Instrumentation and Controls Division

A CONFIRMATORY RESEARCH APPROACH TO THE MEASUREMENT
OF EMI/RFI IN COMMERCIAL NUCLEAR POWER PLANTS*

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A Confirmatory Research Approach to the Measurement of EMI/RFI in Commercial Nuclear Power Plants

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ABSTRACT

The Oak Ridge National Laboratory (ORNL) is conducting confirmatory research on the measurement of electromagnetic/radio frequency interference (EMI/RFI) in nuclear power plants. While it makes a good beginning, the currently available research data are not sufficient to characterize the EMI/RFI environment of the typical nuclear plant. Data collected over several weeks at each of several observation points are required to meet this need. To collect the required data, several approaches are examined, the most promising of which is the relatively new technology of application specific spectral receivers. While several spectral receiver designs have been described in the literature, none is well suited for nuclear power plant EMI/RFI surveys. This paper describes the development of two receivers specifically designed for nuclear power plant EMI/RFI surveys. One receiver surveys electric fields between 5 MHz and 8 GHz, while the other surveys magnetic fields between 305 Hz and 5 MHz. The results of field tests at TVA's Bull Run Fossil Plant are reported.

1. INTRODUCTION

Electromagnetic and radio frequency interference (EMI/RFI) are known to cause upsets and malfunctions in safety related instrumentation and control (I&C) systems [Cir 86, Ewi 94]. Systems can be designed to withstand exposure to EMI/RFI, but the cost of a system can increase rapidly as its EMI/RFI immunity increases [Ott 88]. Thus, the designer of I&C systems is faced with the difficulty of hardening the system enough to withstand any EMI/RFI effects that the system is likely to encounter. At the same time, it is undesirable to include more EMI/RFI immunity than is really needed, as this can lead to dramatic and unnecessary increases in the cost, complexity, and size of the system.

EMI/RFI becomes a particular concern as nuclear plant I&C systems designers begin to use digital circuitry [Ewi 92]. As the digital state of the art progresses, clock rates become faster and logic levels become lower. In practical terms, the more modern the digital system, the smaller is the logic pulse, in both the time and voltage dimensions, and consequently, the greater the likelihood that a pulse can be corrupted by EMI/RFI. To minimize the effects of EMI/RFI, good electromagnetic compatibility (EMC) design and installation procedures must be used. However, what is good EMC design?

In several recent instances, utilities have conducted an EMI/RFI survey of the proposed location of digital equipment to demonstrate to the Nuclear Regulatory Commission (NRC) that ambient levels are substantially below the withstand level of the digital system upgrade [EPR 94]. Many within the industry consider it unnecessary and prohibitively expensive to perform an EMI/RFI survey for each instance and location where a digital system is to be added. Hence, there is considerable interest in establishing a technically well founded design guideline that will eliminate the need for these surveys.

To assist in the process of establishing good EMC engineering practices, EMI acceptance criteria should be determined for the nuclear industry. The Oak Ridge National Laboratory (ORNL) is currently helping NRC to establish a technical basis for acceptance criteria. This assistance consists of both an exhaustive survey of existing standards and practices, as summarized by Ewing et al., and confirmatory experimental research as the need arises [Ewi 92].

Good EMC engineering practice for safety related I&C systems in nuclear power plants is dominated by the question, what field levels should the system be able to withstand? Trying to answer this question leads to another, what are the ambient field levels typically found in a nuclear power plant? This leads to further questions. How is EMI/RFI distributed as a function of frequency? How often do significant EMI/RFI effects occur? How are they distributed in time? Are they roughly evenly spread, or do they occur in isolated clusters in time? Do these distributions vary significantly among plants? As NUREG/CR-5941 states, insufficient data are available to answer these questions from the existing literature [Ewi 94].

This paper examines the present state of research, and what is needed to supplement the currently available data. It considers the alternative techniques for monitoring EMI/RFI in safety related environments, and determines that application specific spectral receivers are best suited for nuclear power plant monitoring. It describes the development and field testing of two devices, one to monitor electric fields, and another to monitor magnetic fields.

2. CURRENT STATE OF RESEARCH

2.1 EMI Measurements in Nuclear Plants

The Electric Power Research Institute (EPRI) recently completed the only systematic and extensive study of EMI/RFI levels in nuclear power plants that has ever been undertaken [EPR 94]. The investigators developed a generic test procedure consisting of six types of measurements based on military standards [MIL 93]. They did the generic measurements in various locations at six different nuclear power plants. The data are reported as a set of "worst case" observations. The implicit assumption throughout the EPRI report is that EMI/RFI levels at each location do not vary significantly over an extended period. While not explicitly stated in the report, the actual test data seem to consist primarily of short duration (on the order of hours) spectrum analyzer readings for various combinations of the six generic tests at each location.

The EPRI study led to several major findings. EMI/RFI levels vary sensitively with location, and consequently, the measurements should be taken at the location of the digital equipment. Above 60 Hz, worst case low frequency conducted emissions at all six plants were at least 20 dB below the EPRI recommended susceptibility level of 142 dB μ A. Worst case high frequency conducted emissions at all six plants were at least 10 dB below the EPRI recommended susceptibility level of 103 dB μ A. Worst case low frequency radiated emissions at all six plants were at least 12 dB below the EPRI recommended susceptibility level that declines logarithmically from 180 dBpT at 30 Hz to 116 dBpT at 40 kHz. Worst case high frequency conducted emissions at all six plants were at least 42 dB below the EPRI recommended susceptibility level of 140 dB μ V/m. Worst case transient conducted emissions at all six plants were at least 25 dB below the EPRI recommended susceptibility level of 158 dB μ A. The study provides a systematic body of data urgently needed by the industry, and not previously available.

There is a need to confirm that the results determined by industry studies completely characterize the EMI environment in NPP. The existing data consists of a series of spot checks of limited duration which are assumed to have captured the worst case values. Industry studies do not provide information on how EMI/RFI varies over an extended period, and they do not address the issues of the rate and distribution of EMI/RFI occurrences raised in Section 1 of this paper. To answer these questions, supplemental information is needed.

2.2 Measurement Techniques

As in the EPRI study, safety related EMI/RFI measurements in other industries are frequently done with a spectrum analyzer. EMI/RFI effects can be especially crucial in hospital operating rooms, where an EMI/RFI induced failure can directly lead to the loss of life, and electric fields emanating from medical equipment can be very high, as much as 44 Volts/meter (V/m) [Nel 94]. Similarly, the operation of high speed railroads is highly automated, depends critically on reliable communications, and occurs in an extremely noisy EMI environment [Gra 94]. An EMI/RFI induced train wreck can lead to extensive loss of life and massive property damage.

In the EPRI study, the hospital study, and the railroad study, a spectrum analyzer was used. Data collection for all three studies required elaborate experimental setups, with many accessories needed to process the EMI/RFI emanations into a form acceptable to the spectrum analyzer, and other accessories to capture the spectrum analyzer output. All three studies required an operator to be present throughout the course of the data collection, and each produced a torrent of raw data that required extensive post-processing.

While this kind of observation may provide a complete picture of EMI/RFI in a surgical operating room or a railroad locomotive, it is unlikely to do so for a nuclear power plant. Both a surgical procedure and a train trip between New York and Washington have in common the fact that either can be completed in a few hours. Consequently, it is practical to keep the experimenter on hand throughout the trip. Both have in common the fact that possibly disruptive levels of EMI/RFI occur almost continuously throughout the duration of the trip. Thus, it is desirable to keep a detailed record of all the occurrences of EMI/RFI for subsequent analysis. Finally, both have in common the fact that

in neither setting is human error a major cause of EMI/RFI occurrences. Therefore, the mere presence of an outside observer does not reduce EMI/RFI.

Contrast this with the situation in a nuclear plant control room. The operating cycle lasts for months rather than hours, and continues around the clock. It would be extremely expensive to have three shifts of experimenters to collect many weeks of EMI/RFI data with a spectrum analyzer at each observation point. In addition, EMI/RFI events in nuclear plant control rooms are rare and intermittent. Most of the time, the EMI/RFI levels are below the noise floor of the monitoring equipment. To hold the recorded data to a reasonable volume, the monitoring equipment must be set up to recognize and discard the "zero" readings, merely noting how many occurred. Finally, it must be recalled that a cause of EMI/RFI in nuclear power plants is human error, such as the unauthorized operation of a handheld transceiver; the mere presence of an outside observer induces the power plant staff to be on its best behavior, and thus reduces the number of EMI/RFI events. (Note: Our experience at power plant sites suggests that an unattended and unadorned gray box quickly fades from the notice of power plant staff, who go on about their business as if it were not there.)

A spectrum analyzer is designed to be used as a diagnostic or troubleshooting device. Given that a disruptive EMI/RFI level is known to exist, a spectrum analyzer in the hands of a skilled operator is the ideal tool to track down the source. However, when utilized for ambient surveys, the spectrum analyzer is awkward and unwieldy, requiring an elaborate hardware setup and a human attendant. While better than no tool at all, it is not the right tool for the job. It is reasonable to ask if another tool might not be better suited to the job of observing EMI/RFI effects over the long term.

Dosimetry might seem a possibility. A dosimeter is a broadband electromagnetic monitoring device designed to measure the exposure of humans or equipment to electromagnetic energy. For example, the Personal RF Dosimeter developed at ORNL measures the exposure of sailors on an aircraft carrier deck to RF fields over an extreme bandwidth [Roc 90]. Similar devices, operating over a narrower bandwidth, measure exposure to near field effects by considering electric fields and magnetic fields simultaneously [Bab 86, Asl 87]. Dosimeters typically are concerned with the total energy resulting from the exposure; in effect, they measure average rather than peak effects. Magnetic field measurement techniques use a shielded loop antenna and rudimentary processing circuitry [Mis 93]. In dosimetry, for both electric and magnetic effects, detection (usually by a hot carrier diode acting as a rectifier) takes place directly at the antenna, and frequency information is thereby discarded before the signal arrives at the processing circuitry.

There are alternatives to the antenna-rectifier scheme for observing electric fields. A recent development in electric field detection is the photonic probe [Mas 89]. These devices depend on phenomena such as the Pockels effect to change the optical properties of dielectric materials as a function of electric field. Typically these have a noise floor at 7 V/m, and are therefore only suitable for observing strong field effects such as electromagnetic pulses that result from nuclear explosions. They are not suitable for power plant ambient monitoring, where the field strengths are usually far less than 10 V/m.

Similarly, there are alternatives to loop-rectifier schemes for observing magnetic fields. Active magnetic sensor elements, featuring wide bandwidth and high dynamic range are being explored [Eum 93]. The technology does not appear to be sufficiently mature for power plant monitoring.

Research in broadband monitoring has recently been done by Gassmann and Furrer [Gas 93]. Their system was designed to measure extremely strong fields (up to 1500 V/m and 6 Amps/meter) in the presence of high powered transmitters. While the system has excellent bandwidth and dynamic range, it does not preserve frequency information.

Dosimeters are fast and cheap. They are useful if the frequency of the EMI/RFI signal is already known, or if the knowledge of frequency does not matter. Dosimeter designs are frequently reported in the literature. Commercial models are much cheaper than spectrum analyzers. Most dosimeters respond to average effects rather than peak effects. However, a digital system is disrupted by the peak value rather than the total energy of an EMI/RFI event. Thus, the data produced by dosimeters are not a good predictor of whether or not the observed event is likely to disrupt a digital system. Often, dosimeters respond only to a very strong field; they are typically not sensitive enough to measure ambient EMI/RFI effects in a power plant control room, and there is no practical way to increase their sensitivity.

If neither the spectrum analyzer nor the dosimeter is well suited for long term ambient EMI/RFI surveys, is there another instrument that can serve this purpose? The EMI/RFI (or spectral) receiver is the right tool for the job, but available commercial models are not quite suited to this particular task. Hewlett Packard has released specifications for the HP 8546A EMI/RFI Receiver [Hew 93]. The system costs about \$65,000, excluding antennas. The specification sheet suggests that it is designed primarily for testing of personal computers for compliance with EMI/RFI regulations issued by various licensing authorities. Because the system features many external controls and several fascinating displays, it is not well suited for long term unattended monitoring in a nuclear plant control room environment. Very recently, Electro-Metrics of Amsterdam NY has published the principles of design of EMI/RFI receivers, but their paper does not include the description of a specific product [Sik 94].

A spectral receiver, customized for long term unattended operation, is the right tool for the job of nuclear power plant EMI/RFI ambient monitoring. Unlike dosimetry, it can preserve frequency information and be made sensitive to low field strengths. Unlike the spectrum analyzer, it does not require an elaborate setup, and can be designed to operate unattended for an extended period. The practicality of using spectral receivers to do the job, the unavailability of suitable devices in the commercial market, and need to collect long term nuclear plant site data, have led ORNL to develop and construct two different kinds spectral receivers, one for high frequency electric fields, and the other for low frequency magnetic fields.

3. SPECTRAL RECEIVER DESIGN REQUIREMENTS

The spectral receivers, or monitors, constructed by ORNL for NRC, are being deployed for automatic, unattended recording of EMI/RFI levels at nuclear plant sites. They are unattended in the sense that no human operator is required while the monitor is making its observations. They operate in the presence and plain view of nuclear plant employees; to reduce the temptation of tampering or mischief, the monitors are unadorned gray boxes, with no external displays, and no external controls except a key lock "off/on" switch whose key can be removed in either setting. The areas to be monitored include turbine rooms, and the monitors must be physically robust enough to withstand extended exposure to an industrial environment.

The monitors must be unobtrusive. Other than sensing the ambient levels of electromagnetic fields, and taking operating power from the plant power system, they do not interact with the nuclear plant environment. They are EMI/RFI hardened; no radiated energy should enter the monitors except through the antenna, and no signals generated by the monitors should escape. The monitors are not intended to be connected to the plant data acquisition system.

While it would be desirable for the monitors to be battery powered, and independent of the plant power system, they require several continuously running active analog elements. To run completely unattended for several months would require enormous (roughly several hundred pounds) batteries with capacities of hundreds of ampere-hours. For a practical system, the tradeoff is between two alternatives. One is to have the monitor battery powered, isolated from the plant power system, but requiring the battery to be replaced every day. The other is to have the monitor powered from the plant power system by a well shielded power supply, and show with test data that the monitor does not interfere with the operation of plant equipment.

The ORNL monitors are capable of unattended operation for several months. They include an onboard uninterruptible power supply, and can withstand a power interruption of up to 20 minutes. In addition, the recorded data are stored on an onboard floppy disk every six hours. Thus, even in case of a major failure, most of the recorded data would be preserved.

The frequency range to be covered is 305 Hz to 8 GHz. This range is determined primarily by MIL-STD-461C, Requirement RS01 (low end) and RS03 (high end) [MIL 93]. As an example of the real-world EMI/RFI environment in an electric utility, consider that the Tennessee Valley Authority (TVA) uses power line carrier (PLC) communications in the 30-300 kHz band, and some PLC below 30 kHz. TVA uses microwave intersite communications in the 7-8.2 GHz band. In addition, there is a risk of EMI/RFI from other low frequency sources such as video monitors [Nic 93]. It was found to be impractical to build a single device to cover the desired frequency range. Two monitors, the magnetic spectral receiver covering 305 Hz to 5 MHz, and the electric spectral receiver covering 5 MHz to 8 GHz, were developed.

No attempt is made to obtain isotropic antenna response, since to do so would require three orthogonal antennas and processing circuitry for each [Nov 93]. Since this is intended as a survey type system, it is not considered that the

improved precision of an isotropic response is worth the expense and the resulting unwieldiness of the equipment.

The output of each of the monitors is a two dimensional matrixed histogram. One dimension is bands (or bins) of frequency. The other dimension is bands (or bins) of peak field strength. The entries in the histogram matrix are the running totals of the number of times (i.e., number of sampling intervals) that the ambient EMI/RFI level falls within the intersection of a strength bin and a frequency bin. Resolution is coarse, being limited by the bin width. The histograms and their time tags are stored to disk every six hours. Thus, the counts for any observation period can be determined by subtracting the running total counts through the previous period from the running total counts through the period of interest.

Typical operation of each monitor is as follows. The monitor is placed in the environment to be observed, and a VGA video monitor and personal computer keyboard are temporarily connected. The monitoring program starts with the histogram counters zeroed. The VGA video monitor and keyboard are disconnected, and the EMI/RFI shielded interface port is sealed. The system is left unattended, and it counts events for up to several months. At the end of the monitoring interval, the interface port is unsealed and the VGA video monitor and keyboard are temporarily reconnected, and the monitoring program is stopped. The running total histogram for each six hour interval is an ASCII file. Data retrieval consists of removing the floppy disk from its drive, and copying the files.

To provide automatic, long term unattended monitoring of EMI/RFI signals of unknown frequency and bandwidth requires circuitry capable of handling extreme bandwidths. The low band of the electric spectral receiver covers an input bandwidth of 5 MHz to 1000 MHz, or 200:1, and an intermediate frequency (IF) bandwidth of 12.5 to 37.5 MHz, or 3:1. The magnetic spectral receiver covers a bandwidth of 305 Hz to 5 MHz, or 16393:1, and can examine the entire 14 octave bandwidth in a single glance. It is noteworthy that in current EMI/RFI practice, a signal with a 2:1 bandwidth is considered ultrawideband [Eng 93]. In view of this, it is not surprising that a device similar to these monitors is not available commercially, and that the design of these monitors includes considerable novelty.

4. ELECTRIC SPECTRAL RECEIVER

One monitor assembled for this research is configured to observe high frequency electric fields. Frequency coverage is from 5 MHz to 8 GHz. The monitor uses two resistive taper antennas as broadband electric field probes. The antennas are connected to independent processing circuits; one covers 20 bands of equal width from 5 to 1000 MHz, and the other covers a single band from 1 to 8 GHz. The conceptual diagram is shown in Figure 1. A photograph of the processing electronics is shown in Figure 2. A photograph of the completed prototype receiver is shown in Figure 3.

Microwave (1-8 GHz) signals are treated as a single band. The microwave antenna output is coupled through a 1 GHz high pass filter to an amplifier having a flat response from 1-8 GHz. In the interest of holding down cost, a relatively high noise figure (6-8 dB) is tolerable. Since the objective is to

Figure 1. Block Diagram of Electric Receiver.

Figure 2. Photo of Electric Receiver Electronics.

detect the presence of relatively strong electric fields, going to great expense to obtain a low noise figure is not necessary.

The amplified output is processed by pseudo-peak detection, using a video detector based on a hot carrier diode. This produces a 6 MHz bandwidth signal that is a replica of the modulation envelope of the original microwave signal. The video detector output is then fed to a peak detector, which takes the envelope input and produces a DC output that is correlated with the peak value of the original microwave signal.

Signals below 1 GHz are processed through a heterodyning scheme. The purpose of the local oscillator (LO) chain is to produce a voltage controlled local oscillator that sweeps from 5 MHz to 1 GHz in a single sweep as the control voltage sweeps from 0 to 20 Volts DC. To obtain this performance, a variable oscillator whose output can be swept from 905 to 1900 MHz is mixed with a fixed oscillator at 900 MHz. The difference at the first mixer output is thus 5 to 1000 MHz. The first mixer also produces a sum signal at 1805 to 2800 MHz. A low pass filter with a 1 GHz cutoff suppresses the sum.

The second mixer mixes the broadband (5 MHz to 1 GHz) output of the antenna, and the swept output of the LO chain. The output of the mixer is two sets of broadband signals, the sum of the splitter output and the LO, and the absolute difference of the splitter output and the LO. The absolute difference is the desired product. By following the second mixer with a low pass filter (LPF), a folded window looking into the RF spectrum is realized. For instance, with a

Figure 3. Photo of Electric Receiver.

LPF of 37.5 MHz, the intermediate frequency (IF) is limited to DC-37.5 MHz. For a given LO frequency, the RF window includes:

$$(LO - 37.5 \text{ MHz}) \leq RF \leq (LO + 37.5 \text{ MHz})$$

The mixer output is amplified by a circuit with a 37.5 MHz cutoff low pass characteristic. Therefore, when the local oscillator sweeps from 42.5 to 962.5 MHz, the amplifier output is a 75 MHz wide window sweeping from 5 MHz to 1000 MHz. The signal is amplified and applied to a peak detector, which produces a DC voltage proportional to the peak value of the signal in the window during the sampling time interval.

The control microprocessor operates on a 35 second sampling sweep, capturing the peak electric field strength observed during each sweep. The 35 second sweep samples each of the 21 individual bands within the spectrum for about 1.5 seconds. A signal must be present for at least 35 seconds to assure that it will be captured; signals of less than 35 second duration will be captured only if the system is looking at that particular band at the time the signal occurs.

The controller carries out the operating cycle as follows. It selects the next local oscillator frequency and the corresponding peak detector, zeroes out the detector, waits 1.5 seconds, reads the peak detector voltage level (which is proportional to the peak field observed during the last second of the 1.5 second wait), and increments the appropriate histogram bin in random access memory (RAM). It moves to the next local oscillator frequency and repeats the process, and so on until the entire range is swept. It repeats the cycle indefinitely until interrupted by a command from the outside world.

5. MAGNETIC SPECTRAL RECEIVER

The other monitor assembled for this research is configured to observe low frequency magnetic fields. Frequency coverage is from 305 Hz to 5 MHz. The monitor uses a passive loop antenna as a broadband magnetic field probe. The conceptual diagram is shown in Figure 4. A photograph of the processing electronics is shown in Figure 5. A photograph of the completed prototype receiver is shown in Figure 6. The 305 Hz to 5 MHz coverage spans 14 octaves. The magnetic monitor captures peak magnetic field strength in each octave during each sampling cycle.

The magnetic spectral receiver repeatedly cycles through the 14 octaves every 1/2-second. The monitor takes 128K samples at a sampling rate of 10 million samples per second, thus filling the queue in 12800 microseconds. At a processing duty cycle of about 3%, it takes the five digital signal processing (DSP) chips a little more than 30 times as long to extract the information from the data as it does to collect it. Thus, the whole process will take about 30 times 12800 microseconds, or 384000 microseconds. At the conclusion of the processing, the octave registers are updated, and the cycle repeats. Any signal that occurs while the queue is filling will be captured. Since the queue fills for only 12800 microseconds out of each half second cycle, only signals lasting more than a 1/2-second are certain to be captured.

Figure 4. Block Diagram of Magnetic Receiver.

Figure 5. Photo of Magnetic Receiver Electronics.

Figure 6. Photo of Magnetic Receiver.

The low frequency magnetic spectral receiver uses a minimal hardware configuration, consisting of an antenna, a preprocessing filter, broadband amplifier, analog-to-digital converter, digital processor, and controller. Due to the extreme bandwidth (14 octaves), the desirability to minimize hardware complexity, and the desirability to maximize the amount of time each octave is observed, all signal processing is done digitally.

The analog part of the system operates as follows. The antenna produces a current proportional to the incident magnetic field in the band of 20 Hz to 5 MHz. A passive 7-pole analog Butterworth high pass filter is used to suppress the power frequency, its third harmonic, and any other undesired signals below 305 Hz. An analog low pass filter is used to prevent aliasing of signals above 5 MHz. A DC to 5 MHz amplifier is used to scale and translate the signal to a level suitable for input to the analog-to-digital (A/D) converter.

Eight bit A/D conversion is done with a self contained chip. While this imposes an upper limit of about 36 dB on the useful dynamic range, it is sufficient for this application. A sampling rate of 10 M-samples per second provides the Nyquist limit at the highest input frequency.

The processing is done on a sample and hold basis. The A/D converter is enabled until the queue fills. Then the A/D converter is disabled, and the queue is processed by DSP0. DSP0 strips out the upper octave and notes the peak value. DSP0 also strips out the lower 13 octaves and feeds the filtered signal to DSP2. DSP2 obtains the peak value for the next highest octave,

strips out the bottom 12 octaves, and feeds the filtered signal to DSP3. DSP3 obtains the peak value for the two next highest octaves, strips out the bottom 10 octaves, and feeds the filtered signal to DSP4. DSP4 obtains the peak value for the four next highest octaves, strips out the bottom six octaves, and feeds the filtered signal to DSP5. DSP5 obtains the peak value for the last six octaves, and feeds all the peak readings to the controller.

6. FIELD TESTING

Prior to deployment at a nuclear site, about 10 weeks of observations were made with the electric spectral receiver in the control room and a switchgear room at TVA's Bull Run Fossil Plant. Bull Run is the world's largest single unit fossil plant. At 980 MW, it is comparable in size to a typical nuclear unit. The primary objective of these observations was to assess the performance of the receiver under conditions similar to those that might be encountered in a nuclear plant. Assessing the state of EMI/RFI ambient conditions in the Bull Run control room was of secondary interest.

ORNL employees were present only at setup, and to copy the recorded data at the end of the collecting periods. Otherwise, the receiver operated completely unattended. The captured data are the result of normal operations at Bull Run. No events were contrived to see what sort of EMI/RFI they might generate. No microwave EMI/RFI was observed.

In the control room, two sets of observations were taken. The first week's results are summarized in Table 1. During this period the receiver was set at medium sensitivity (noise floor of 0.4 V/m).

Table 1. Bull Run Control Room Observations (Electric Field)

Date: 6/11/94 through 6/17/94
Total Number of Readings: 16300
Receiver Noise Floor: 0.4 V/m

Occurrence of non-zero readings:

Band (MHz)	Lower Bin Limit (V/m)	Upper Bin Limit (V/m)	Number of Readings
5-26.5 or 50-76.5	2.2	6.5	1
301-326 or 350-376	1.1	1.6	10
301-326 or 350-376	1.6	2.5	2
326-350 or 376-401	1.1	1.7	2
401-426 or 450-476	0.4	0.8	4
401-426 or 450-476	1.2	1.8	13
401-426 or 450-476	1.8	2.8	15
401-426 or 450-476	2.8	4.5	10
401-426 or 450-476	4.5	7.0	3
426-450 or 476-501	0.4	0.6	7
426-450 or 476-501	1.0	1.4	5

Since few non-zero readings were observed during the first week, the receiver sensitivity was increased by removing 10 dB of the attenuation that had been placed between the antenna and the receiver input terminal. Then, a month of observations were made as summarized in Table 2. Both sets of observations (Table 1 and Table 2) were made with the receiver in the same location.

A reading is made by one sweep of the receiver through all of its 21 frequency bins, which requires 35 seconds. Therefore, a week of continuous observation generates about 16300 readings, most of which are below the receiver noise floor. The 20 non-microwave frequency bins each consist of the band of 12.5 MHz to 37.5 MHz above and below the local oscillator frequency. The microwave bin is the entire 1-8 GHz band. Due to variation as a function of frequency in antenna factor and mixer conversion loss, the field strength bin limits are different for each local oscillator frequency. Receiver noise floor is controlled by varying the amount of lumped attenuation between the antenna and the receiver.

For both sets of observations, non-zero events were rare, about one non-zero event per 200 readings (on average, one non-zero event every 90 minutes). For June 11-17, 1994, a total of 16300 readings were taken. Out of these, there were 72 non-zero readings (readings above the receiver noise floor). For June 17-July 14, 1994, a total of 63300 readings were taken. Out of these, there were 286 non-zero readings. The rarity of non-zero events shows the need for continuous long term observation. Catching a significant EMI/RFI event during a spot check is a matter of blind luck.

A similar set of observations was made in the "L&N" room at Bull Run, so called because it houses switchgear manufactured by Leeds and Northrup. This is intended to be an electrically quiet (low EMI) location. The results are summarized in Tables 3 and 4. Generally the "L&N" room was found, as expected, to be much quieter than the control room.

The predominant EMI/RFI activity at Bull Run is attributable to hand held transceivers. These transceivers are widely used at the site. Bull Run security personnel say that the transceivers operate near 419 MHz. At a local oscillator frequency of 438 MHz, the electric monitor responds to any signal in the bands of 401-426 MHz or 450-476 MHz. Consequently, this is the band in which hand held transceiver activity would be detected.

Before deployment at a nuclear site, four days of observations were made with the magnetic spectral receiver in the control room at TVA's Bull Run Fossil Plant. As with the electric receiver field test, the primary objective of these observations was to assess the performance of the receiver under conditions similar to those that might be encountered in a nuclear plant. One set of observations was taken. The results are summarized in Table 5. Assessing the state of EMI/RFI ambient conditions in the Bull Run control room was of secondary interest.

ORNL employees were present only for setup and removal of the receiver. Otherwise, it operated completely unattended. The captured data are the result of normal operations at Bull Run. It is noteworthy that one day before the receiver was removed, Bull Run began a scheduled 8-week maintenance outage. No events were contrived to see what sort of EMI/RFI they might generate.

Table 2. Bull Run Control Room Observations (Electric Field)

Date: 6/17/94 through 7/14/94
 Total Number of Readings: 63300
 Receiver Noise Floor: 0.06 V/m

Occurrence of non-zero readings:

Band (MHz)	Lower Bin Limit (V/m)	Upper Bin Limit (V/m)	Number of Readings
5-26.5 or 50-76.5	0.31	0.92	9
5-26.5 or 50-76.5	0.92	1.75	4
5-26.5 or 50-76.5	1.75	2.92	4
26-50 or 76-101	0.37	0.62	3
26-50 or 76-101	0.62	0.93	5
26-50 or 76-101	0.93	1.64	6
26-50 or 76-101	1.64	2.91	2
26-50 or 76-101	4.03	>4.03	1
101-126 or 150-176	0.17	0.25	2
101-126 or 150-176	0.25	0.4	8
101-126 or 150-176	0.4	0.62	3
126-150 or 176-201	0.17	0.28	1
126-150 or 176-201	0.28	0.4	2
301-326 or 350-376	0.16	0.23	3
301-326 or 350-376	0.23	0.35	12
301-326 or 350-376	0.35	0.57	6
326-350 or 376-401	0.16	0.24	5
326-350 or 376-401	0.24	0.35	2
326-350 or 376-401	0.35	0.57	3
326-350 or 376-401	0.57	0.89	1
401-426 or 450-476	0.11	0.17	42
401-426 or 450-476	0.17	0.25	20
401-426 or 450-476	0.25	0.4	4
401-426 or 450-476	0.4	0.64	11
401-426 or 450-476	0.64	0.99	5
401-426 or 450-476	1.05	>1.05	23
426-450 or 476-501	0.08	0.14	38
426-450 or 476-501	0.14	0.2	7
426-450 or 476-501	0.2	0.32	1
501-526 or 550-576	0.1	0.16	3
526-550 or 576-601	0.11	0.16	1
601-626 or 650-676	0.13	0.18	2
601-626 or 650-676	0.18	0.28	1
626-650 or 676-701	0.13	0.2	2
626-650 or 676-701	0.2	0.28	3
801-826 or 850-876	0.21	0.3	41

Table 3. Bull Run "L&N" Room Observations (Electric Field)

Date: 7/14/94 through 8/5/94
Total Number of Readings: 47000
Receiver Noise Floor: 0.06 V/m

Occurrence of non-zero readings:

Band (MHz)	Lower Bin Limit (V/m)	Upper Bin Limit (V/m)	Number of Readings
126-150 or 176-201	0.28	0.4	1
401-426 or 450-476	0.17	0.25	3
401-426 or 450-476	0.25	0.4	3

Table 4. Bull Run "L&N" Room Observations (Electric Field)

Date: 8/5/94 through 8/17/94
Total Number of Readings: 28000
Receiver Noise Floor: 0.06 V/m

Occurrence of non-zero readings:

Band (MHz)	Lower Bin Limit (V/m)	Upper Bin Limit (V/m)	Number of Readings
101-126 or 150-176	0.4	0.62	2
126-150 or 176-201	0.28	0.4	1
126-150 or 176-201	0.4	0.62	3
401-426 or 450-476	0.17	0.25	9
401-426 or 450-476	0.25	0.4	3

For several bands that include operating frequencies of video monitor deflection coils, several hundred thousand readings are seen just a little above the noise floor of the receiver. There are several monitors of assorted vintages in the Bull Run control room. This level of video monitor activity is not unexpected. Otherwise, as with electric fields, the magnetic fields are present only a small percentage of the time. Through 40 kHz, the Bull Run data are at least 29 dB below the EPRI recommended withstand. EPRI provides no recommendation above 40 kHz. [EPR 94]

Table 5. Bull Run Control Room Observations (Magnetic Field)

Date: 10/3/94 through 10/7/94
Total Number of Readings: 574000

Occurrence of non-zero readings:

Band (kHz)	Lower Bin Limit (mA/m)	Upper Bin Limit (mA/m)	Number of Readings
.61-1.22	24.5	49.0	6
1.22-2.44	12.7	25.4	3
2.44-4.88	7.1	14.2	3
2.44-4.88	14.2	28.4	1
4.88-9.77	3.36	6.72	293234
9.77-19.53	1.67	3.36	81537
9.77-19.53	3.36	6.72	151
19.53-39.06	.863	1.72	149441
19.53-39.06	1.72	3.46	155
19.53-39.06	3.46	6.91	15
39.06-78.125	.502	1.004	8743
39.06-78.125	1.004	2.008	4370
39.06-78.125	2.008	4.017	56
78.125-156.25	.335	.669	15117
78.125-156.25	.669	1.339	632
78.125-156.25	1.339	2.678	312
78.125-156.25	2.678	5.356	1
156.25-312.5	.289	.579	11676
156.25-312.5	.579	1.158	14
156.25-312.5	1.158	2.316	4
312.5-625	.264	.529	554
312.5-625	.529	1.058	12
312.5-625	1.058	2.116	3
312.5-625	2.116	4.232	2
312.5-625	4.232	8.464	5
312.5-625	8.464	16.928	1
625-1250	.267	.534	128
625-1250	1.07	2.14	3
625-1250	2.14	4.28	5
625-1250	4.28	8.56	3

7. CONCLUSIONS AND FURTHER RESEARCH

ORNL has assembled, tested, and deployed spectral receivers specifically intended for EMI/RFI monitoring in nuclear power plants. Both units are designed to operate unattended for weeks or months. Both are EMI/RFI hardened so as not to become a source or victim of EMI/RFI in the plant under observation. Both preserve frequency data and provide time stamping of data.

One receiver is designed to monitor magnetic fields. It covers 305 Hz through 5 MHz, and records peak magnetic field strength data in 14 one-octave-wide frequency bins. It can be used with a loop antenna to observe radiated fields, or with a current transformer to observe conducted fields. The unit was calibrated in the transverse electromagnetic (TEM) cell at Philips Consumer Electronics in Knoxville, Tennessee. It has been field tested at TVA's Bull Run Fossil Plant, and is currently deployed at Arkansas Nuclear One, in the Unit 2 control room.

The other receiver is designed to monitor electric fields. It covers 5 MHz to 8 GHz, and records peak electric field strength data in 21 frequency bins. The unit was calibrated in the anechoic chamber at the National Institute of Standards and Technology in Boulder, Colorado. It also has been field tested at TVA's Bull Run Fossil Plant, and is currently deployed at Arkansas Nuclear One, in the Unit 2 control room.

The following conclusions can be drawn from the field test data acquired at Bull Run:

- The receivers work in real world conditions, and do not disrupt power plant routine.
- Potentially disruptive EMI/RFI events were observed, but were rare.
- Extended continuous monitoring is required to assure that significant EMI/RFI events are observed.
- A week of continuous monitoring is not a sufficiently long observation period. A month may be.
- A susceptibility limit of 10 V/m (140 dB μ V/m) is sufficient to withstand all ambient electric fields observed at Bull Run.
- A susceptibility limit corresponding to the sloping scale recommended by EPRI is sufficient to withstand all ambient magnetic fields observed at Bull Run.
- Video monitor activity is barely detectable above the magnetic receiver noise floor, but low level field strengths are usually present.

A major conclusion of the Bull Run observations is that handheld transceivers are the dominant source of undesired electric fields in and around its control room. The electric spectral receiver recorded fields in the 401-426 MHz band as high as 5-7 V/m. According to Bull Run security, their handheld transceivers operate at 419 MHz. Careful experiments with handheld transceivers show that they can produce an electric field as high as 95 V/m at

a distance of 12 cm from the antenna [Ada 93]. At a distance of 16 feet, a handheld transceiver typically produces a field of 2.5 V/m [Cir 86]. Thus, the electric spectral receiver readings are consistent with operation of a handheld transceiver near the monitor.

The other major conclusion of the Bull Run observations is that while magnetic fields are detectable at a wide range of frequencies, they are at such a low level as to not be a cause for concern.

Over the next year, ORNL plans to use the two monitors to observe long term EMI/RFI effects at several nuclear sites. Both monitors were recently deployed at Arkansas Nuclear One in Russellville. In mid-November they will be moved to Oconee in Clemson, South Carolina, to observe the EMI/RFI effects associated with a nuclear unit startup. Discussions are underway with various nuclear plant operators about possible deployment at other sites. The results of these long term nuclear plant EMI/RFI surveys, and their implications for achievement of electromagnetic compatibility, will be reported in a future paper.

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