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SUSCEPTIBILITY OF DIGITAL INSTRUMENTATION AND CONTROL SYSTEMS TO DISRUPTION BY ELECTROMAGNETIC INTERFERENCE*

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ABSTRACT

The potential for disruption of safety-related digital instrumentation and control (I&C) systems by electromagnetic interference/radio-frequency interference (EMI/RFI) bears directly on the safe operation of advanced reactors. It is anticipated that the use of digital I&C equipment for safety and control functions will be substantially greater for advanced reactor designs than for current-generation nuclear reactors, which primarily use analog I&C equipment. In the absence of significant operational experience, the best available indication of the potential vulnerability of advanced digital safety systems to EMI/RFI comes from environmental testing of an experimental digital safety channel (EDSC) by the Oak Ridge National Laboratory (ORNL). The EDSC is a prototypical system *representative of* advanced reactor safety system designs with regard to architecture, functionality and communication protocols, and board and component fabrication technologies. An understanding of the electromagnetic environment to be expected for advanced reactors can be drawn from ORNL's survey of ambient EMI/RFI conditions in the current generation of nuclear power plants. A summary of the results from these research efforts is reported in this paper. The lessons learned from the EMI/RFI survey and the EDSC tests contribute significantly to determining the best approach to assuring electromagnetic compatibility for the safety-related I&C systems of advanced reactors.

I. INTRODUCTION

Digital components are gradually being introduced in safety-related nuclear power plant instrumentation and control (I&C) systems. As analog replacement parts become increasingly unavailable and as digital systems prove to be increasingly flexible, powerful and reliable, more digital I&C upgrades will be installed in the current generation of nuclear power plants. Perhaps even more significant for the long-term future of nuclear power, the widespread use of safety-related digital I&C systems is envisioned for advanced light water reactors (ALWRs)[1] such as the Westinghouse *AP-600*, the GE Nuclear *Advanced Boiling Water Reactor* or the ABB CE *System 80+*. Similarly, the use of distributed digital I&C systems is foreseen in modular high-temperature gas-cooled reactors.[2]

In previous research sponsored by the U.S. Nuclear Regulatory Commission (NRC), the Oak Ridge National Laboratory (ORNL) studied reactor protection system designs proposed for ALWRs.[3] An environmental, functional, and aging template was developed for a protection division of each ALWR design and then compared to a similar template for an instrument string typically found in an analog protection division of a present-day nuclear power plant. Analysis of these templates identified both functional and environmental issues related to the use of microprocessor-based components in safety-related I&C systems. As a result, a methodology was proposed for evaluating the environmental qualification needs of safety-related I&C equipment (specifically, when to include accelerated aging in the qualification program). In addition, further research aimed at developing enhanced guidance for the qualification of advanced safety-related I&C systems was formulated based on the findings of the template study.

One notable finding was that there exists the potential for increased vulnerability to electromagnetic interference (EMI) and/or radio-frequency interference (RFI) for advanced digital safety systems. It was concluded that test criteria and guidelines for EMI/RFI emissions and susceptibility that are specific to the nuclear power plant environment should be developed. Therefore, the NRC Office of Nuclear

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Regulatory Research engaged ORNL to assist in developing the technical basis for regulatory guidance on EMI/RFI and power surge withstand capability (SWC) issues.

This paper will report the findings of research conducted by ORNL to investigate the susceptibility of digital I&C systems to EMI/RFI effects and to determine the electromagnetic environment to be expected in nuclear power plants.

II. ELECTROMAGNETIC COMPATIBILITY

The susceptibility of digital technology to electromagnetic effects is of concern to the nuclear industry because faster microprocessor clock rates and lower logic voltage levels can increase the potential for disruption by EMI/RFI. The nature of the problem is illustrated in Figure 1. The state of a microprocessor is affected by the logic voltage levels of various clock and control lines connected to it. Typically, a desired change of state is induced by a voltage transition (on a rising or falling edge) as shown in the figure. If EMI/RFI is coupled onto the signal line, it can disrupt the process. The combination of the logic voltage level and the EMI/RFI can possibly be misinterpreted as an edge, thereby causing a change of state when none was intended.

To minimize the effects of EMI/RFI, good electromagnetic compatibility (EMC) design and installation procedures must be used. It is not trivial to ask what constitutes good EMC design. A well-designed system must be sufficiently hardened to withstand EMI/RFI levels that can reasonably be expected to occur in its environment, but overdesign increases costs without accompanying benefit. The cost of EMI/RFI hardening increases rapidly as a function of the degree of hardness.[4,5]

This NRC-sponsored research has led to the recommendation of specific test criteria and methods by which to confirm compatibility of equipment with its intended environment and to the endorsement of industrial guidance on installation practices to ensure proper grounding, shielding and isolation.[6] Military standard (MIL-STD) test criteria were selected because they provide a well-established, systematic approach by which the susceptibility of equipment to known or expected electromagnetic conditions can be evaluated and the contribution of the equipment to the electromagnetic ambient conditions through its own emissions can be determined. These recommended testing practices are based on the military services' considerable experience (almost 30 years) in evaluating EMI/RFI effects.

One aspect of the research into establishing EMC for digital I&C equipment involves the determination of the likely failure modes and mechanisms associated with EMI/RFI. This information helps to verify the significance of EMI/RFI as an environmental stressor and confirm that MIL-STD test methods are adequate to detect the vulnerabilities of microprocessor-based equipment to electromagnetic effects.

Another important element of the research is the identification of the expected electromagnetic environment in which the digital I&C equipment is likely to be installed. The template study[3] concluded that ALWR safety systems will likely be qualified to the similar environments as those for current light-water reactors (LWRs). Thus, knowledge of EMI/RFI levels in conventional LWRs contributes an important element to the technical basis for EMI/RFI qualification of digital I&C for ALWRs.

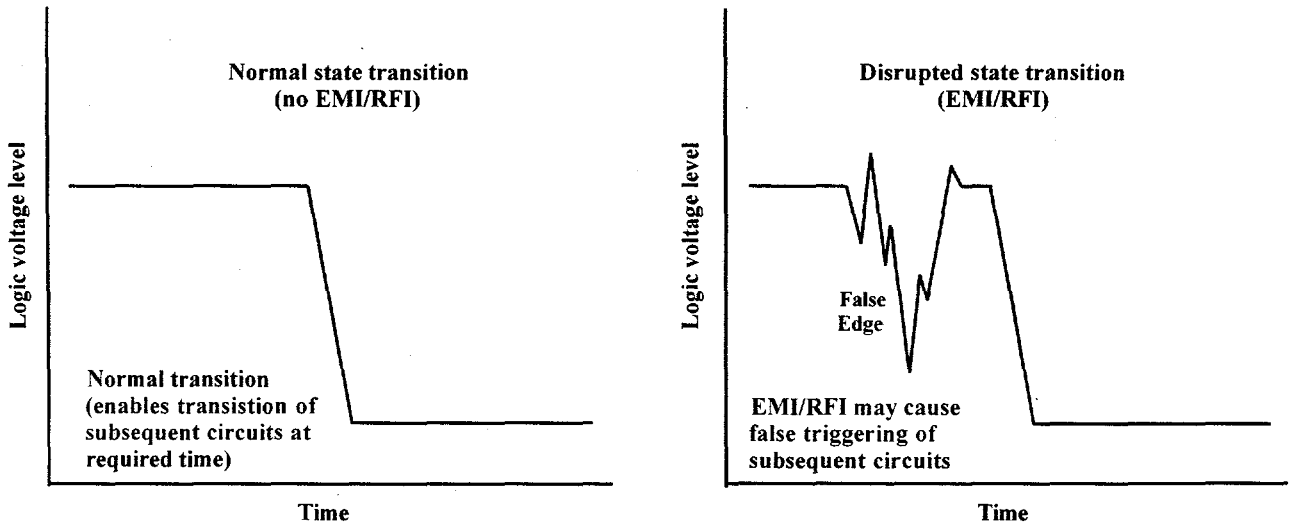

Figure 1 Illustration of the potential for false triggering of digital circuits due to electromagnetic noise

III. SAFETY CHANNEL EMI/RFI TEST RESULTS

ORNL research into the potential vulnerabilities and upsets of microprocessor-based I&C systems helps address the question of how the performance of an advanced digital safety system might be disrupted by EMI/RFI. The approach employed involved environmental testing of an experimental digital safety channel (EDSC).[7] The EDSC, shown diagrammatically in Figure 2, was constructed by ORNL researchers using system architecture, functionality and communication protocols, and board and component fabrication technologies that are *representative of* ALWR reactor protection systems. The EDSC consists of two major functional subsystems: the test system (i.e., the equipment under test) and the test control system. The test system represents a single channel of an advanced reactor protection system and consists of the process multiplexing unit (PRS/MUX), a digital trip computer (DTC), and an engineered safety feature multiplexing unit (ESF/MUX). The test control system stimulates the test scenarios (i.e., generates analog signals corresponding to various reactor conditions), simulates the other three channels of a reactor protection system (some advanced designs include isolated interchannel communication for trip voting), and monitors and logs the performance of the test system during environmental testing. The host processor (HOSTP) performs the test control functions. The design details of the EDSC have been reported previously.[8]

To investigate system-level vulnerabilities, the EDSC was subjected to a range of environmental stressors, including EMI/RFI. The EMI/RFI tests were performed according to applicable[6] test criteria and methods stipulated in MIL-STD 461C[9] and MIL-STD 462,[10] respectively. MIL-STD 461C establishes the military's emission and susceptibility requirements for electronic, electrical, and electromechanical equipment and subsystems. It also provides a basis for evaluating the electromagnetic characteristics of equipment and subsystems by setting operational acceptance criteria. The test methods corresponding to the MIL-STD 461C requirements are described in MIL-STD 462.

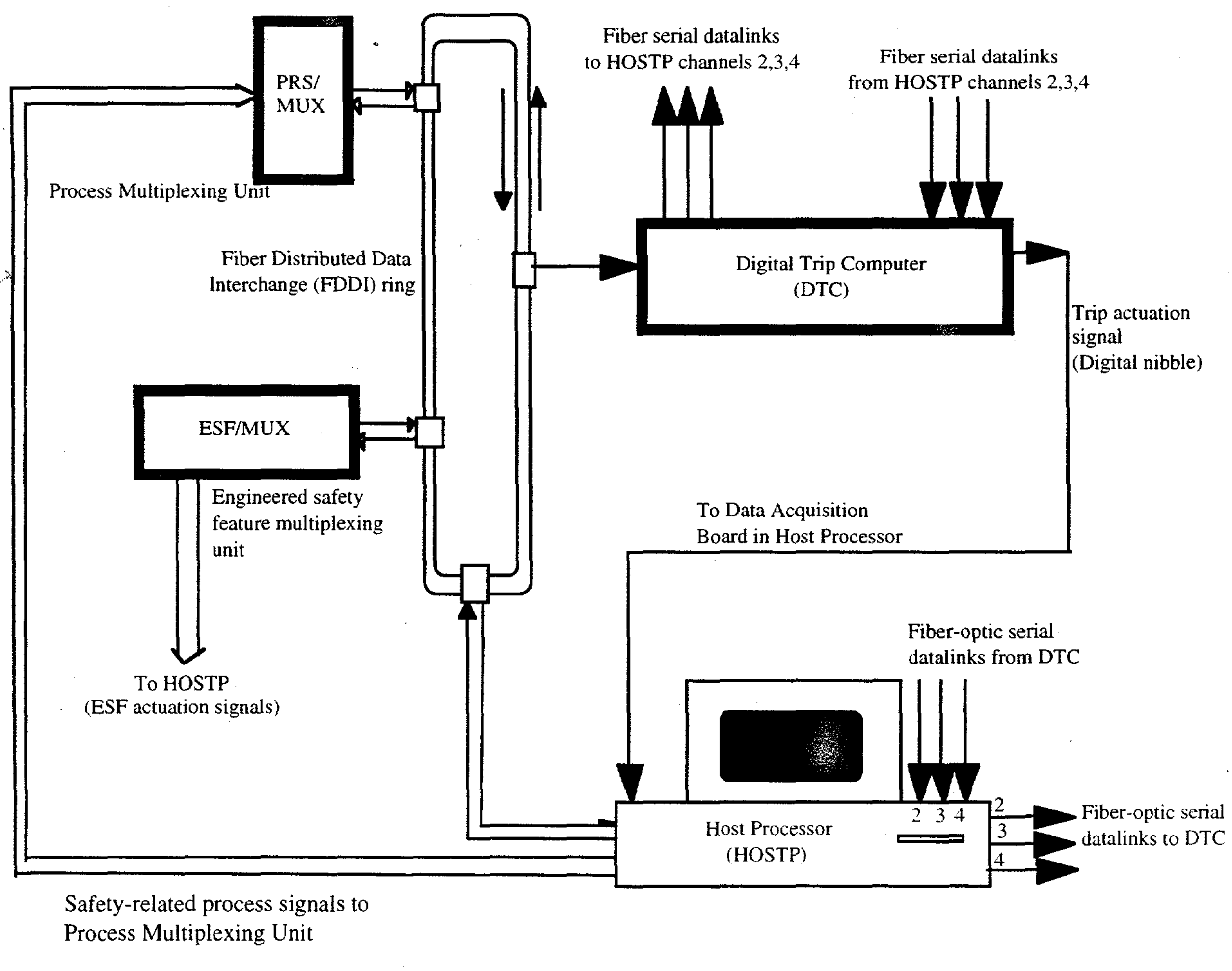

Figure 2 Block diagram of the experimental digital safety channel

The objective of the EMI/RFI tests was to identify/confirm system-level EMI/RFI-induced upsets and failure modes in microprocessor-based safety systems. The tests also enabled comparisons to be made with other environmental stressors, including smoke exposure, based on a common testing subject performing a nuclear safety function. The tests were not intended to ascertain whether the EDSC met emissions criteria. Therefore, only susceptibility test methods and criteria were used in the experimental investigation. The tests performed were the following:

CS01—Conducted Susceptibility, Low Frequency;
CS02—Conducted Susceptibility, High Frequency;
CS06—Conducted Susceptibility, Spikes;
RS01—Radiated Susceptibility, Magnetic Fields;
RS02—Radiated Susceptibility, Spikes; and
RS03—Radiated Susceptibility, Electric Fields.

The EDSC experienced one hard failure (i.e., permanently damaged component) during testing. The power supply for a multiplexer backplane was damaged during the RS03 test under exposure to an electric field strength of 72 V/m at 20 MHz, which is a significantly higher level than what might reasonably be expected for nuclear power plant environments in typical I&C equipment locations. The largest number of upsets (i.e., 47% of all errors) observed during testing involved errors in serial datalinks. These errors included communications retransmissions and timeouts, as well as a few instances of loss of data accuracy. There were three occasions during the tests where communication across the fiber-optic network was upset, resulting in retransmissions.

Of the six EMI/RFI susceptibility tests performed, the EDSC and its interfaces were found to be least susceptible (no errors) to radiated magnetic fields in the range 30 Hz to 50 kHz (RS01). Most of the errors were found to occur with the conducted spike test (CS06) and the radiated electric field test (RS03). However, these errors occurred at field strengths that are higher (above 20 V/m) than called for in the MIL-STD specifications (operational acceptance criteria) used as guidelines for the tests.

High-voltage spikes on power leads were found to cause a greater number of upsets and within a relatively short time (i.e., seconds) compared to low-voltage, sinusoidal noise on the same power leads. In the latter case, errors did not occur until several minutes into the application of the noise voltage. These results are consistent with expectations, since EMI/RFI-related upsets/failures are typically caused by the EMI/RFI inducing a high enough voltage to cause malfunctions such as false triggering of digital devices, inadvertent bit changes in memory devices, or breakdown of on-chip protection. If an EMI/RFI burst is going to have an effect via these mechanisms, it is reasonable to expect it to do so in a relatively short time within the application of the EMI/RFI burst.

While the EDSC test demonstrated system-level effects for both conducted and radiated EMI/RFI, the commercial components employed exhibited greater susceptibility to conducted EMI/RFI. This observation was expected given the more direct coupling between the interference source and the equipment for conducted interference. It should be noted that the relative susceptibility of particular systems can be mitigated by diligent application of recommended grounding, shielding, isolation, and surge withstand practices.[6]

The EMI/RFI test results and results for other environmental stressors are discussed in detail in NUREG/CR-6406.[7]

IV. EMI/RFI SITE SURVEY RESULTS

Also relevant to the EMI/RFI qualification of digital safety systems, both for digital upgrades and for advanced reactor designs, is the expected electromagnetic environment in which the systems will operate. Obviously, a system should be made sufficiently resistant to EMI/RFI to perform its required function. (In essence, it should be sufficiently hardened to be compatible with its working environment.) Determining appropriate susceptibility testing levels therefore requires a fairly detailed characterization of ambient conditions at the site of the equipment installation. Characterization of EMI/RFI ambient conditions requires long-term observations; this has long been recognized,[11] particularly in the British nuclear power industry.[12,13]

To properly characterize the EMI/RFI environment at current LWRs and to estimate the expected environment at ALWRs, ORNL conducted a long-term survey of ambient electromagnetic conditions at several nuclear power plants.[14] A representative sampling of power plant conditions (reactor type, operating mode, site location) monitored over extended observation periods (e.g., continuous measurements for up to 5 weeks at a single location) were selected to more completely determine the characteristic electromagnetic environment for nuclear power plants. Observations covered a 14-month period and 8 different nuclear units, representing all U.S. reactor manufacturers. A full range of operating modes—full-power operation, low-power operation, startup, coastdown, plant outage, and an unscheduled event resulting in a plant trip—were observed.

The nuclear units monitored included the following: one Combustion Engineering (CE) pressurized water reactor (PWR), three Babcock and Wilcox (B&W) PWRs, one General Electric (GE) boiling water reactor (BWR), and three Westinghouse (W) PWRs. Participating utility companies included Duke Power, Public Service Electric and Gas, Entergy Operations and the Tennessee Valley Authority.

The measurement system[15] employed consists of two instruments developed by ORNL for long-term, unattended monitoring of ambient electromagnetic emissions. This approach minimized intrusion on the normal day-to-day operation of the plant. The requirements of this survey resulted in several novel instrument developments.[16] The magnetic spectral receiver can be configured to measure radiated or conducted electromagnetic levels over a frequency range of 305 Hz to 5 MHz. The implementation of the receiver uses a multiresolution digital filter bank, implemented in dedicated hardware. The electric spectral receiver measures radiated electric fields over a frequency range of 5 MHz to 8 GHz. Its design uses heterodyne conversion and an analog peak detector.

The survey establishes characteristic operating envelopes that bound the observed electromagnetic conditions at the nuclear power plants.[14] Bounding envelopes for the survey are based on the highest EMI/RFI strength observations and the associated expanded uncertainties for the measurements. The expanded uncertainty establishes an interval about the measurement results in which the values of the measured phenomenon can be expected to lie with a high level of confidence (95%). Table 1 presents the bounding observation envelope for radiated electric fields. Table 2 presents the bounding observation envelope for radiated magnetic fields. Table 3 presents the bounding observation envelope for conducted EMI/RFI events.

Regarding the confidence that can be placed in the measured data, the ORNL survey generated ~650,000 electric field observations, ~35.7 million magnetic field observations, and ~6.4 million conducted EMI/RFI observations. However, only a few thousand spectra show electromagnetic fields at potentially disruptive levels. Yet, it is the strength and rate of occurrence of these rare higher levels that should determine EMI/RFI susceptibility test levels. A statistical analysis of the data collected in this survey indicates that the probability of observing a significant EMI/RFI event in a random 30-minute spot check is on the order of 0.003. Thus, the results of the survey confirm that long-term monitoring is needed to adequately characterize the electromagnetic environment at a site. Finally, the wealth of data from this survey, captured during continuous monitoring for extended periods at each plant location under the variety of operating conditions, provides great confidence that the highest strength EMI/RFI events were captured.

The measurement approach and comparative analysis of the survey results are presented in detail in NUREG/CR-6436.[14]

V. CONCLUSIONS

Digital I&C equipment hardened to withstand EMI levels greater than the bounding observation envelopes indicated in Section IV can be expected to operate reliably in the EMI/RFI environment typical of nuclear power plants. The EMI/RFI susceptibility test results for the EDSC show that this level of EMI/RFI immunity is practical to obtain and demonstrate that recommended test methods are adequate to identify system vulnerabilities. Thus, the compatibility of safety-related digital I&C systems with the electromagnetic environment to be expected at nuclear power plants can be confirmed by applying the MIL-STD test criteria and methods.[6] The template studies performed by ORNL show that it is reasonable to extend these findings to ALWRs.[3] Therefore, the results from the NRC-sponsored research at ORNL contribute significantly to the determination of the best

Table 1 Bounding envelope for radiated electric fields

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

Table 2 Bounding envelope for radiated magnetic fields

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

Table 3 Bounding envelope for conducted EMI events

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

approach to ensuring electromagnetic compatibility in the safety-related systems of advanced reactors.

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