The guidelines in TR-102323 describe the recommended series of tests to be performed to support the installation of digital, analog, or hybrid electronic equipment for use in a nuclear power generating station. The set of recommended tests for safety-related equipment is different from the set recommended for non-safety-related equipment. The guidelines in TR-102323 include conducted and radiated emissions and susceptibility tests to ensure new equipment introduced to the plant will not be susceptible to credible plant electromagnetic emissions and fail to operate as designed and that new equipment will not introduce electromagnetic emissions that would disrupt the operation of already installed equipment. The susceptibility tests are low-frequency conducted susceptibility (such as CS101), high-frequency conducted susceptibility (such as CS114), low-frequency radiated susceptibility (such as RS101), high-frequency radiated susceptibility (such as RS103), surge withstand (such as IEC 61000-4-5), electrically fast transient (EFT) (such as IEC 61000-4-4), and electrostatic discharge (ESD) (such as IEC 1000-4-2). In addition to these susceptibility tests, a number of conducted and radiated emissions tests are also recommended.

The acceptance requirements for the tests can be based on either a “point of installation” survey at the plant location where the equipment is to be installed, or the generic levels recommended in TR-102323. TR-102323 recommends conducted susceptibility test levels based on conducted and radiated emissions measurements obtained at seven plants in 1993 and 1994 and on the requirements of comparable military and commercial standard tests. The collection of emissions spectra at the plants was performed in conjunction with EMI surveys to support installation of new instrumentation and control equipment. Different items were installed at each plant, so the surveys covered a variety of plant areas and components, including the control room, the turbine room, and the emergency diesel rooms.

The conducted emissions surveys were performed in accordance with the requirements of tests CE01, CE03, and CE07 of MIL-STD-461C (Reference 1) and MIL-STD-462 (Reference 7) at six of the plants. The surveys at one plant were taken in mid-1994, after MIL-STD-461D (Reference 2) and MIL-STD-462D (Reference 8) were issued, thus the conducted emissions surveys were performed per tests CE101 and CE102. Tests CE01 and CE101 are low-frequency conducted emissions tests covering from 30 Hz to 15 kHz, and CE03 and CE102 are high-frequency conducted emissions tests covering from 15 kHz to 50 MHz. Test CE07 was a time-domain transient conducted emissions measurement, so it was not used as a basis for CS114 test levels.

Tests CE03 and CE102 are not specifically designed to provide the basis for CS114 test limits. Per MIL-STD-461 Revisions C through E, conducted emissions tests CE03 and CE102 are used in the laboratory to measure the conducted emissions produced by a piece of equipment to ensure the equipment does not produce excessive noise on interconnecting cables that could adversely affect other equipment. For TR-102323, the tests were used as the methods of taking measurements to characterize the maximum high-frequency, continuous-wave, steady-state conducted plant emissions environment from radiated and conducted sources that a piece of equipment would have to withstand without malfunctioning. This is a different basis than the one used to establish the recommended CS114 test limits in MIL-STD-461E. The MIL-STD-461E CS114 limits are based on testing equipment specifically against the conducted emissions induced in interconnecting cables by radio-frequency radiated emissions. This is why the MIL-STD test levels roll off at the low frequency end, reflecting the resonance behavior of radiated coupling onto a cable of a fixed length and characteristic impedance. Test CS114 was selected for use in TR-102323 as part of qualifying equipment for electromagnetic compatibility (EMC) in nuclear power plants because it provides a standardized method for testing equipment for high-frequency conducted susceptibility. However, the recommended test levels were based on conducted emissions data that included both radiated and conducted sources.

The CE03 conducted emissions spectra measured at various plant locations were used to produce a composite emissions envelope for that plant. These envelopes were then plotted together and used to produce the "Highest Composite Plant Emissions Envelope," a line that bounds the emissions envelopes of all the collected measurements. The bounding conducted emissions level was then used as the basis for establishing the conducted susceptibility test requirements for power cables in TR-102323 Revisions 0, 1, and 2.

EPRI Report TR-102323 Revision 2 recommends a separate CS114 test level for signal cables because the power cable levels were excessive relative to commercial standards for signal cable conducted susceptibility test levels. The recommended signal cable conducted susceptibility test level in TR-102323 Revision 2 was established based on review of the requirements of MIL-STD-461E and IEC Standard 61000-4-6.

2.1.1 High-Frequency Conducted Susceptibility Test CS114

CS114 is a MIL-STD-461E test of "conducted susceptibility, bulk cable injection, 10 kHz to 200 MHz." The purpose of CS114 testing is "to verify the ability of the EUT (equipment under test) to withstand RF (radio-frequency) signals coupled onto EUT associated cabling" (Reference 3 section 5.12.3.1). Test CS114 determines the susceptibility of equipment to continuous wave conducted emissions. The test uses inductive coupling rather than radiated coupling because of the difficulty in creating the required currents on lengths of cable that can be handled in the laboratory at lower frequencies.

The test is applied to all interconnecting cables, including power and signal cables. The test limit used by the military is based on the location where the equipment under test is to be used, e.g. inside aircraft, at ground installations, above deck of a ship, etc. The five curves graphing the military limits are shown in Figures 1-1 and 1-2. The test procedure begins with pre-calibrating a current injection probe placed around a cable that has 50 Ohm characteristic impedance with a

50 Ohm load terminated on one end and a 50 Ohm attenuator at the input to a measurement receiver on the other end. The calibration setup records the "forward power" to the injection probe required to produce the required current in the test cable over the frequency range from 10 kHz to 200 MHz.

For the check of conducted susceptibility of the EUT, the probe is placed around each cable bundle attached to each electrical connector on the EUT. The test applies the required current to complete power cables (high sides and returns) and power cables with returns and chassis grounds excluded. The test also applies current to power cables bundled with interconnecting leads as follows: entire bundle, power leads separate from interconnecting leads, and power leads with grounds and returns excluded. While the forward power level recorded during calibration is supplied, the EUT is monitored for degradation of performance, and whenever susceptibility to the applied current is noted, the threshold for degradation is found. The threshold is determined by reducing the interference signal until the EUT returns to normal operation, then reducing the interference by another 6 dB, followed by increasing the interference until the susceptibility reoccurs. This level is the threshold of susceptibility.

If the combined loop impedance of the EUT and either the interconnecting equipment (for signal cables) or the power supply connected via a Line Impedance Stabilization Network, or LISN (for power cables) is lower than the loop impedance of the calibration setup (i.e., below 100 Ohms), the signal generator may not be able to achieve the forward power level recorded during calibration for a given frequency without the application of damaging current levels or because of limitations of the signal generator. In those cases, MIL-STD-461E states that even if the forward power level is below that measured during calibration of the injection probe, the CS114 requirement is met so long as the EUT is not susceptible with a current induced in the cable under test that is at least 6 dB greater than the specified current limit (i.e., four times higher).

2.1.2 Conducted Emissions Measurement Detector Settings

2.1.2.1 Detector Voltage Reading

All versions of MIL-STD-461 and MIL-STD-462 require the use of peak detectors for emissions tests. As discussed in MIL-STD-462D, a peak detector measures

> "the peak value of the modulation envelope in the receiver bandpass. Measurement receivers are calibrated in terms of an equivalent root mean square (RMS) value of a sine wave that produces the same peak value. When other measurement devices such as oscilloscopes, non-selective voltmeters, or broadband field strength sensors are used for susceptibility testing, correction factors shall be applied for test signals to adjust the reading to the equivalent RMS values under the peak of the modulation envelope. The peak detector senses the largest level of the signal envelope and displays an output equal to the RMS value of a sine wave with the same peak. The specification of a peak detector ensures that the worst case condition for emission data is obtained."

Figure 2-1 shows graphically the relationship of the output of a peak detector to its input signal.

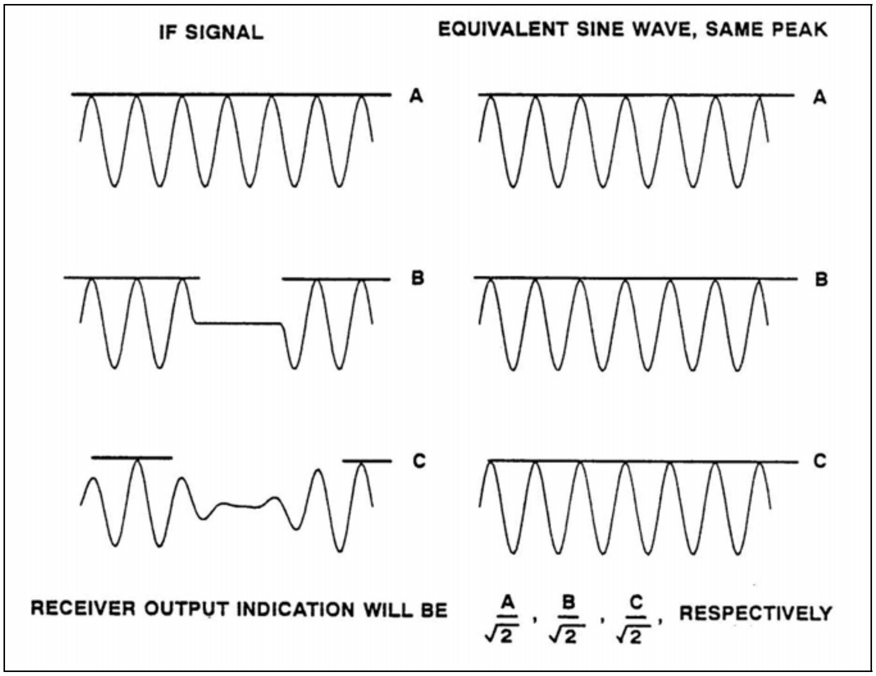

Figure 2-1. Illustration of Peak Detector Response (Reference 3)

When used during a frequency sweep, the 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. There is no procedural requirement in CE03 to perform several sweeps over time to attempt to ensure the worst-case emissions levels are measured. For the surveys supporting NUREG/CR-6436, "Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants," (Reference 16), measurement equipment was left in place over long periods of time, up to several weeks for some radiated emissions cases, to determine whether the emissions environment varied significantly over time and to ensure the worst-case emissions were measured. This is not a practical solution for EMI surveys performed on behalf of utilities to support installation of new equipment. The practice by at least one EMC measurement laboratory during in-plant EMI surveys is to perform several consecutive measurements at each location with the detector set up to retain the maximum recorded level from any of the measurements. Based on discussions with personnel at EMI test laboratories, it is their experience that this practice provides reasonable assurance that the highest continuous-wave level has been recorded.

The difference in analyzer output between the use of peak detection and use of average or RMS voltage detection depends on the waveform under analysis. The differences in response for each detector to pure waveforms have been calculated and are shown in Table 2-1. The table agrees with the previous discussion that a peak detector, when used to measure random Gaussian noise, will not provide meaningful data unless sufficient time is provided to ensure the maximum impulse has been observed. The table shows that for pulse train inputs, the difference between the output of a peak detector and that of an average detector would be 36.99 dB (16.99 + 20) for pulse trains with pulses of equal amplitude 1 V above and below zero volts ($\alpha = 0$) where a signal pulse is present 1% of the time ($d\alpha = 0.01$). For recurrent impulses with a repetition frequency of 1000 Hz, the peak detector output would be 22.3 dB (12.3 + 10) above that of the average detector. As can be seen from the graphical depiction of peak detector response in Figure 2-1 and the calculated differences between peak detector and other detectors response in Table 2-1, the peak detector will display the highest measurement of voltage for a variety of input waveforms regardless of whether the peak input is representative of the waveform for the majority of the time. See section 2.3.2.4 for a more detailed discussion.

Table 2-1. Comparison of Detector Output Values for Different Waveforms (Reference 18)

Waveform	RMS Responding Meter Indicates	Average Responding Meter Indicates	Peak Responding Meter Indicates	Quasi-peak Responding Meter Indicates	Differences (dB)		
					Average-RMS	Peak-RMS	Quasi-Peak-RMS
Sine Wave	0.707	0.707	0.707	0.707	0.0	0.0	0.0
Gaussian Noise	1σ	0.887σ	NOTE (1)	1.83σ	-1.04	-	5.25
Pulse Train $\alpha = 0$ $d\alpha = 0.1$	0.316	0.1	0.707	-	-10.0	6.99	-
Pulse Train $\alpha = 0$ $d\alpha = 0.01$	0.10	0.01	0.707	-	-20.0	16.99	-
Recurrent NOTE (2) Impulses with $f_p = 100$	1.0	0.10	13.5	6.08	-20.0	22.3	15.7
Recurrent NOTE (2) Impulses with $f_p = 1000$	1.0	0.316	4.27	3.62	-10.0	12.3	11.2

NOTES:
(1) A peak reading has limited meaning for random noise unless a sufficient observation time is allowed to assure that the maximum likely impulse has been sensed.

(2) For these two examples, we have set B (radio noise bandwidth) = 1.35 kHz, Δf_{imp} (impulse bandwidth) = 1.35 · 10 kHz, Δf6dB (6 dB bandwidth) = 1.07 · 10 kHz, R_d/R_c (detector resistance/antenna cable resistance) = 600, f_p = impulse repetition rate, p (α) (detector response function) = 0.45 for f_p = 100, p (α) = 0.85 for f_p = 1000 (see Reference 29).

2.1.2.2 Detector Input Bandwidth

In MIL-STD-461C and MIL-STD-462, there are no specified analyzer bandwidths or sweep times for narrowband emissions measurements. Also, MIL-STD-461 revisions prior to Revision D provided both narrowband and broadband limits over much of the frequency range of most emission requirements, so both types of measurements were needed. The lack of specified analyzer bandwidths resulted in the need for a check to determine whether the narrowband or broadband measured emissions were to be used in establishing the emissions level of a piece of equipment.

Per MIL-STD-462, whether the dominant radiated or conducted emissions are narrowband or broadband was to be determined by manually tuning the spectrum analyzed to the center frequency of interest and recording the frequency and amplitude. The analyzer or receiver was tuned over a range of +/- 2 impulse bandwidths around the center frequency. A change in peak response of 3 dB or less indicated a broadband emission. A change greater than 3 dB indicated a narrowband emission.

Thus, the effects of the particular bandwidths chosen for use by a test facility were addressed by providing for interpretation of the change in peak response of the emissions with respect to the chosen bandwidths. As stated in the discussion of bandwidth requirements in MIL-STD-462D: "The bandwidths and classification techniques used by various facilities were very inconsistent and resulted in a lack of standardization. The basic issue of emission classification was often poorly understood and implemented." Revisions D and E of the MIL-standards have made three changes to address this issue: input bandwidths are specified, only narrowband measurements are required, and classification of broadband or narrowband emissions is not used.

The bandwidths and frequency sweep times required for emissions measurements per MIL-STD-462D are listed in Table 2-2. MIL-STD-461E has a similar table with the only difference being that the second and third frequency ranges are divided at 150 kHz rather than 250 kHz. Note that the step increase in bandwidth at certain frequencies within the frequency range of a test can introduce artifacts into the measured emissions spectra. The artifacts usually consist of step increases in displayed emissions level because of the increase in emissions receiver bandwidth, which results in an increase in measured emissions. If conducted emissions were continuous wave only, then the measurements would not be dependent on the equipment input frequency, and there would be no discontinuity.

Table 2-2. MIL-STD-462D Frequency Sweep Requirements

Frequency Range	6 dB Bandwidth	Dwell Time	Minimum Measurement Time Analog Measurement Receiver
30 Hz – 1 kHz	10 Hz	0.15 sec	0.015 sec/Hz
1 kHz – 10 kHz	100 Hz	0.015 sec	0.15 sec/kHz
10 kHz – 250 kHz	1 kHz	0.015 sec	0.015 sec/kHz
250 kHz – 30 MHz	10 kHz	0.015 sec	1.5 sec/MHz
30 MHz – 1 GHz	100 kHz	0.015 sec	0.15 sec/MHz
Above 1 GHz	1 MHz	0.015 sec	15 sec/GHz

This effect can be seen in the discontinuity between emissions spectra measured per CE01 and those measured by CE03 (Figure 2-2). Since the CE01 upper frequency, 15 kHz, is the lower frequency of CE03, it would be expected that the emissions spectra and composite envelopes would be equal at that frequency. However, the measured emissions at the minimum frequency of CE03 are higher than those at the maximum frequency of CE01. This is because a higher input bandwidth was typically used for CE03 than for CE01, resulting in higher emissions being recorded by CE03 than by CE01 at 15 kHz. The composite emissions envelopes for CE03 begin 10-20 dBμA higher than the end of the CE01 envelopes.

The discussion in one EMI survey analysis report (Reference 28), notes this and explains that CE01 measurements were taken using 1.5 kHz narrowband bandwidth and CE03 measurements were taken using a 3 kHz narrowband bandwidth. NTS performed the EMI mapping that Reference 28 refers to in the first half of 1994 (Reference 29), so it would be reasonable to assume that these bandwidths were used by NTS for the CE01 and CE03 measurements at all the plants referred to in TR-102323. Note that the CE102 input bandwidth for 10 kHz to 250 kHz (150 kHz per revision E) is only 1 kHz, rather than 3 kHz. A higher input bandwidth results in higher measurements of conducted emissions.

2.2 REVIEW OF CONDUCTED SUSCEPTIBILITY REQUIREMENTS

In August 2002, the NRC issued NUREG/CR-6782, *Comparison of U.S. Military and International Electromagnetic Compatibility Guidance, Draft Report for Comment*. This NUREG compares the recommendations of TR-102323 Rev 2, MIL-STD-461E, RG 1.180 Rev. 0, DG-1119 (the draft of RG 1.180 Rev. 1), and IEC 61000-4-6 for conducted susceptibility test procedures and requirements. The relationships between the frequency coverage and susceptibility level requirements are shown graphically in Figures 1-1 and 1-2 of this report. Significant differences among the requirements are discussed below. These differences are not reviewed in detail here because NUREG/CR-6782 already performs a readily available review and because the differences in limits and test procedures do not greatly enhance understanding of the conservatism of CS114 level recommendations in TR-102323 Revisions 1 and 2 and in RG 1.180 Rev. 1 for frequencies below approximately 200 kHz.

The MIL-STD-461E requirements are based on tests performed on equipment installed in an aircraft and measurements of conducted emissions produced by coupling of high frequency radio interference. The MIL-STD-461E requirements do not differentiate between power source cables and control or signal cables. Since the coupling of radio waves is a resonance phenomenon, the test limit curves of MIL-STD-461E have a ramp-up as frequency increases, a plateau at the resonance band, and then ramp-down to the upper frequency bound of the test (see Reference 3, Appendix section 50.12). The CS114 test limits 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. The RF field frequency was varied from 10 kHz to 400 MHz and the field strength was varied from 20 to 200 V/m. The current induced on the tube was measured, and these measurements were compared to a similar study done in the United Kingdom to establish requirements for their Ministry of Defence Standard 59-41, "Electromagnetic Compatibility" (Reference 31). The U.S. MIL-STD-461 committee then used the results of the two studies to establish the limits for CS114 testing in MIL-STD-461 Revisions D and E.

The TR-102323 power cable conducted susceptibility test level recommendation follows the MIL-STD-461E CS114 Curve #4 level of 97 dBµA for frequencies above 1 MHz, and remains at that level for frequencies below 1 MHz, while the MIL-STD-461E test level decreases as frequency decreases below 1 MHz. RG 1.180 Rev. 1 matches the TR-102323 recommendation for frequencies above 200 kHz, but has a higher level of 100 dBµA below 200 kHz in order to maintain an 8 dBµA margin to the TR-102323 reported highest composite CE03 envelope to account for transients and analysis uncertainty. Thus, below 200 kHz, the RG 1.180 Rev. 1 CS114 test levels are 3 dBµA higher than TR-102323 recommended CS114 test levels. The IEC low-frequency conducted susceptibility test 61000-4-16 is only applied to power cables, and its upper limit is 150 kHz. The MIL-STD-461E low-frequency conducted susceptibility test CS101 also applies only to power cables, and its upper limit is 150 kHz.

The RG 1.180 Rev. 1 signal cable conducted susceptibility requirement does not vary with frequency and is significantly higher than the MIL-STD-461E requirement below approximately 150 kHz. The RG 1.180 Rev. 1 requirement for signal cables is within one dBµA of the requirement of IEC 61000-4-6, but that IEC test does not extend below 150 kHz. Discussions with EPRI EMI Working Group members familiar with the IEC EMC standards indicate that this is probably because of the small amount of RF energy coupled onto conductors at frequencies below 150 kHz. TR-102323 Revision 2 recommends use of MIL-STD-461E Curve #2 for signal cables; however, it also suggests that a higher level from MIL-STD-461E may be appropriate until sufficient data are collected to support use of Curve #2. The higher level consists of a combination of Curve #3 below 2 MHz and Curve #4 above 2 MHz. Using the suggested combination of Curves #3 and #4, TR-102323 Revision 2 has higher levels above 2 MHz than either RG 1.180 Rev. 1or IEC 61000-4-6 and has lower levels below 2 MHz. Using the recommended level of Curve #2, TR-102323 Revision 2 results in lower test levels at all frequencies than either RG 1.180 Rev. 1 or IEC 61000-4-6.

2.3 Review of Conducted Emissions Data Supporting TR-102323

Several of the reports containing data collected as part of the preparation of the original TR-102323 were reviewed. Also, three reports providing analyses of the data were reviewed. Most reports were prepared for the dual purposes of verifying the electromagnetic compatibility of a new item of digital I&C equipment for a specific plant, and collecting additional EMI survey information to support characterizing a generic electromagnetic environment at operating nuclear power plants for EPRI.

The reports obtained for this review are listed below:

Table 2-3. List of EMI Survey Reports Obtained for this Review

Report Contents	EMI Mapping Locations	Report Number, Date	Conducted Emissions Measurements
Data	Diesel Room	NTS 31319-94M, 2/10/94	CE01 CE03 CE07
Data	Control Room	NTS 31267-94M, 11/19/93	CE01 CE03 CE07
Data	Control Room	NTS 60251-94N-1, Rev. 3, 6/30/93	CE01 CE03 CE07
Data	Control Room	NTS 31288-94M, 1/20/94	CE01 CE03 CE07
Data and Analysis	Control Room	Wyle 68900-01, 9/8/94	CE101, CE102, CE07
Data	Auxiliary Electric Control Room	NTS 31590-95M, 5/31/94	CE01, CE03, CE07
Analysis	Control Room	NTS 31267-94M-1, Rev. 0, 1, and 2, 1/13/94 to 3/7/94	CE01 CE03 CE07
Analysis	Control Room	NTS 60251-94N-2, Rev. 3, 8/2/93	CE01 CE03 CE07
Analysis	Control Room	NTS 31288-94M-1, 2/14/94	CE01 CE03 CE07
Data and Qualification Report for Specific Equipment	Control Room, Turbine Room, OCC	Wyle 60082-01, 3/27/02	CE101, CE102 on power & signal separately

The first five reports listed in Table 2-3 were incorporated in EPRI TR-102323 Revisions 0-2. Reports of EMI survey data from two other plants were also used to produce TR-102323, but were not available for this review. The conducted emissions data from the seven reports established the conducted emissions environment used to set the conducted susceptibility test recommendations. The EMI data and analysis reports in the last five rows of Table 2-3 were not used as part of the basis for TR-102323 Revisions 0-2 recommendations.

2.3.1 Equipment and Methods Used to Collect and Analyze Data for TR-102323

Measurements of conducted emissions on power and signal leads over the frequency spectrum 15 KHz to 50 MHz were taken in accordance with test method CE03 of MIL-STD-462. There are four analysis reports available for review. Six of the seven data collection reports are by the same test laboratory and their measurements were recorded using very similar test equipment. It is reasonable to assume that all the data from those six plants were analyzed using the same methods as the three for which the analysis reports are available. The measurements and analysis for the seventh plant were performed in accordance with MIL-STD-462D rather than MIL-STD-462. The analysis of the data report for that plant included the data from Revision 0 of EPRI TR-102323 and was performed by a different EMI test laboratory than the analysis of the data from the other plants. Nonetheless, the results of analysis of that plant's CE102 measurements were very similar to the results for the measurements per CE03 at other plants.

2.3.1.1 Equipment Used for CE03 Measurements in 1993-1994

The current measurements were made using a clamp-on current probe connected to an HP 8566S Automated Microwave Measurement System or an HP 8566B Spectrum Analyzer running HP 85864A Automated EMI Measurement System Software. The spectrum analyzer/ measurement system power supply was isolated by a noise-filtering transformer. An HP 310 central processing unit controlled the bandwidth and scanning speed of the HP 8566B spectrum analyzer and ensured a continuous scan of frequencies in the desired range. At the end of each frequency sweep, the CPU initiated the next sweep and processed trace data from the preceding sweep. The processing included:

- Applying the transducer correction factor
- Accounting for preamplifier gain and external attenuation
- Plotting output on the display unit in semi-log format (log frequency, linear amplitude)

The following different current probes were used in various tests:

- Stoddard Aircraft 91550-1, 10 KHz to 100 MHz for CE03
- Electrometrics RF PCL-11, 20 Hz to 50 KHz for CE01
- Electrometrics RF PCL-30, 9 KHz to 110 MHz for CE03

The differences in current probes in use were corrected by the current probe transfer characteristic programmed into the EMI Analyzer and did not affect the measurements. At some sites, a ten-foot length of RG9B/U coaxial cable was used, and at others a twenty-five-foot length of RG223/U coaxial cable was used. The differences in cable lengths would not have had any effect on the data if the test cable lengths were the same as those used during the calibration to obtain the current probe transfer impedance. The analysis reports do not have a record of the cable lengths used for the measurements or a statement confirming that these were the same as for calibration of the probe.

2.3.1.2 Narrowband/Broadband Discernment Method

The analysis reports for CE03 data collected for TR-102323 use a different method of determining the validity of the broadband and narrowband spectra than that specified in MIL-STD-462. The method used by the analyses consists of comparing the measured spectra to the narrowband and broadband spectra of a "typical" digital pulse stream to determine whether the measured broadband spectrum represented high enough levels to be of significance. The difference in the amplitudes of the broadband and narrowband spectra of the digital pulse stream was compared to the difference between the narrowband and broadband measured composite emissions envelopes. If the measured data differed by less than the analyzed difference, the measured narrowband data was judged to be the measurement of the conducted emissions of interest and the broadband data were ignored.

The reasoning is as follows. If the difference between the measured narrowband and broadband spectra is less than that for a digital pulse stream, then the emissions in the broadband measurement can be ignored, as the amplitude of a digital pulse stream that generated the broadband spectrum would not exceed the amplitude of a similar pulse stream that generated the narrowband spectrum. This method of determining whether the broadband spectrum or the narrowband spectrum represented the emissions measurement that had the potential of interfering with the operation of equipment is not the method recommended in MIL-STD-462. However, it was probably more efficient when using a computer-controlled EMI Analyzer than manually adjusting the analyzer center frequency at each step over the range of the impulse bandwidth and assessing the measured response. This deviation did not affect the validity or accuracy of the composite emissions spectra used in TR-102323, as those were produced independently of the NTS analysis reports.

2.3.1.3 Conducted Emissions Data Analysis

The general method for producing a composite conducted emissions spectrum for each plant was to produce a graph by taking the highest level of current measured in a selected frequency band and plotting it. A smooth envelope was drawn using from one to three straight line segments to bound the peak composite conducted emissions graph. This procedure was performed using the CE03 data by analysts at NTS, and the results are in their analysis reports. The procedure was performed again independently by an experienced EMI testing engineer to produce the emissions envelopes in TR-102323 Revision 1. The CE102 measurements were taken at the seventh plant by technicians from a different laboratory and analyzed by the same EMI testing engineer who prepared the analyses for Report TR-102323 Revision 1 (Reference 26).

Composite Emissions Envelopes

Composite emissions envelopes were produced using the CE03 data for four plants and the CE102 data for a fifth plant. These spectra were produced by dividing the frequency of the test into either twenty-seven or thirty-one bins, depending on the highest frequency measured, then recording the highest measured current in each bin as the level of the composite spectrum. For three of these plants, both the data and analysis reports were available, so the smooth envelopes in the analysis reports were plotted against the composite envelopes developed by MPR. MPR confirmed that the smooth envelopes in analysis reports by NTS and CHAR Services do bound the composite of all CE03 or CE102 measurements in the data reports. An example of one of the composite envelopes from an NTS report is in Figure 2-2.

However, when the smooth envelopes of CE03 data from the NTS laboratory analysis reports are plotted against the CE03 highest composite plant emission levels from Figure 4-3 of EPRI TR-102323, the envelopes do not match one of the composite envelopes in that graph. The smoothed emissions envelopes from plants also do not match any of the envelopes. However, the CHAR Services CE102 envelope for Plant 5 matches the TR-102323 envelope for Plant G.

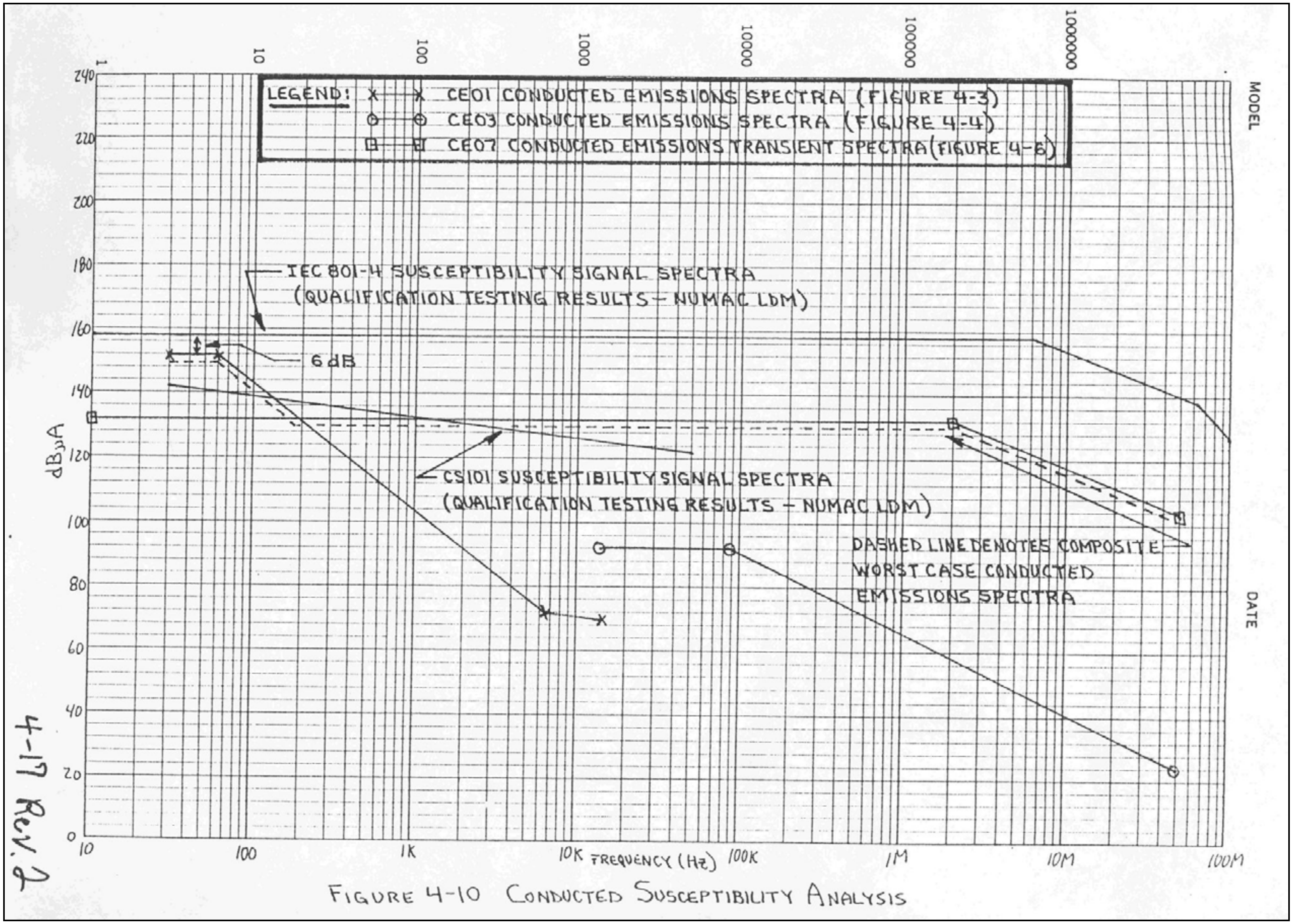

Figure 2-2. Example Conducted Emissions and Susceptibility Envelopes in an NTS Report

Figure 2-3 shows the composite levels from the EMI survey analysis reports by NTS for Plants 2 and 3, CHAR Services for Plant 5, and a separate evaluation of the survey data for Plants 1 and 4 graphed together with the composite levels in EPRI TR-102323. According to discussions with principal contributors to TR-102323 Revision 1, CHAR Services principally developed the composite conducted emissions envelopes used in TR-102323. The reason for the lack of correspondence between the envelopes in NTS analyses, the survey data, and the envelopes in TR-102323 is probably that NTS did not exclude any spectra to produce the composite emissions envelopes, while the analysts at CHAR Services excluded measurements taken at locations that are not representative of expected operating conditions and measurements that indicate an error on the part of the technician. Since CHAR Services analysis of the NTS data was performed by the same person, during the same time frame as when TR-102323 was initially issued, it was assumed that the criteria used to produce the smooth envelope for the data obtained by CHAR Services were also used for the other plants' conducted emissions data.

The smooth composite emissions envelopes from the NTS reports and from the review for this report of measured spectra all have the same overall characteristics and do not exceed the "Highest Composite Emissions Envelope" used to establish the CS114 test level recommended by TR-102323. Thus, although the effects of the difference in methods to produce smooth conducted emissions envelopes may be worth investigation, they are not pertinent to a review of the causes for high emissions envelopes at lower frequencies and were not further analyzed for this report.

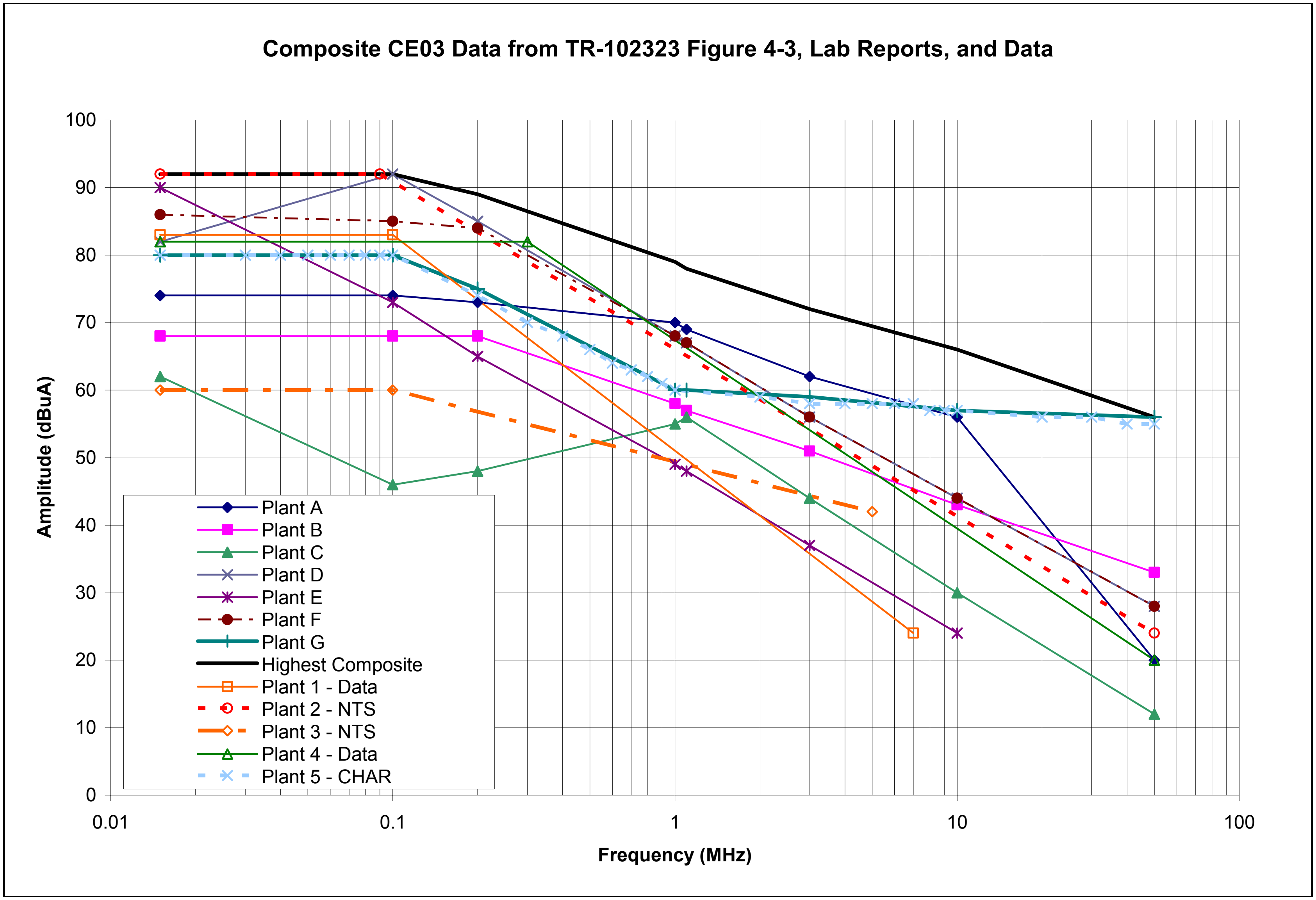

Figure 2-3. Comparison of TR-102323 and Analysis Report Composite CE03 Data

Differentiation between Power and Signal Cables

Tests CE01 and CE03 performed for measurements in support of EPRI did not require power and signal cables to be measured separately. This is because the requirements of MIL-STD-461E and preceding revisions do not differentiate between power and signal cables in conducted susceptibility testing requirements. Regulatory Guide 1.180 Rev. 0 did not apply the CS114 test to signal cables, only power and control cables, as did TR-102323 Revision 1. However, EPRI TR-102323 Revision 2 and RG 1.180 Rev. 1 make the distinction between power and signal cable requirements in order to apply susceptibility tests to signal cables. The levels for conducted susceptibility testing of signal cables were investigated by the NRC using an "experimental digital safety channel" consisting of equipment meant to represent typical process control components, and the results are reported in NUREG/CR-5609, "Electromagnetic Compatibility Testing for Conducted Susceptibility Along Interconnecting Signal Lines, Draft Report for Comment" (Reference 14). The results in NUREG/CR-5609 were incorporated in RG 1.180 Rev. 1.

Nevertheless, present industry practice is for point of installation measurements to differentiate between conducted emissions on signal and power cables in order to allow qualifying equipment for use in the environment without subjecting signal cables to overly restrictive test levels that are not anticipated or credible in the installed plant environment. The test procedure used during the generic site surveys was for conducted emissions measurements to be taken with as many bundled cables as would fit into the current probe. The higher measured conducted emissions were usually on power cables. However, the concurrent "point of installation" mapping usually involved separate measurement of signal and power cables, and this can be seen from the labeling of the test locations as well as the characteristics of the measurement spectra.

Where the measurement spectra were clearly signal/control cables only or power cables only, the data were separated to produce composite spectra of conducted emissions measured on signal and control cables without including power cables. The data reports for four plants contain sufficient information to separate the measurements on bundles containing only signal or control cables from the measurements containing only power cables. Figure 2-4 has the composite conducted emissions spectra for power cables at these plants. Also, Figure 2-4 includes the graph of levels measured at a fifth plant on both power and signal cables, as signal cable measurements were not differentiable based only on the labeling of the data.

The levels in the data report for one plant (Reference 24) are significantly higher than the other plants for both power and signal cables. Several cables surveyed for conducted emissions at that plant were connected to a variable frequency drive and the switching power supply for that drive. This equipment produced a great deal of noise on its power supply lines up to a power line filter that was installed to reduce the conducted noise. The envelope in this report does not include spectra measured on power cables connected on the load side of this filter in the composite emissions envelope for that plant. This screening is similar in approach to that performed by CHAR Services on all the data for the TR-102323 composite emissions spectra, but on a less detailed level.

Figure 2-5 shows the conducted emissions data from CE03 and CE102 for cables whose purpose was control or signal. Only one plant, Plant 5, had conducted emissions on signal cables that significantly exceeded the CS114 test level recommended in TR-102323 Revision 2 (Curve #2 of MIL-STD-461E). Review of the control cable emissions data for Plant 5 noted that control cables routed next to or in the same bundle as ground cables had significantly higher emissions than other control cables. More detailed analysis of the data was not performed for this report, but may yield more information as to the reason for the higher conducted emissions on control cables there than at other plants.

Comparison of Figure 2-4 to Figure 2-5 confirms that the power cable conducted emissions are significantly higher than those on cables or bundles of cables for signal or control at all plants.

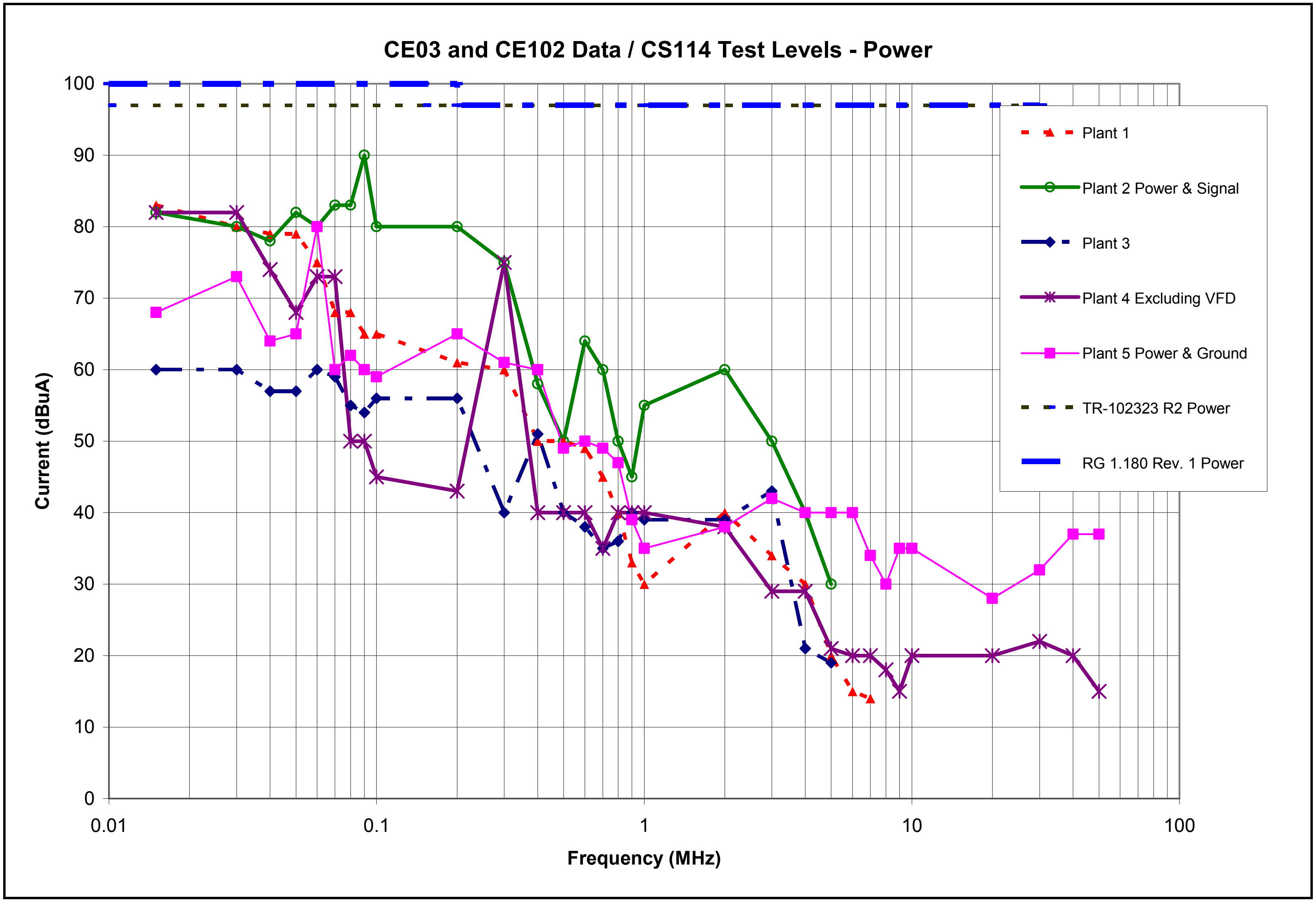

Figure 2-4. Conducted Emissions Data and CS114 Test Levels – Power Cables

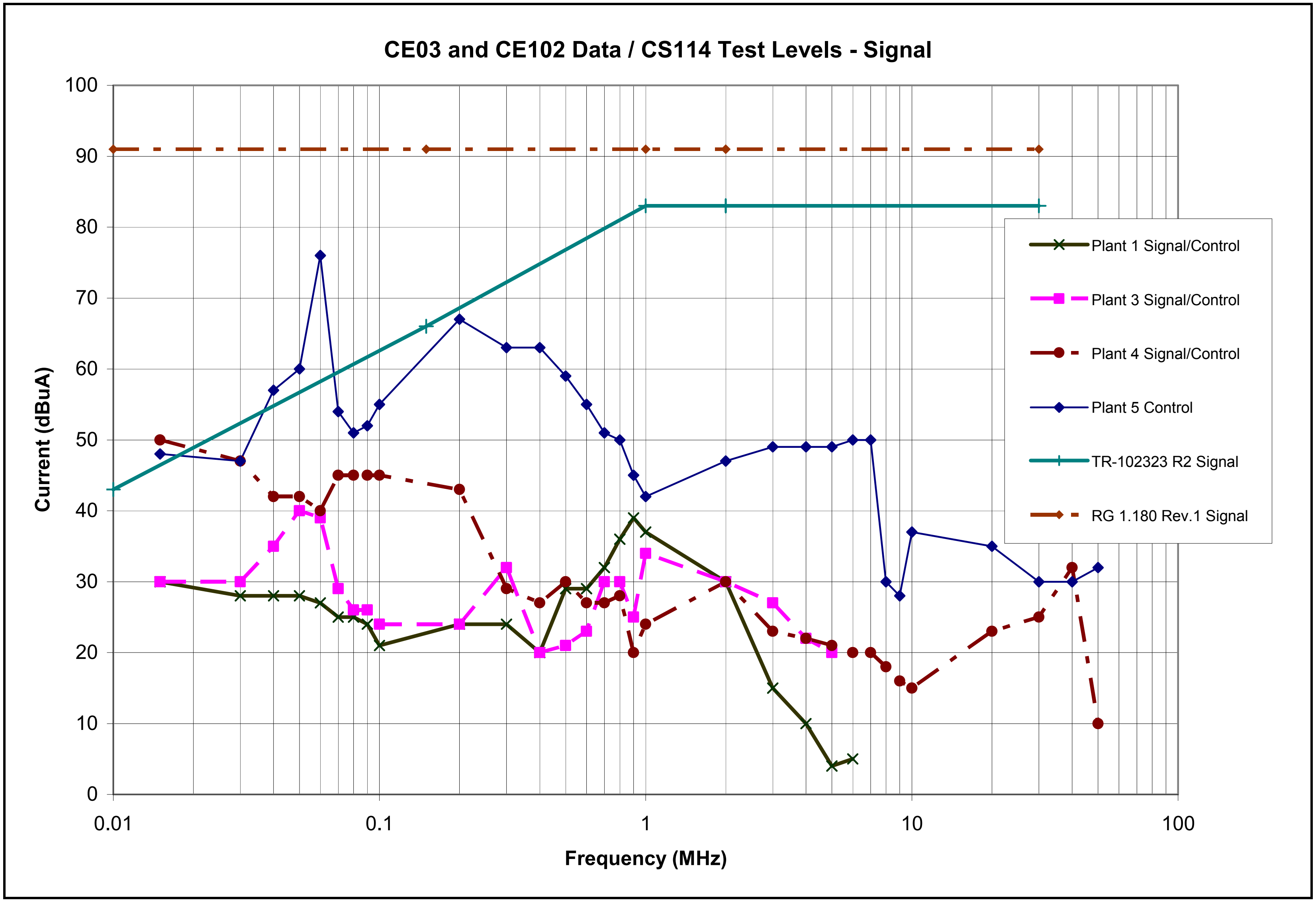

Figure 2-5. Conducted Emissions Data and CS114 Test Levels – Signal Cables

Impedance Correction Factor

The NTS analysis reports discuss an impedance correction factor to be applied to conducted emission data to correct the current measurements for the difference between the impedance of equipment where measurements were taken in plants and the impedance of the power supply connections of equipment under test in the laboratory. For CE03 laboratory measurements, power supply cables were connected to equipment under test using 10 μF pass-through capacitors. The impedance correction factor at a given frequency is the difference, in dB referenced to 50 Ohms, between the impedance of one of these capacitors at that frequency and the impedance of a "prime power source."

The impedance correction factor graph from an analysis report by NTS is shown in Figure 2-6. For frequencies from 30 Hz to 45 kHz, the prime power source impedance is -60 dB. Then it increases at 20 dB/decade until reaching approximately 34 dB at 10 MHz, then remains at 34 dB at higher frequencies. In the frequency range of CE03, 15 kHz to 50 MHz, the correction factor ranges from -18 dB at 15 kHz to 0 dB at 1 MHz to +12 dB at 50 MHz. The estimated prime power source impedance in the reports was based on experience. The reports did not expand on the development of the prime power source impedance. While the very low impedance at low frequencies increasing to impedance that is probably in the range of the characteristic impedance of power cabling at higher frequencies is logical, there is no documentation to support the estimate.

Based on discussions with members of the EPRI EMI Working Group, attempts to correct conducted emissions measurements and conducted susceptibility tests for impedance effects in support of EMI test standards have not been successful. One of the main reasons for this is the difficulty in obtaining measurements of impedance of actual installations, which is compounded by the wide variety of circuit configurations and the need to measure the phase of voltage and current measurements to characterize the phase angle of the impedance. Another factor is that at lower frequencies the wavelength of the emissions can be comparable to the length of cables under measurement, so the point of measurement will affect the measured phase and impedance.

The CE03 composite emissions envelopes produced by NTS to support equipment qualification do not include the impedance correction factor. Thus, the accuracy of the correction factor does not affect the validity of the equipment qualification reports. There is no attempt to include an impedance correction factor in MIL-STD-461E or in NRC publications (NUREGs) that report analyses of conducted emissions measurements.

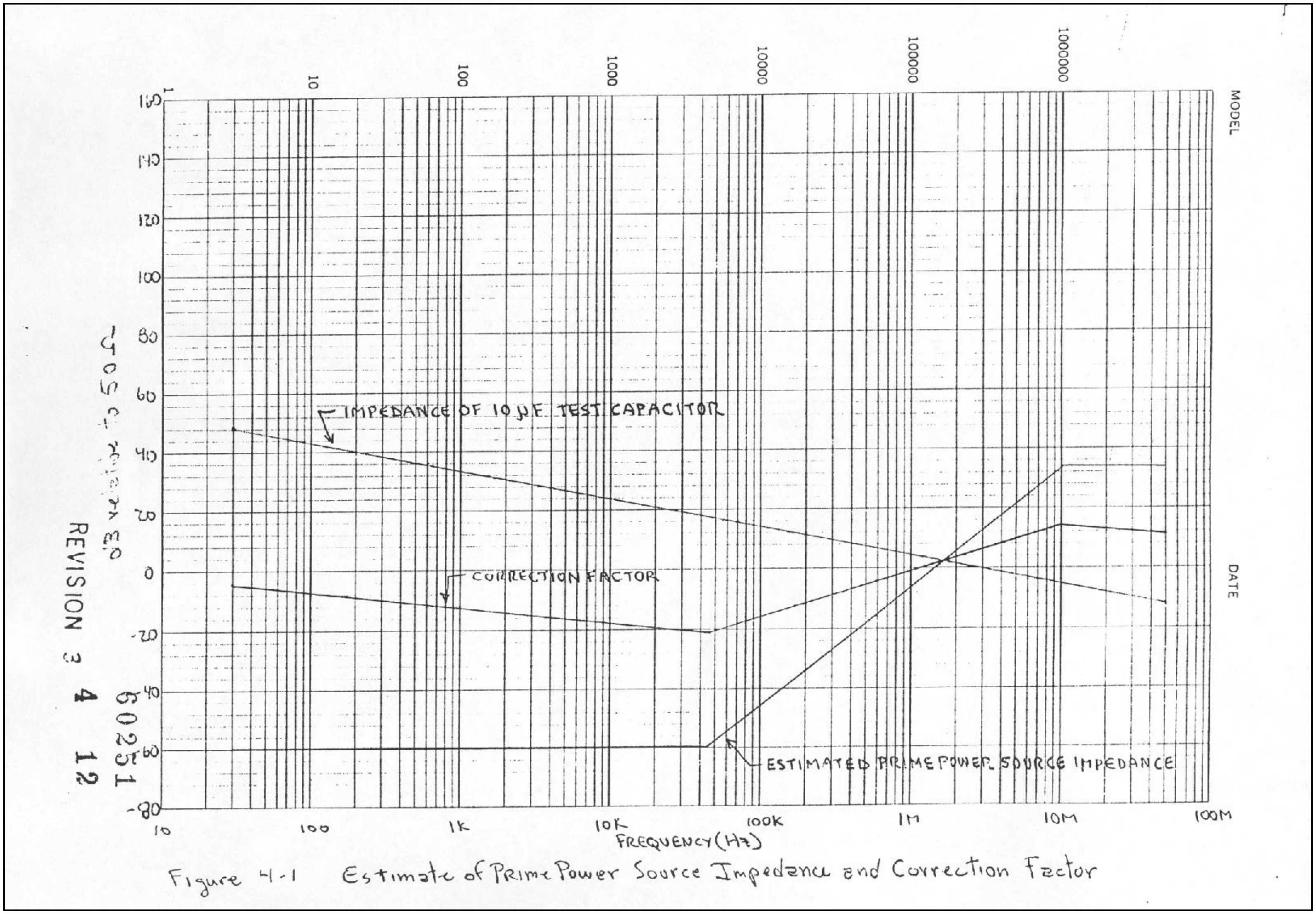

Figure 2-6. Impedance Correction Factor from an NTS Analysis Report (Reference 20)

2.3.2 Possible Problems with Emissions Measurements and CS114 Limits

Based on discussions with members of the EPRI EMI Working Group and review of the test data and analysis reports, there are several factors that could have, to varying degrees, introduced unrealistic and inappropriate increases in the signal levels of the conducted emissions envelope shown in Figure 4-3 of EPRI TR-102323 Revision 2. Descriptions of possible problems with the measurement or analysis of the conducted emissions data follow, with brief descriptions of the effect of each problem on the data and conclusions about whether the problem is likely to contribute to the high measured emissions.

2.3.2.1 Conducted Emissions Envelopes Do Not Separate Signal and Power Cables

In most cases, the current probe was placed around power and signal cables together with the stated objective of placing the probe around "as many cables as possible." Measurements at survey locations to specifically support the installation of a new digital component usually separated signal from power cables. At other locations, power and signal cables were usually bundled together. In a few surveys, the current probe was placed on power and signal leads separately for common and differential mode conducted emission measurements. The labels used for the spectra measured do not always allow identification of what cables were in the current probe or what they carried. This results in the following four areas of weakness in the conducted emissions data presented in TR-102323, that are generally concurred with by members of the EPRI EMI Working Group contacted for this review.

1. The conducted emissions envelopes in TR-102323 Revision 1 do not distinguish between signal and power cable CE03 data. Since conducted emissions are significantly higher on power cables than on signal cables (see Figures 2-4 and 2-5), this results in overstating the level of conducted emissions on signal cables.

2. Many of the measurements were taken by placing the current probe around as many cables as would fit that were in the same bundle in a selected cabinet. The cables were not segregated by system or power supply. This results in an inability to systematically identify sources of conducted emissions or characterize typical conducted emissions on classes of cabling for general application as a guideline for testing.

3. The cables that were in the current probe cannot be assumed to always have included the power and return (or line and neutral) conductors for power cables or all phases of three-phase power supplies. The effect of unbalanced power lines being in a current probe is to produce significantly higher magnetic fields than when power lines are measured together so as to result in cancellation of unbalanced magnetic fields. Conducted emissions measurements would have been inaccurately higher than actual due to this phenomenon. This could also result in measuring intended differential-mode signals as opposed to common-mode noise signals, which are the intent of the testing.

4. The measurements included few or no shielded cables and did not graph the emissions on those separately, which would have allowed assessment of the reduction in conducted emissions due to the use of shielding.

The combination of measured data from signal and power cables in TR-102323 graphs of the highest composite emissions has contributed to the perceived need to establish higher than necessary CS114 test requirements for signal cables. The body of public data on conducted emissions on signal and power cables at nuclear power plants is limited and may not be directly applicable to present-day testing. Although the NUREG/CR-5609 investigation determined that the experimental digital safety channel was susceptible to high-frequency conducted emissions at current levels from 49 to 70 dBμA, the recommended susceptibility test level was 91 dBμA for all frequencies of CS114, based on setting a level 6 dBμA above the maximum CS114 level for ground installations. The signal cable conducted susceptibility recommended test level for CS114 in RG 1.180 Rev. 1 is not based on plant emissions data, because the data that were collected were judged to not be applicable to signal cables.

The data presented in Figures 2-4 and 2-5 for conducted emissions on power and signal cables support the use of CS114 test levels recommended by TR-102323 Revision 2 for signal and power cables. However, further investigation may be necessary to validate the CS114 test levels recommended for signal cables, because the Plant 5 data show emissions from 60 kHz to about 100 kHz higher than the MIL-STD-461E CS114 test limits. Since the practice at plants for several years has been to have EMI Laboratories or in-house technicians take CE102 measurements on signal cables apart from the measurements on power cables when surveys are performed in order to support equipment qualification, a significant body of data now exists with separate composite emissions spectra for signal and power cables.

2.3.2.2 CE03 Input Bandwidth Was Higher than CE102

One possible cause of higher emissions being measured at lower frequencies is that, as discussed earlier, CE03 measurements were taken using an input bandwidth of 3 kHz over frequencies from 15 kHz to several MHz, while MIL-STD-461D requires using an input bandwidth of 1 kHz over frequencies from 10 kHz to 250 kHz (10 kHz to 150 kHz per MIL-STD-461E) for tests including CE102.

For the plants where analysis reports by NTS are available, the CE03 conducted emissions levels at 15 kHz are about 20 dBμA above the CE01 measurement at 15 kHz. As discussed in section 2.1.2.2, this is likely to be due to the increase in input bandwidths, which were 1 kHz for CE01 and 3 kHz for CE03. In the analysis reports, the CE01, CE03, and CE07 data were assembled to produce a composite emissions envelope that bounded all three of these composites in order to establish the conducted susceptibility test envelope for the item of equipment being qualified for electromagnetic compatibility. Since the envelope included the higher levels from CE07 measurements and did not discard CE01 data with power frequency harmonics, those effects tended to dominate the CE03 measured emissions.

In one EMI mapping data analysis report, it was noted that discontinuities in the CE102 spectra occur at 250 kHz when the bandpass changes from 1 kHz to 10 kHz and at 30 MHz when the bandpass changes from 10 kHz to 100 kHz. At both these discontinuities, the spectrum after the bandwidth increase is higher by 8 to 10 dBμA, which further corroborates the idea that a wider bandpass results in higher measured conducted emissions. Comparison of the CE102 composite emissions spectrum below 200 kHz for Plant 5 to the CE03 spectra for Plants 1 to 4 on power cables shows that the Plant 5 measured emissions are 14 dB lower at 15 kHz. However, the

Plant 5 CE102 conducted emissions do not fall below the CE03 data by a consistent margin and in fact are comparable to the CE03 measurements for frequencies above 50 kHz.

An evaluation of whether actual conducted emissions envelopes are lower than those represented in TR-102323 Figure 4-3 could be performed using measurements of conducted emissions taken in accordance with CE102 at the plants for which there are measurements taken using CE03, allowing a direct comparison of the two. The CE101 and CE102 measurements could also be used to establish that the discontinuity between CE01 and CE03 data is an artifact caused by the step increase in input bandwidth and establish the need to produce composite emissions spectra and CS114 test requirements based solely on CE101 and CE102 data.

2.3.2.3 Analysis Did Not Properly Correct for Impedance of EUT

The field measurements were taken with current probes clamped around cables of indeterminate length and impedance. In the laboratory, conducted emissions forward power testing limits are established based on the 100 Ohm calibration fixture loop impedance. The CE03 measurement system converted the signals to dBμA using a transfer function that assumed an impedance of the cable and system under test that is the same as the fixture used to measure the current probe transfer impedance. As this impedance was probably significantly different from the impedance of the actual equipment and system under test, this is very likely to have resulted in measurements of conducted emissions that may not be appropriately represented by laboratory conditions. The "impedance correction factor" described in the NTS EMI data analysis reports is an example of an attempt to refer the measured conducted emission levels back to laboratory conditions (see sections 3.4 and 4.5 of this report).

The opinion of personnel who perform field testing is that the CS114 levels are conservative because the power needed in the laboratory test rig to duplicate the current levels measured on installed equipment is high. While the current levels measured by CE03 and CE102 and used to establish CS114 test levels are recorded accurately, the power content of the emissions is not fully characterized. This could result in calculating higher conducted emissions than were actually present. The use of these measurements to establish conducted susceptibility test requirements that will be based on "forward power" levels determined using a 100 Ohm calibration fixture could result in overly high current levels. The CS114 test criteria acknowledge this by allowing the test requirements to be met even if the forward power level is not reached, so long as the cable under test has current induced that is at least 6 dB higher than that required by the applicable curve.

It is the experience of EMC test laboratory engineers that field measurements of conducted emissions are rarely within 20 dBμA of the recommended test levels of TR-102323 Revision 1 or NRC Regulatory Guide 1.180 Revision 0. Further, their experience when they test equipment per MIL-STD-461E test CS114 is that the signal generator must generate inordinately high power levels to create the required current levels in test specimens to either match the EMI conducted emissions survey results or the requirements of the applicable standard.

For the reasons indicated in the prior discussion of the Impedance Correction Factor developed by NTS, it is not likely that new laboratory tests to determine a method to measure the impedance of equipment under test in the field under all conditions will prove feasible.

Attempting to develop an impedance correction factor to apply to all the previously obtained CE03 data is also not a promising avenue of investigation. The anecdotal evidence from EMI test engineers is that the CS114 test requirements are overly conservative, particularly at frequencies below 200 kHz.

2.3.2.4 CS114 Test Limits Are Being Based on Measurements of Transient Emissions

TR-102323 states the CE03 measurements "represent continuous-wave, steady-state high-frequency conducted plant emissions" (page 4-8 of TR-102323 Revision 2). However, since peak detectors were used, as required by the test standards, the emissions measured in the field include a combination of transient and continuous emissions on the cables under test. Per the previous discussion of peak detector response, the peak detector does not discriminate between "bursty" or random currents and the continuous-wave currents on the cable (References 32, 33, 35, 36, 37, and 38). This would result in a higher continuous conducted emissions environment being inferred than is actually present.

The source of these random currents at lower frequencies would be stronger for power cables, as the switching and equipment start/stop transients are more frequent and of greater magnitude on those cables. Also, the conducted emissions measured using a peak detector could be expected to be higher for lower frequencies when the length of cable from the transient source to the point of measurement is not a significant fraction of a wavelength, and thus the cable characteristic impedance would not greatly attenuate or shift out of phase the transient.

As discussed in a previous section, the scope of CS114 testing only includes continuous wave emissions, and equipment susceptibility to transient emissions is measured in separate tests using different methods. It would be more appropriate to develop a method of measuring only the conducted emissions that are continuously present. This method would need to establish the continuous wave conducted emissions level without being overly sensitive to short-duration increases in conducted emissions.

One measurement method that was suggested by a member of the EPRI EMI Working Group is to use the average voltage detector function of an EMI Analyzer or Spectrum Analyzer. This would still produce RMS voltage measurement, as discussed above, but would provide a measurement that reduces the possibility that short-duration phenomena will be recorded as continuous emissions. The measured conducted emissions spectra would then represent only the continuous wave emissions on the cabling. Since CS114 places continuous wave emissions on cabling to the equipment under test, the average measurement could provide a more technically appropriate measurement of the ability of the equipment under test to withstand a realistic measure of the environment where it will be installed.

One issue with using average voltage measurement is that the measurement device will allow multiple settings of the integration time constant. Establishing the proper time constant to exclude transient emissions, while including emissions that are present on a cable at all times, but do not exhibit a continuous waveform, will require achieving consensus among several parties. However, a straightforward method to determine a reasonable time constant has been proposed. The process would consist of measuring conducted emissions over a range of time constants, beginning with a very short time constant, for which the measurement would resemble the peak detector's output, then stepwise increasing the integration time constant. As the time constant is increased, the measured emissions should asymptotically approach a limiting value, which can be considered to include only the continuous phenomena.

2.3.2.5 CS114 Limits Should Be Based on Emissions from Radiated Sources Only

MIL-STD-461E states that CS114 was developed to allow testing of equipment susceptibility to EMI from RF sources that is coupled onto the equipment cables at frequencies too low to allow effective coupling from radiated sources in the laboratory. In the CS114 test procedure, the purpose of CS114 testing is stated as "to verify the ability of the EUT (equipment under test) to withstand RF (radio-frequency) signals coupled onto EUT associated cabling" (Reference 3 section 5.12.3.1). The conducted emissions measurements per CE03 and CE102 used to establish CS114 test limits in TR-102323 are measurements of all current on cables regardless of the ultimate source of that current. Thus, the emissions measurements include current produced by both conducted and radiated noise sources, and are higher than would result from radiated EMI sources only. This is particularly true for lower frequencies because of their long wavelengths (approximately 2000 meters for 150 kHz) which, relative to frequencies above 2 MHz, couple little energy into conductors of lengths found in power plants.

Section 50.12 of MIL-STD-461E (Reference 3, pages A-73 and A-74) describes the radiated electric fields used to induce current in the laboratory testing that developed the limit curves for CS114. The electric field used for Curve 5 (the highest test level) was 200 V/m (166 dBμV), which is very strong and much higher than would be expected in a nuclear power plant. As a point of comparison, RG 1.180 Rev. 1 recommends a test level of 10 V/m in RS103, and levels ranging from 59 to 72 dBμV in RE102. The conducted emissions produced by radiated emissions in a nuclear power plant should be representative of realistic expected or measured radiated emissions levels. Appendix A of MIL-STD-461E states that an electric field of 1 V/m induced 1.5 mA of current in the test set-up used to establish the CS114 test levels. Using this result, an electric field of 10 V/m would induce current of 15 mA, or 83.5 dBμA.

Paragraph 50.12 of the appendix to MIL-STD-461E contains further clarifications of the focus of test CS114 on radiated interference, the resulting shape of the limit curves, and tailoring the limits for specific applications, as stated in the following quotes from MIL-STD-461E:

- "The basic concept is to simulate currents that will be developed on platform cabling from electromagnetic fields generated by antenna transmissions both on and off the platform."
- "The shape of the limit reflects the physics of the coupling with regard to resonant conditions, and the cable length with respect to the interfering frequency wavelength. At frequencies below resonance, coupling is proportional to frequency (20 dB/decade slope)."
- "Possible tailoring by the procuring activity for contractual documents is a [CS114 limit] curve amplitude based on the expected field intensity for the installation and a breakpoint for the curve based on the lowest resonance associated with the platform."

A concern expressed by some members of the EPRI EMI Working Group is that the CS114 test is being misapplied in that the test levels are based on current produced by both conducted and radiated emissions sources. The clarifications in the updated MIL-STD-461E, published in 1999, reinforce this concern, and indicate that the shape of the limit curve and possibly the peak level in TR-102323 are not appropriate for the intended test. This, in combination with the fact that the current that is measured in the field does not represent actual delivered power due to the inability to measure loop impedance, results in overly high CS114 test levels at low frequencies.

2.3.2.6 Changes from CS02 to CS114 Were Not Properly Addressed

The original TR-102323 was prepared with the goal of applying tests in MIL-STD-461C to EMI testing for nuclear power plants. The high-frequency conducted susceptibility test in MIL-STD-461C is CS02. 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. The limit for CS02 tests was 1 Volt from a 50 Ohm power source, with the restriction that if the power reaches 1 Watt without generating the required voltage or affecting operation of the EUT, then the equipment is considered to have passed the test. Table 2-4 compares tests CE03 (per MIL-STD-461C), CS02 (per MIL-STD-461C) and CS114 (per MIL-STD-461E). The table shows the differences between the technique used to gather high-frequency conducted emissions data from the field and the techniques used to test equipment for susceptibility to high-frequency conducted emissions in the laboratory. CS114 in MIL-STD-461D differs slightly from CS114 in MIL-STD-461E in two of the characteristics listed in Table 2-4. For the older standard, the upper frequency is 400 MHz rather than 200 MHz and the test limit is either the forward power level or applied current at the level from the appropriate curve, rather than the forward power level or applied current 6 dBμA above the current from the curve. Also, the limit curves in the older standard are somewhat lower (more stringent) for frequencies above 30 MHz.

Revision 1 of TR-102323, issued after MIL-STD-461D, allowed the use of either CS02 or CS114 to test for high-frequency conducted susceptibility. The limit for CS02 was based on 7 Volts rms being induced on a cable with 50 Ohm impedance (Reference 5, page B-11). This was equated to a susceptibility limit for CS114 of 103 dBμA induced current, based on the induced voltage having a power level of 1 Watt, as follows: 1 Watt divided by 7 Volts rms results in approximately 143,000 μA, or 103 dBμA. TR-102323 Revision 1 did not specify a power level for the tests, only a current (CS114) or voltage level (CS02).

The difference in test methods between MIL-STD-461C test CS02 and MIL-STD-461D test CS114 was not comprehensively addressed in TR-102323 Revision 1. Two areas that may not have been reviewed in depth are the differences in the way interference signals are applied and the concept that the power level from the interference signal should be limited. The test level was changed for the different test method without addressing the effect of the differences in test equipment impedance or delivered power.

Table 2-4. Comparison of High-Frequency Conducted Emissions and Susceptibility Tests

Test:	CE03	CS02	CS114
Purpose	Measure High-Frequency Conducted Emissions from Equipment	Measure Equipment Susceptibility to High-Frequency Conducted Emissions Caused by Radiated Emissions	Measure Equipment Susceptibility to High-Frequency Conducted Emissions Caused by Radiated Emissions
Frequency Range	15 kHz-50 MHz	50 kHz-400 MHz	10 kHz-200 MHz
Cables Tested	Power and Control	Power and Control	Power, Control, and Signal
Method of Applying Test Signal	n/a	Capacitively Coupled	Inductively Coupled
Method of Measuring Test Signal	Inductive current transducer and EMI Analyzer	Voltmeter on EUT and Wattmeter on signal amplifier	Forward power level as needed to develop test current level in cable with 50 Ω termination
Test Bandwidth Characteristics	Not specified in test procedure (3 kHz input band-width probably used for TR-102323 data)	1 kHz tone with 50% modulation	1 kHz pulse with 50% duty cycle
Test Limit	Emitted current below curve chosen for specific application in MIL-STD-461C	No susceptibility with 1 V on EUT from 50 Ω source or 1 W of power output if 1 V cannot be developed	Forward power per calibration check or current that is 6 dBμA above test level if this current is reached prior to the forward power

3
Summary of Findings

3.1 Test CS114 Purpose, Method, and Limits

The purpose of CS114 testing per MIL-STD-461E is "to verify the ability of the EUT (equipment under test) to withstand RF (radio-frequency) signals coupled onto EUT associated cabling" (Reference 3 section 5.12.3.1). Test CS114 was developed to use inductive coupling of emission signals at frequencies that were too low to use radiated coupling because the long wavelengths involved required excessively long conductors connected to the equipment under test. Thus, the test is not strictly meant as a check of conducted susceptibility to all conducted emissions, but rather as a check of conducted susceptibility to radiated emissions. The test applies a continuous wave signal to power and signal wires and increases applied current until either the test limit is reached for the signal frequency or the equipment malfunctions.

The MIL-STD-461E CS114 test limits are five curves of current levels. The curve to be applied to a given piece of equipment is chosen in accordance with Table VI of MIL-STD-461E based on the expected emissions environment where the equipment will be used. The test limit may also be further modified, since tailoring of the peak level and breakpoint is possible for specific applications (see Section 2.3.2.5 of this report).

3.2 Basis for TR-102323 High Frequency Conducted Susceptibility Limits

The conducted susceptibility limits recommended by TR-102323 Revision 1 for use in CS114 testing were based on envelopes of conducted emissions measured at six plants using test CE03 and a seventh plant using test CE102. The conducted emissions measured in actual operating nuclear power plants were used as the basis for establishing the conducted susceptibility test limits.

Tests CE03 and CE102 are not specifically designed to provide the basis for CS114 test limits. Per MIL-STD-461 Revisions C through E, conducted emissions tests CE03 and CE102 are used in the laboratory to measure the conducted emissions produced by a piece of equipment to ensure the equipment does not produce excessive noise on interconnecting cables that could adversely affect other equipment. For TR-102323, the tests were used as the methods of taking measurements to characterize the worst-case conducted emissions environment from radiated and conducted sources that a piece of equipment would have to withstand without malfunctioning. This is a different basis than the one used to establish the recommended CS114 test limits in MIL-STD-461E. The MIL-STD-461E CS114 limits are based on testing equipment specifically against the conducted emissions induced in interconnecting cables by radio-frequency radiated emissions. Test CS114 was selected for use as part of qualifying equipment for electromagnetic compatibility (EMC) in nuclear power plants because it provides a standardized method for testing equipment for high-frequency conducted susceptibility.

The original TR-102323 was prepared with the goal of applying tests in MIL-STD-461C to EMI testing for nuclear power plants. The high-frequency conducted susceptibility test in MIL-STD-461C is CS02. This test was replaced by CS114 in later revisions of MIL-STD-461. The change in testing methodology from MIL-STD-461C test CS02 to MIL-STD-461D test CS114 was not properly addressed. The change in test methods resulted in the invalid use of plant emissions data collected per CE03 and CE102 to recommend test levels applicable to CS114 in TR-102323 Revision 1. Consideration for the power (actual energy) and nominal impedance of installed systems during plant measurements would have resulted in more accurate test levels. Also, measurements of the actual radiated emissions environment could have been applied to the system characteristic data to develop estimates of conducted currents caused by radiated emissions. These data would have formed the basis of appropriate CS114 test levels that more closely model the high frequency, continuous-wave conducted emissions environment in nuclear power generating stations.

All the individual plant conducted emissions envelopes share the same general characteristics. Specifically, the emission levels are higher at frequencies below 100 to 200 kHz and then decrease as the frequency increases to the upper bound of the conducted emissions test at 50 MHz (see Figures 2-4 and 2-5).

3.3 Emissions on Power Cables versus Signal Cables

The plant emissions envelopes were produced by analysis of the measurements taken on numerous cable bundles at each plant under varying operating conditions. When emissions envelopes were established in EPRI Report TR-102323 Revisions 0 and 1, measurements from cable bundles with signal cables were not differentiated from those that included power cables. The data in some of the original emissions mapping reports were analyzed to produce emissions envelopes for signal cables separated from power cables. Graphs of these emissions envelopes show that emissions levels on signal cables are significantly lower than those for power cables.

The review of the methods used to measure the conducted emissions per CE03 did not find a generally applicable correction or reanalysis method that would allow adjusting the conducted emissions envelopes for both signal and power cables. Composite conducted emissions envelopes for signal cables are significantly lower than those for power cables and could be used without collecting new data to support lower CS114 test requirements for signal cables.

3.4 Impedance Considerations

Test CS114 is performed in a laboratory setup with specified cable loop impedance. Personnel with experience in performing conducted emissions surveys and conducted emissions susceptibility tests consider the power levels represented by the test requirements to be substantially higher than the power level of conducted emissions encountered in actual plant environments. The opinion of these personnel that the CS114 levels are conservative is based on their observation that the power needed in laboratory tests to duplicate the current levels measured on installed equipment is inordinately high. This is because of the difference between loop impedance of the two installations, which they consider to be higher for laboratory conditions than for installed equipment.

Also, the differences between test CS02 and test CS114 do not appear to have been thoroughly reviewed as to their effect on the power delivered to the EUT. 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. The limit for CS02 tests was 1 Volt from a 50 Ohm power source, with the restriction that if the power reaches 1 Watt without generating the required voltage or affecting operation of the EUT, then the equipment is considered to have passed the test.

3.5 Test Equipment Input Bandwidth Considerations

Based on a reference to CE03 testing methods in an EMC data report, National Technical Systems CE03 measurements were taken using a higher input bandwidth, 3 kHz, than is required for CE102, which is 1 kHz at the lower end of the frequency spectrum of the test. The input bandwidth for CE03 testing was not prescribed by MIL-STD-461C and was chosen by the test laboratory. The bandwidth to be used for test CE102 is specified in MIL-STD-461D and MIL-STD-461E. In the data reports used in this review, MIL-STD-461C test CE01, which measures low-frequency conducted emissions from 30 Hz to 15 kHz, was performed with an input bandwidth of 1.5 kHz. In the measurement reports reviewed for this report, there is a twelve to eighteen decibel increase in the current measured at the upper frequency of CE01 (input bandwidth of 1.5 kHz) relative to the current at the lower bound of CE03 (input bandwidth of 3 kHz).

The difference in input bandwidth between CE03 and CE102 results in higher emissions being measured by CE03 than by CE102, particularly at lower frequencies. Comparison of CE102 measurements at one plant to the CE03 measurements at other plants indicates that conducted emissions were 8 to 10 dBµA lower for CE102 measurements for frequencies below approximately 50 kHz. An effort to establish a correction for the CE03 measurements to adjust for the input bandwidth used would require comparison of CE03 to CE102 measurements at the same locations at the same plants.

3.6 Transient versus Continuous Emission Considerations

Both MIL-STD-461 tests CE03 and CE102 require the use of peak detector measurement of conducted emissions. This measurement equipment setting is likely to capture transient emissions and result in the reporting of higher continuous wave conducted emissions than are actually present. A possible means to identify the increase in measured conducted emissions because of using peak detection is to use the average voltage detector function of an EMI Analyzer or Spectrum Analyzer. Also, use of the average voltage detector setting would provide a measurement that reduces the possibility that short-duration phenomena will be recorded as continuous emissions. The measured conducted emissions spectra would then represent only the continuous wave emissions on the cabling. The ability of the equipment under test to withstand this level as measured by CS114 would be a more realistic requirement than the presently recommended levels. (Note that separate qualification tests are performed for transient susceptibility.)

4 Recommendations

The investigations described above revealed several technical factors, including inappropriate methods for collecting and analyzing test data and the use of plant conducted emissions data rather than radiated emissions data to recommend conducted susceptibility test levels for CS114. These factors have contributed in varying degrees to the adoption of overly conservative high-frequency conducted susceptibility CS114 test levels in TR-102323 (and Regulatory Guide 1.180). This investigation also generated several suggestions for tasks that should be considered as part of an effort to develop a technical basis for test levels that are more appropriate. Some combination of these tasks may constitute the most effective approach.

4.1 Develop CS114 Limits Based on MIL-STD-461E

The use of CE03 conducted emissions measurements to establish recommended limits for CS114 testing should be evaluated to determine whether another measurement of the EMI environment in nuclear power plants would be more appropriate. While CS114 is meant to test susceptibility of equipment to conducted emissions induced by radiated RF energy, measurements of current on cables capture conducted emissions from both conducted and radiated sources. Also, as noted in the discussions of loop impedance, these measurements of current do not characterize the delivered power. Thus, when currents based on these measurements are applied in test laboratory set-ups, the power required is much higher and results in stressing the equipment under test to levels beyond what they will realistically encounter once installed.

MIL-STD-461E explains that CS114 was intended to examine susceptibility to radiated emissions being picked up on signal and power cables in aircraft. Susceptibility to noise from conducted sources is addressed in CS101 for frequencies below 150 kHz. For frequencies above 150 kHz, tests CS115 and CS116 address transient conducted noise susceptibility. The TR-102323 recommended limits, in contrast, are based on CE03 and CE102 data that include noise introduced to the cables through both radiation and conduction. The impact of the conducted emission contribution is potentially amplified by impedance differences between the test equipment and plant systems (see item on impedance effects).

Development of a new basis for CS114 test levels might be approached by analytically adjusting the MIL-STD-461E curves to reflect cable lengths more characteristic of power plants, or through collection of new power plant data using a test setup similar to that used to establish MIL-STD-461E CS114 limits but with conditions based on representative power plant cable configurations. This approach would result in test levels that roll off at the low frequency end (like the CS114 curves in MIL-STD-461E), reflecting the characteristic resonance behavior of radiated coupling onto a cable of a characteristic fixed length.

The original TR-102323 test levels were produced for use with test CS02, and the change to test CS114 included differences in application of the interference signal that may result in overly high signal power being applied to the EUT compared to the power of conducted emissions found in actual plant installations. New in-plant measurements could result in finding that laboratory testing per CS114 should include limitations on the power of interference signals so as to result in a test that more closely represents the operating environment for the equipment.

This process could also include a review of the frequency range and power level of noise emitters actually encountered in nuclear power plants and a determination of whether the CS114 curves in MIL-STD-461E are representative of the radiated emissions environment in nuclear power plants. The CS114 test current levels in TR-102323 Revision 2 and RG 1.180 Rev. 1 would require high electric field levels to be induced. The conducted emissions produced by radiated emissions in a nuclear power plant should be characterized using expected or measured radiated emissions levels by a method similar to the way the levels in MIL-STD-461E were established.

The review should also include recommendations for adjusting the basis of the CS114 test limits developed by a comparison of the power level induced on equipment by the existing recommended CS114 test limits, in both TR-102323 Revision 2 and RG 1.180 Rev. 1, to the power level of high-frequency conducted emissions expected to be actually encountered by the equipment once installed in a power plant. Testing and research into these areas could result in a more accurate method of establishing high-frequency conducted susceptibility test limit recommendations for equipment to be installed in nuclear power plants.

4.2 Develop New Conducted Emissions Baseline

New conducted emissions measurements should replace the CE03 measurements documented in TR-102323. These measurements should be taken using a procedure based on test CE102. The modifications should include measurement using the narrowest bandwidth possible on the EMI analyzer and also using average rather than peak voltage detection (see Section 4.3). This would match as closely as possible the emissions that equipment under test per CS114 would be subjected to. The method of proceeding with this recommendation would be to take such conducted emissions measurements at one plant where CE03 or CS102 data was taken for TR-102323 Revision 1 and note the difference between the narrowband measurement and measurement per the MIL-STD test. This difference would establish a technical basis for reduction of the CS114 test levels

This recommendation addresses differences between the CE03 procedure that was used to develop most of the TR-102323 conducted emission data for determining the CS114 test levels and the more up-to-date CE102 procedure. Preliminary indications are that adopting the updated CE102 procedure would lead to an 8-10 dBμA decrease in the recommended TR-102323 CS114 test levels for power cables. Modification of CE102 by reducing input bandwidth would probably reduce recommended CS114 test levels further. The emissions data would be separated according to whether the measurements were taken on power or signal cables. This body of new conducted emissions data would then be used to produce new composite emissions envelopes on which to base revised CS114 test limits.

The CE01 and CE03 measurements taken in 1993 and 1994 and used to establish the conducted emissions environment for EPRI TR-102323 have fundamental problems with identifying the function of cables tested and the input bandwidths used. Surveys performed since Revision D of MIL-STD-461 (issued in January 1993) have required performance of tests in accordance with procedure CE102. The new test procedure requirements would include the detector bandwidth and dwell times as well as making other factors consistent between measurements. Also, the CE03 measurements were performed without clearly distinguishing between signal and power cables. The data thus gathered has produced composite envelopes that exceed the results of most conducted emissions tests performed in recent years using the methods of CE102.

Collection of data in accordance with CE102 at locations within a plant where data was previously taken per CE03 would more firmly establish that the differences in collection methods, and particularly in input bandwidth, resulted in higher measured emissions at lower frequencies when CE03 was performed. New in-plant measurements should focus on determining whether the levels of conducted emissions current and power applied in CS114 accurately represent the actual expected operating environment for the equipment.

Rather than taking new data, it may be possible to obtain existing MIL-STD-461E/CE102 data from EPRI member utilities for this new baseline. If desired by the utilities, the test laboratories that collected the data could be contracted to eliminate the names of the plants where data was collected in order to make the data "anonymous." This body of new conducted emissions data could then be reviewed to produce composite emissions envelopes based on consistent, up-to-date procedures. These envelopes could be compared to those in the present TR-102323 for significant differences and possibly to replace the data collected per CE03.

4.3 Justify Using Average Voltage Measurement as a Basis for CS114 Limits

At present, peak emissions levels from measurements per CE03 and CE102 are applied in CS114 as continuous wave emissions on cabling to the equipment under test. The average measurement of conducted emissions in a plant may provide a more technically appropriate measurement of the conducted emissions environment that could serve as a basis for the CS114 test levels. It is recommended that technical justification be developed for the use of average voltage detector settings for EMI analyzers to measure continuous emissions and reject transient conducted emissions. If successful, this effort would lead to development of a recommended procedure that measures only continuous conducted emissions, which are the type of interference to which test CS114 determines the susceptibility of equipment.

As previously described, CS114 is meant to determine the effect of continuous-wave, steady state conducted emissions on equipment. The effects of conducted transients on equipment are assessed using tests such as CS115 and CS116. The use of a peak detector to produce a conducted emissions spectrum that forms the basis for CS114 testing may have inappropriately introduced non-persistent emissions into the CS114 test levels. A measurement method that filters the transient conducted emissions or records only the continuous-wave conducted emissions will probably result in lower measured levels of conducted emissions.

One measurement method that was suggested by a member of the EPRI EMI Working Group is to use the average voltage detector function of an EMI Analyzer or Spectrum Analyzer. This would still produce RMS voltage measurement, as discussed above, but would provide a measurement that reduces the possibility that short-duration phenomena will be recorded as continuous emissions. The measured conducted emissions spectra would then represent only the continuous wave emissions on the cabling. Since CS114 places continuous wave emissions on cabling to the equipment under test, the average measurement could provide a more technically appropriate measurement of the ability of the equipment under test to withstand a realistic measure of the environment where it will be installed.

One issue with using average voltage measurement is that the measurement device will allow multiple settings of the integration time constant. Establishing the proper time constant to exclude transient emissions while including emissions that are present on a cable at all times but do not exhibit a continuous waveform will require achieving consensus among several parties. During discussion of the effect of using the average setting on an EMI Analyzer, the person who recommended measuring suggested a straightforward method to determine a proper time constant. The process would consist of beginning measurement of conducted emissions at a very short time constant so the measurement would resemble the peak detector's output, then stepwise increasing the integration time constant. At each longer time constant, the change in measured emissions would be noted, and the succeeding measurements should be lower. Once the difference in emissions is below a threshold, the emissions measurement can be considered to include only continuous phenomena and would be recorded.

4.4 Produce Separate Signal Cable Conducted Emissions Envelopes

Conducted emissions envelopes for signal cables should be produced where the conducted emissions data measured using CE03 or CE102 is separated from measurements taken on power cables. The resulting signal cable conducted emissions envelopes would be used to support lower CS114 test levels for signal cables, as recommended in TR-102323 Revision 2.

As noted, the measurements of conducted emissions per CE03 did not differentiate between signal and power cables. The bases for recommended levels for CS114 tests on signal cables in TR-102323 Revision 2 are MIL-STD-461E levels and IEC 61000-4-6 requirements. Conducted emissions envelopes for signal cables using the data from CE03 measurements will allow development of recommended signal cable CS114 test levels based on a bounding emissions envelope.

The conducted emissions envelopes for signal cables based on data collected per test CE03 would likely still be higher than would result using recent surveys in accordance with CE102 because of the difference in input bandwidth between CE03 and CE102. This recommendation could be implemented as an interim effort while the development of means to base CS114 test limits only on radiated sources is in progress or while the up-to-date conducted emissions envelopes based on CE102 measurements are being prepared. Essentially, this recommendation consists of the combination of the analysis in this report and the recommended test levels for signal cables in TR-102323 Revision 2. Completion should only require inclusion of the analysis in this report into a future Revision 3 to TR-102323.

4.5 Evaluate Effect of Difference in Loop Impedance

The effects of the difference between the loop impedance of installed power and signal wiring and the loop impedance of the CS114 test configuration should be investigated. The approach would be to develop a correction factor for the difference in loop impedance between installed equipment and laboratory test setups. This task could verify that the required CS114 test levels are overly conservative when used for qualifying safety-related equipment, even if a generic correction factor cannot be developed, and could also confirm the anecdotal evidence that the power levels applied to equipment under test in the laboratory are more conservative than those the equipment will encounter in its installed application.

The impedance difference between laboratory conditions and field installations affects the current needed in the laboratory to duplicate the power level of conducted emissions on installed equipment. Research that confirms the anecdotal evidence that the power levels applied to equipment under test in the laboratory are more conservative than those the equipment will encounter in its installed application could result in refinements to the conducted emissions measurement and conducted emissions susceptibility test methods. It would also ensure that the impedance difference results in a conservative error in the recommended test levels.

The opinion of personnel who perform field testing is that the CS114 levels are conservative because the power needed in the laboratory test rig to duplicate the current levels measured on installed equipment is inordinately high. This common belief should be technically evaluated and substantiated or refuted. This could verify that the required CS114 test levels are conservative when used for qualifying safety-related equipment, even if a generic correction factor cannot be developed.

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