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ANALYSIS OF AMBIENT CONDITIONS IN NUCLEAR POWER PLANTS

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Kofi Korsah

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ABSTRACT

This document reports the results of further analysis of data obtained from a survey of ambient electromagnetic conditions in representative nuclear power plants reported in reference 2 (NUREG 6436).

In 1995, the U.S. Nuclear Regulatory Commission (NRC) Office of Nuclear Regulatory Research engaged the Oak Ridge National Laboratory (ORNL) to perform measurements to characterize the electromagnetic interference (EMI) and radio-frequency interference (RFI) levels that can be expected in nuclear power plant environments. Based on the results, a set of recommended electromagnetic operating envelopes for safety-related instrumentation and control (I&C) systems in nuclear power plants were proposed in NUREG 6431, *Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants*.

Those recommendations were applicable to all locations in the plant. However, the question has arisen since the publication of this document whether the recommendations are too severe for certain locations in the nuclear power plant environment and therefore, whether there is a need for location-specific operating envelopes. The objective of this report is therefore to try to answer the question: *Are the electromagnetic envelopes recommended in NUREG/CR-6436, which is based on data reported in NUREG/CR-6436, too severe for certain locations in the nuclear power plant and if so, is there is a need for plant- or location-specific operating enveloeps?* To answer this question, the data obtained from the EMI/RFI surveys and documented in NUREG/CR-6436 were further analyzed primarily by location, and compared with each other as well as with the envelopes suggested in NUREG/CR-6431. Seven sites were analyzed, out of a total of 9 sites surveyed and reported in NUREG/CR-6436. These seven sites are those for which both magnetic as well as electric field data were available. For the other two sites only magnetic field data, or only electric field data, was available. The locations analyzed were without regard to plant type. For example, all control rooms in all PWRs and BWRs surveyed were analyzed together, all cable spreading rooms in all plant types were analyzed together, etc. The most significant conclusions of relevance to answering the question posed in this report are the following (these conclusions are true for both electric and magnetic field data).

- While there is some variation in the electromagnetic ambient levels among the various locations examined, all the levels were within about 30 dB of each other.

- The levels in all the seven locations examined are well below the recommended operating envelope suggested in NUREG/CR-6431.

- The plot of overall bounding values, which encompasses <u>all</u> the locations surveyed in NUREG/CR-6436, is also within the recommended operating envelope. However, the bounding envelope is rather close to the recommended operating envelope in the frequency window of 400 MHz - 700 MHz.

- The majority of counts for all frequency ranges, as recorded by the magnetic and electric spectral receivers, were within the noise floor for all the plants monitored. This is significant because it suggests that typical electromagnetic fields at power plants may be "quieter" than anticipated.

We conclude from these results that information to date on ambient electromagnetic fields in nuclear power plants support the recommendation of <u>only one set of operating envelopes for all nuclear power plants</u>. Furthermore, the electromagnetic envelopes recommended in NUREG/CR-6436, which is based on data reported in NUREG/CR-6436, are not too severe, and there is no need for location-specific or plant-specific operating envelopes.

UNITS OF MEASUREMENT

Electromagnetic fields consist of three components: the induction field, the near field, ad the far field (or radiation field). The induction and near fields decay rapidly with distance from the source. At some distance from the source (typically a sixth of a wavelength) far field effects dominate, and in free space the electromagnetic field behaves as a propagating transverse electromagnetic (TEM) wave.

In free space $|\mathbf{E}|$, the magnitude of the electric field, and $|\mathbf{H}|$, the magnitude of the magnetic field, are related by the characteristic impedance of free space η. In particular,

$$|\mathbf{E}| / \eta = |\mathbf{H}|$$

For brevity, the symbols E and H , rather than $|\mathbf{E}|$ and $|\mathbf{H}|$, are used in this document to denote the magnitude of these parameters.

The SI (Systeme Internationale) units of measurement of electric field E is the Volt per meter (V/m). However, the logarithmic unit dBμV/m is used extensively in discussions of electromagnetic interference (EMI). The electric field E, in dBμV/m, is given by the equation:

$$E[\text{dB}\mu\text{V/m}] = 20 \times \log_{10}(E[\mu\text{V/m}] / 1[\mu\text{V/m}])$$

and 1 μV = 10^{-6} V.

In EMI standards and the general EMI literature, magnetic fields may be reported in terms of magnetic induction (magnetic flux), typically denoted by B, for which the SI units of measurement is the tesla (T). Just as in the case of the electric field above, the logarithmic unit dBpT is typically used, where

$$B[\text{dBpT}] = 20 \times \log_{10}([B[\text{pT}]/ 1[\text{pT}])$$

and 1 pT = 10^{-12} T.

Magnetic fields may also be reported in terms of the magnetic field strength, denoted H, for which the SI unit of measurement is the Ampere per meter (A/m). The **B** and **H** vectors are equivalent in vacuum.

In this document, electric field data are reported in dBμV/m and magnetic field effects are reported in units of dBpT.

1. INTRODUCTION

1.1 BACKGROUND

Instrumentation and Control (I&C) systems of new generations (e.g., advanced light-water reactors (ALWRs) and Generation IV systems) as well as upgrades of existing plants, are expected to make use of both analog and digital/microprocessor-based equipment and will be significantly different from the predominantly analog-based I&C systems in use for safety-related functions at current nuclear power plants. The limited operational experience with digital systems raised concerns about upsets and malfunctions in safety-related I&C systems due to electromagnetic interference (EMI), radio-frequency interference (RFI), and power surges. Accordingly, the Nuclear Regulatory Commission (NRC) Office of Regulatory Research engaged the Oak Ridge National Laboratory (ORNL) to assist in developing the technical basis for regulatory guidance on EMI/RFI immunity and power surge withstand capability (SWC).

Previous findings and recommendations on EMI/RFI and SWC test criteria, test methods, and installation practices were reported in NUREG/CR-5941, *Technical Basis for Evaluating Electromagnetic and Radio-Frequency Interference in Safety-Related I&C Systems*.[1] That report discusses the technical basis for recommended electromagnetic compatibility (EMC) design and installation practices to ensure operational safety in equipment and presents testing techniques to assure that the EMC practices do, indeed, achieve their intended purpose.

Until recently, little was known about the prevailing ambient electromagnetic environment in nuclear power plants. This lack of information made it difficult to recommend electromagnetic operating envelopes—that is, the level of interference that safety-related I&C systems should be able to withstand without upset or malfunction—with a high degree of confidence in their adequacy. This lack of information prompted ORNL to profile the electromagnetic emissions levels at selected plant sites. Those profiles were reported in NUREG/CR-6436, *Survey of Ambient Electromagnetic and Radio-Frequency Interference Levels in Nuclear Power Plants*.[2] The results of the survey were also incorporated into the development of the technical basis for realistic operating envelopes. This technical basis and recommendations for electromagnetic operating envelopes to augment the test criteria and test methods recommended in NUREG/CR-5941 were reported in NUREG/CR-6431, *Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants*.[3] Those recommendations were applicable to all locations in the plant. However, the question has arisen since the publication of this document whether the recommendations are too severe for certain locations in the nuclear power plant environment and therefore, whether there is a need for plant-specific operating envelopes. In this report, the data obtained from the EMI/RFI surveys and documented in NUREG 6436 are further analyzed to determine if EMI/RFI envelopes need to be location-specific.

1.2 SUMMARY OF ORNL ELECTROMAGNETIC SURVEY FINDINGS

1.2.1 Overview of Spectral Receivers Used in the Surveys

Electric and magnetic spectral receivers were designed and constructed at Oak Ridge National Laboratory to perform long-term, automatic, unattended measurement and recording of electric and magnetic fields at

nuclear power stations. (Conducted measurements may also be characterized by using a current probe (current transformer) with the magnetic spectral receiver.)

The electric and magnetic spectral receivers are shown in Figures 1.1 and 1.2 respectively.
Both receivers require no external connections except for 120 VAC power. Once set up and running, the instruments require no operator attention other than shutdown to retrieve stored data or transfer to a new location. The spectral receivers each include an uninterruptible power supply (UPS) with sufficient capacity to ride through a power interruption up to 20 minutes long.

The radio-frequency (RF) circuitry of both spectral receivers is contained in a standard 19 inch (48.26 cm) rack mount chassis 10 inches (25.4 cm) high. This chassis also contains the UPS. The receiving antenna is mounted on top of the RF chassis. Each spectral receiver also includes a data acquisition and control subsystem (DACS) based on the Intel 80386SX processor. The DACS is housed in a smaller chassis attached to the RF chassis.

A key switch located on the side of the RF chassis is the only operator interface located in plain view of passers-by. Other interfaces, required to start up the units, retrieve data or perform an orderly shutdown, are hidden behind access panels.

Shield A, which is located on the top of the DACS chassis (See Figure 1.1 or 1.2), allows access to the restart button and connectors for a video monitor (VGA) and keyboard. The video monitor and keyboard are required to initiate measurements, perform an orderly shutdown, and view measurement results as they come in, but are removed for unattended operation.

Shield B, which is located on the side of the DACS chassis (see Figure 1.1 or 1.2) allows access to the on-board floppy disk drive that stores accumulated data. The magnetic spectral receiver also includes Shield C (See Figure 1.2), that allows access to a lithium battery that provides back-up power for memory elements storing digital signal processor (DSP) control programs.

1.2.2 Electric Spectral Receiver

The electric spectral receiver (Figure 1.1) was designed to observe high frequency radiated electric fields (5 MHz to 8 GHz). It uses two resistive tapper antennas as broadband electric field probes. The antennas are coupled to independent processing circuits, one covering 20 bands of equal width from 5 to 1000 MHz (1GHz), and the other a single band from 1 to 8 GHz. Thus, microwave (1 to 8 GHz) signals are treated as a single band. The microwave antenna output is coupled through a 1 GHz high pass filter to a broadband microwave amplifier. The amplifier output is processed by pseudo-peak detection, which produces a 6 MHz bandwidth signal that is a replica of the modulation envelope of the original microwave signal. The output of the video detector is then fed to a peak detector, which produces a DC signal that is proportional to the peak value of the original microwave signal.

Signals below 1 GHz are processed with the aid of a heterodyning scheme, employing a local oscillator and mixer arrangement such that the mixer output always sweeps from 5 MHz to 1 GHz. This signal is amplified and applied to a peak detector (different from the microwave peak detector), which produces a DC voltage proportional to the peak value of the signal in the window during the sampling time interval.

The electric receiver operates on a 35-s sampling sweep, capturing the peak electric field strength observed during each sweep. The 35-s sweep examines each of the 21 individual bands within the spectrum for about 1.5 s.

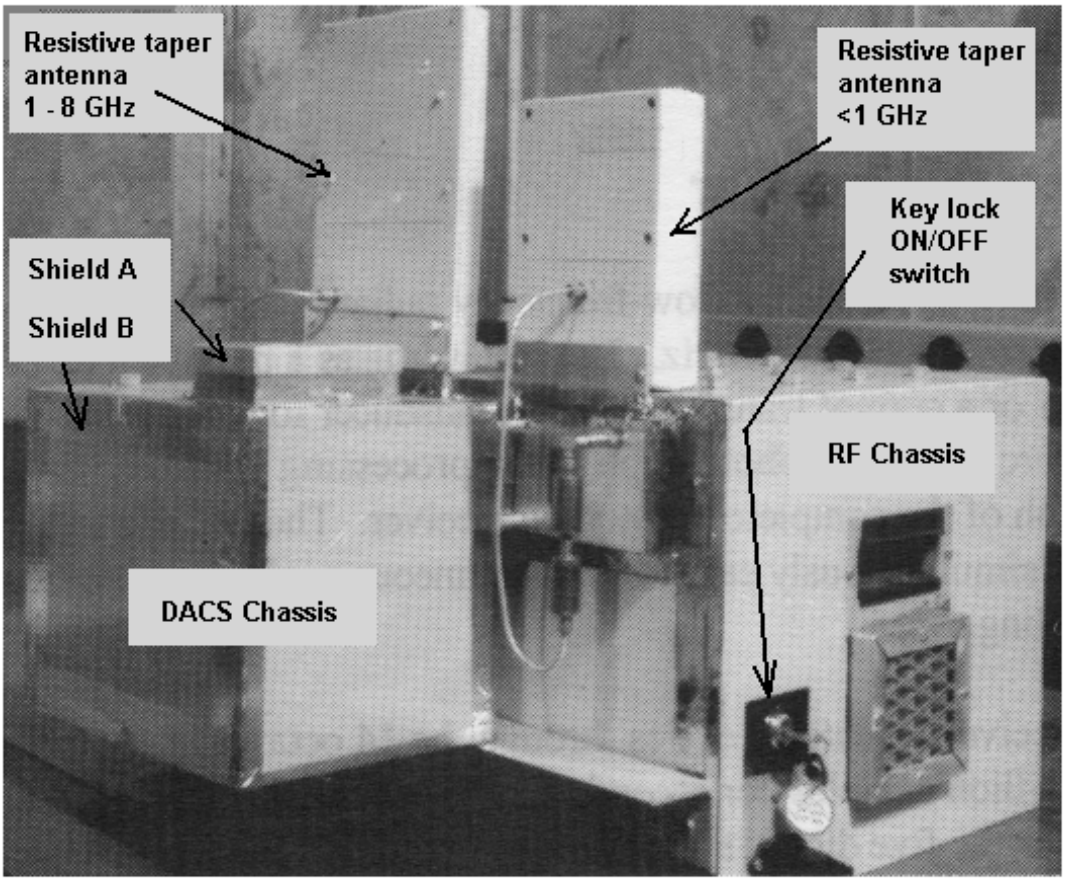

Figure 1.1 Electric spectral receiver

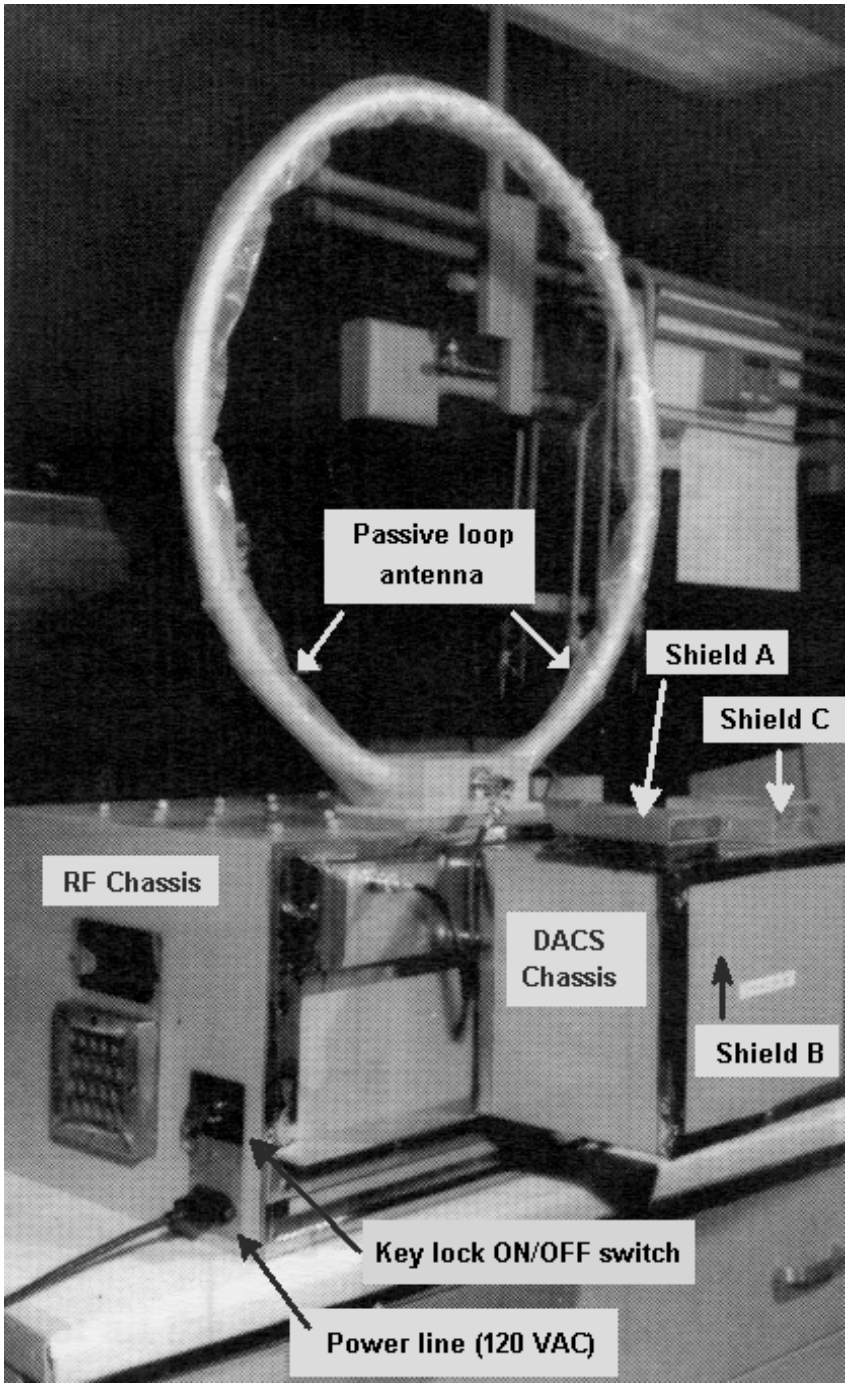

Fig. 1.2 Magnetic spectral receiver

1.2.3 Magnetic Spectral Receiver

The magnetic spectral receiver (Figure 1.2) was designed to observe low frequency radiated magnetic fields or conducted effects. Frequency coverage is from 305 Hz to 5 MHz. The 305-Hz to 5-MHz coverage spans 14 octaves, and the receiver simultaneously captures instantaneous peak magnetic field strength present in each octave during each sampling cycle (the receiver repeatedly cycles through the 14 octaves every 0.5 s).

The input signal from the loop antenna or current transformer is processed in a passive 7-pole Butterworth high-pass filter and a low-pass filter arrangement to suppress the power line frequency, harmonics and other undesired signals below 305 Hz, and prevent aliasing from signals above 5 MHz. The signal is then processed in a video amplifier to offset and scale the signal to a level suitable for analog-to-digital (A/D) conversion. The A/D converter samples at a rate of 10 MHz, establishing the Nyquist limit for the highest input frequency at 5 MHz. Eight-bit conversion is used, establishing a limit of ≈36 dB for the instrument dynamic range.

As mentioned above, the magnetic spectral receiver operates on roughly a 0.5 s cycle. The A/D converter is enabled until a 128K queue fills up. The queue is then processed in wavelet filters implemented in 5 digital-signal-processing (DSP) chips to extract the signal amplitude in 14 octave-wide frequency bins. Signal processing takes roughly 30 times longer than data acquisition. At the conclusion of the processing, the octave registers are updated and the cycle repeats. Only disturbances that occur during the 12.8 ms period that the queue is filling are captured.

1.2.4 Format of Data Output from Spectral Receivers

The output of each receiver is a two-dimensional (2-D) matrixed histogram: one dimension is band (or bin) of frequency, and the other dimension is band (or bin) of peak field strength. The entries recorded in the histogram matrix are the running total (over the entire observation period) of the number of receiver operating cycles that the ambient EMI/RFI level fell within the intersection of a particular strength bin and a particular frequency bin (referred to as a count).

Portions of actual data files stored during operation of the electric and magnetic spectral receivers are shown in Figures A.1 and A.2 respectively in Appendix A. A data run is the period of data acquisition since the receiver was last shut down (to retrieve data stored on the floppy disk), and is usually about a week long. Data is formatted in blocks. Each block of data constitutes one complete cycle, in which the electric receiver cycles through each of 20 individual bands within the spectrum, or the magnetic receiver cycles through each of the 14 octaves or bins. The receivers were programmed to store an updated histogram to disk every 6h.

Further details of the spectral receivers, data acquisition, and survey procedures are provided in NUREG/CR-6436.

1.2.5 Summary of ORNL Surveys at U.S. Nuclear Power Plants

Ambient electromagnetic conditions were measured with the electric and magnetic spectral receivers at eight nuclear power plants operated by four participating utilities. The plants surveyed included one boiling water reactor (BWR) supplied by GE Nuclear Energy and seven pressurized water reactors (PWRs) supplied by Westinghouse Electric [3 units], Babcock and Wilcox (B&W) [3 units], and ABB Combustion Engineering [I unit]. Measurements were taken over a 14-month period at a variety of

operating conditions and observation locations within the plants. The operating conditions monitored included full-power operation, coastdown, low-power operation, shutdown, outage, startup, and plant trip. The locations for placement of the spectral receivers were determined in consultation with the responsible site engineer based on likely high field levels, proximity to safety-related T&C systems, and current planned digital equipment installation sites. The EMI/RFI survey measurement locations are shown in Table 1.1. Some participating units provided measurement opportunities near reactor protection system (RPS) cabinets containing digital systems, as well as near conventional analog equipment. The measurement period at each location ranged from 1 to 5 weeks.

A large amount of data was generated during the plant site surveys: ~35.7 million magnetic field observations and ~650,000 electric field observations. This large volume of data was taken during extended observation periods under a wide variety of power plant conditions (reactor type, operating modes, site locations). The highest strength electromagnetic observations from the ORNL survey at the eight nuclear units are presented in Tables 1.2 and 1.3. Table 1.2 presents the highest strength magnetic field observations and Table 1.3 presents the highest strength radiated electric field observations.

Measurements of electric and magnetic field data were acquired under various conditions such as reactor type, operating mode, and reactor manufacturer. The following is a summary of the findings:

The electric field levels did not vary dramatically by mode or reactor vendor, although the one BWR included in the survey was found to be consistently quieter than the most extreme effects of the seven PWRs. In the frequency range of 100 – 1000 kHz, radiated magnetic fields were consistently present with a peak value in the range of 90 – 105 dBpT. This was consistently true irrespective of mode, reactor manufacturer, reactor type, or room type. In theory, the TEM relationship between the electric fields and magnetic fields does not hold at low frequencies, and the radiated magnetic fields drop rapidly with distance from the source. This suggests that, when dealing with a single source in the frequency range of 100 – 1000 kHz, strong radiated magnetic effects are not expected. However, a power plant is not a single source but rather an environment fed by many sources, and the results obtained showed that there was a consistent background of radiated magnetic field with occasionally strong peaks, at least through 1 MHz.

The study found that although the highest observed levels were relatively high, their <u>occurrence</u> was not very high. For radiated electric fields, the highest recorded levels occurred only 5 times out of 643,519 counts. For radiated magnetic fields, the highest recorded levels occurred 7, 825 times out of 35,734,893 counts.

With regard to how EMI/RFI effects vary over time, the study found that the observed levels varied quite noticeably over time. At all the observation locations, what was observed was a fairly steady background level whose distribution in strength and frequency varies with location. At each observation point, superimposed on steady state background, was an apparently random set of occurrences that differed from one 6-h frame to the next.

The data collected in the survey showed that short-term observations (less than two weeks) are not sufficient to characterize the EMI/RFI properties of a given plant site. Based on the observations, the probability of capturing the worst-case EMI/RFI effect from a single scan of the spectrum is no greater than 0.0002. Six hours of observations will characterize the steady state background of a given location. However, it requires about two weeks of observations at most sites to have a reasonable probability of observing a true bounding envelope. Longer observation periods increase the probability of observing the bounding envelope of EMI/RFI but may not be cost-effective.

Finally, analysis of the results showed that the measured conditions do not exceed the recommended envelopes in NUREG/CR-6431, "Recommended Electromagnetic Operating Envelopes for Safety-Related I&C Systems in Nuclear Power Plants." In particular, the smallest difference between the data and the envelopes for any observed EMI/RFI event in any frequency band was found to be about 10 dB.

While the adequacy of the operating envelopes were confirmed by the survey results, the question of whether or not the envelopes are too stringent for certain locations in the power plant environment was not addressed. This report addresses this question.

Table 1.1 EMIIRFI survey measurement locations

Measurement Sites
Main Control Rooms
Control Area Equipment Rooms
Electrical Equipment Rooms
Auxiliary Instrument Rooms
Cable Spreading Rooms
Relay Rooms
Electrohydraulic Controller Room
Turbine Deck
Electrical Penetration Rooms

Table 1.2 ORNL highest observations-Nominal bounding values of observed radiated magnetic fields (ref. 2)

Octave Lower Bound (kHz)	Field Strength (dBpT)	Total Counts at Maximum	Grand Total Counts
0.31	107	1	35,734,893
0.61	108	100,530	35,734,893
1.22	104	6	35,734,893
2.44	104	41	35,734,893
4.88	117	452	35,734,893
9.77	117	7,825	35,734,893
19.53	106	7,318	35,734,893
39.06	100	69	35,734,893
78.12	101	5	35,734,893
156.25	102	4	35,734,893
312.5	101	20,457	35,734,893
625	101	2	35,734,893
1250	51	35,734,893	35,734,893
2500	51	35,734,893	35,734,893

Table 1.3. ORNL highest observations—Nominal bounding values of observed radiated electric fields (ref. 2)

Frequency Band (MHz)	Field Strength (dBμV/m)	Total Counts at Maximum	Grand Total Counts
5-100	137	5	643,519
100-200	132	27	643,519
200-300	109.9	1	643,519
300-400	110	1	643,519
400-500	127.3	3	643,519
500-600	106.2	12	643,519
600-700	108.8	1	643,519
700-800	115.5	2,356	643,519
800-900	107.6	1	643,519
900-1000	125.1	1	643,519

2. ANALYSIS OF ORNL SURVEY DATA

2.1 BOUNDING ENVELOPES FOR RADIATED MAGNETIC FIELDS BY LOCATION

The observed radiated magnetic field data was analyzed by location and is shown in Table 2.1. The seven locations1 for which both magnetic field and electric field data were acquired include (1) Control room, (2) Penetration Room, (3) Cable Spreading Room, (4) Turbine Deck, (5) Control Area Equipment Room, (6) Relay Room, and (7) electrohydraulic room. Magnetic field data was also obtained for the electric equipment room, and this location is therefore included in Table 2.1 as well as subsequent plots.

The maximum observed strength value for each frequency bin was calculated by determining the maximum bin in which at most one count occurred, and then calculating the equivalent strength (in dBpT) for that bin. As previously noted, large amounts of data (~35.7 million observations) were acquired over a two-week period during the survey. In many cases, the vast majority of the counts occurred in the same bin; only one or two counts occurred in other bins. A "count" is the result of a single spectral analysis performed by the magnetic spectral receiver and thus represents a little less than 0.5s of elapsed (collection plus wavelet analysis) time.

In this analysis, counts in a strength bin was considered statistically significant if at most one count occurred in a particular bin in at least two data blocks.2 [The total number of counts in all blocks for a particular location was 35,734,893 (~35.7 million) for the magnetic field data, while the corresponding grand total for all counts for the electric field data was 643,519. Thus for the magnetic field data, two counts out of this total constitutes 56 parts per billion, while for the electric field data it is about 3 parts per million. This threshold was arbitrarily set with the objective of increasing confidence in the observed count(s) as being true signals, and not spurious ones.]

Table 2.1 lists the maximum observed radiated magnetic fields by location. These maximum observed values for each location are plotted in Figs. 2.1 through 2.7. Fig. 2.8 shows these 7 separate plots, compared to the operating envelope suggested in NUREG/CR-6431 [identical to RS01/RS101 operating envelope in MIL-STD 461D]. Note that Fig. 2.8 also includes a plot of the overall bounding values for radiated magnetic fields for all 9 measurement sites in the NUREG/CR-6436 study. This plot appears higher than any of the locations because (1) as mentioned earlier, data for **both** magnetic and electric fields were recorded for only 7 out of the 9 measurement sites (Table 1.1) in the NUREG/CR-6436 study. Thus, only these 7 measurement sites are analyzed in this report; (2) unlike the plots for the 7 locations, there is no restriction in the NUREG/CR-6436 plot of having at least two data blocks with at most one count in the same strength bin. Thus the overall bounding values encompass all events captured by the magnetic spectral receiver, including bins that may have had only one count throughout the observation period.

The following observations may be made from the plots:

---

a While either radiated magnetic or electric field measurements were performed at 9 different locations, there were only seven locations in which both magnetic and electric field measurements were performed. These seven locations are analyzed in this report.
b The original data was organized in blocks of 6h duration each.

1. For most of the frequency range of interest, all the seven locations analyzed have levels within about 30dB of each other.
2. Levels in all the seven locations examined are well below the recommended operating envelope suggested in NUREG/CR-6431.
3. The overall bounding envelope for all sites for which data was taken (NUREG/CR-6436) is also within the recommended operating envelope suggested in NUREG/CR-6431.
4. For radiative magnetic fields the quietest location was found to be the cable spreading room.
5. Below about 3KHz, the highest emissions are in the control area equipment room, while above 12KHz, the control room and the electrohydraulic equipment room have higher levels than the other locations.
6. The highest observations in each frequency band were used for each of the locations plotted. Therefore each of the plots envelopes the worst case level. As noted in (2), these levels are well below the recommended operating envelope. In addition, the plot of the overall bounding values, which encompasses <u>all</u> the locations, is also within the recommended operating envelope. The data therefore does not suggest that more than one set of recommended electromagnetic operating envelopes should be developed

Table 2.1 Maximum Radiated Magnetic Fields by Location

Location:	Lower Freq. Bound (kHz) →	0.3	0.61	1.22	2.44	4.88	9.77	19.53	39.06	78.12	156.25	312.5	625	1250	2500
	Corresponding Bin Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Control Room Maximum field (dBpT)		95.5	95.8	84.2	85.1	78.6	90.5	84.8	86.1	82.6	87.3	80.5	68.6	50.7	50.9
Penetration Room Maximum field (dBpT)		101.5	101.8	96.2	91.1	84.6	78.5	72..8	74.1	82.6	75.3	80.5	74.6	50.7	50.9
Cable Spreading Room Maximum field (dBpT)		95.5	89.8	84.2	79.1	72.6	72.5	66.8	68.1	64.6	63.3	74.5	74.6	50.7	50.9
Turbine Deck Maximum field (dBpT)		95.5	89.8	84.2	84.1	78.6	72.5	72.8	68.1	82.6	57.3	80.5	80.6	50.7	50.9
Control Area Equipment Room Maximum field (dBpT)		107.5	107.8	96.2	91.1	84.6	78.5	78.8	80.1	76.6	81.3	74.5	74.6	50.7	50.9
Relay Room Maximum field (dBpT)		101.5	95.8	96.2	91.1	90.6	78.5	72.8	62.1	70.6	69.3	74.5	74.6	50.7	50.9
Electrohydraulic Room Maximum field (dBpT)		95.5	95.8	90.2	85.1	78.6	72.5	78.8	86.1	88.6	81.3	86.5	86.6	50.7	50.9

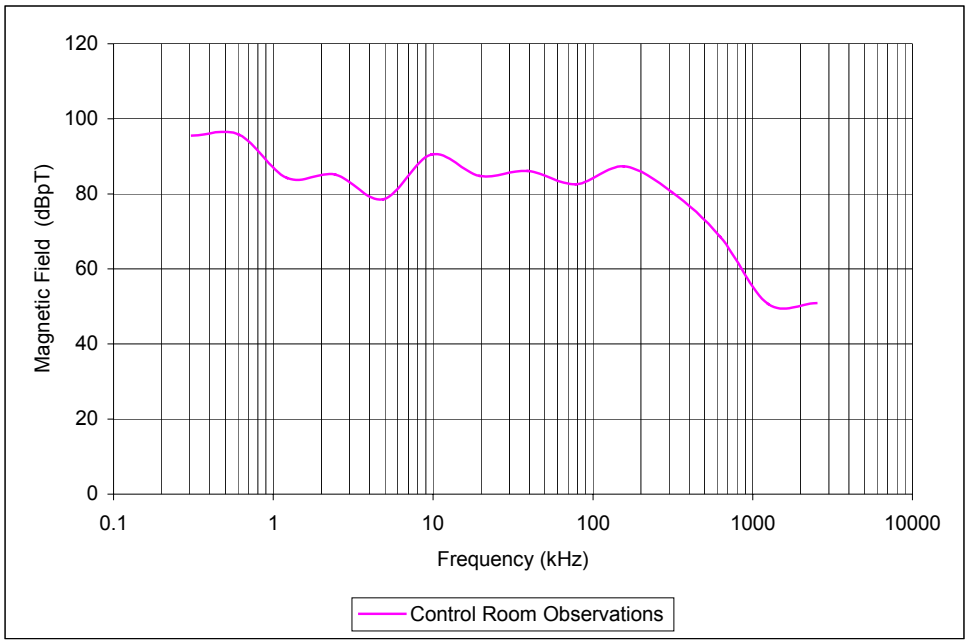

Fig. 2.1 Maximum radiated magnetic field observations in control room.

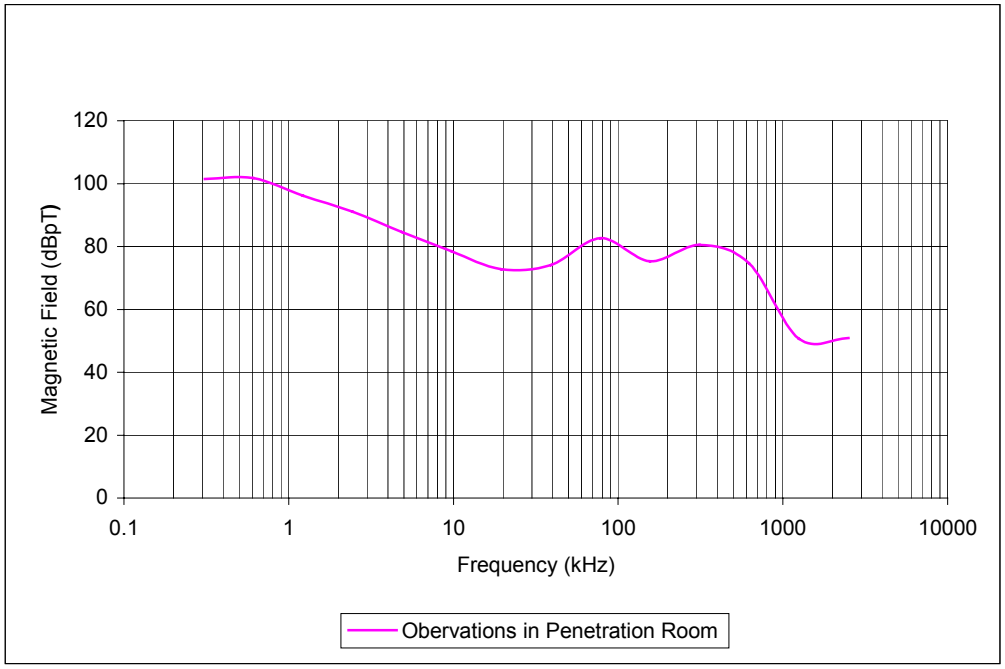

Fig. 2.2 Maximum radiated magnetic field observations in penetration room.

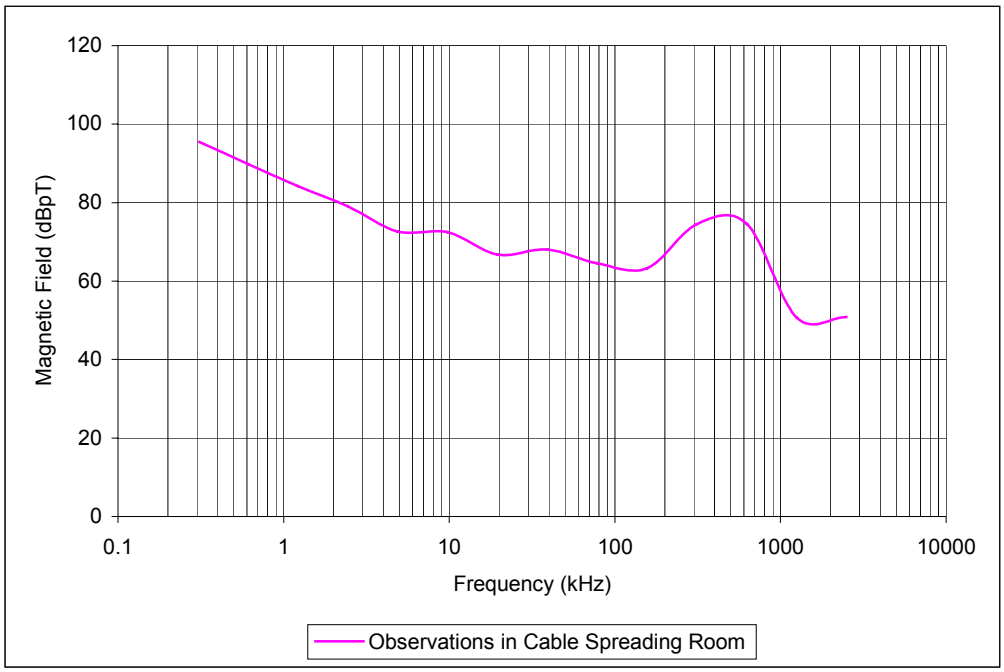

Fig. 2.3 Maximum radiated magnetic field observations in cable spreading room.

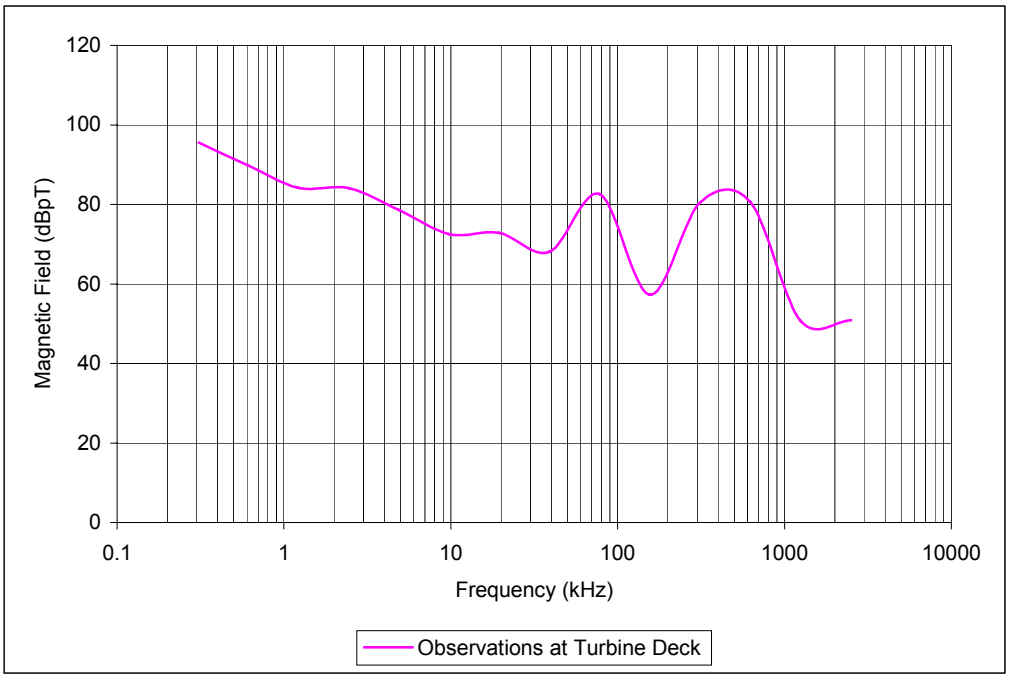

Fig. 2.4 Maximum radiated magnetic field observations at the turbine deck.

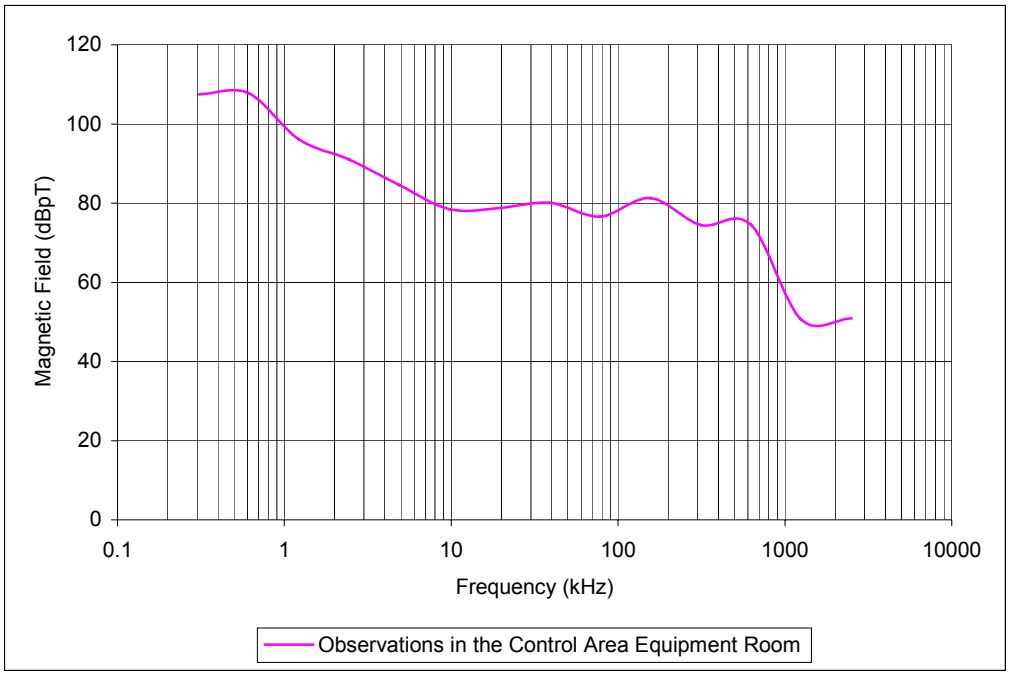

Fig. 2.5. Maximum radiated magnetic field observations in the control area equipment room.

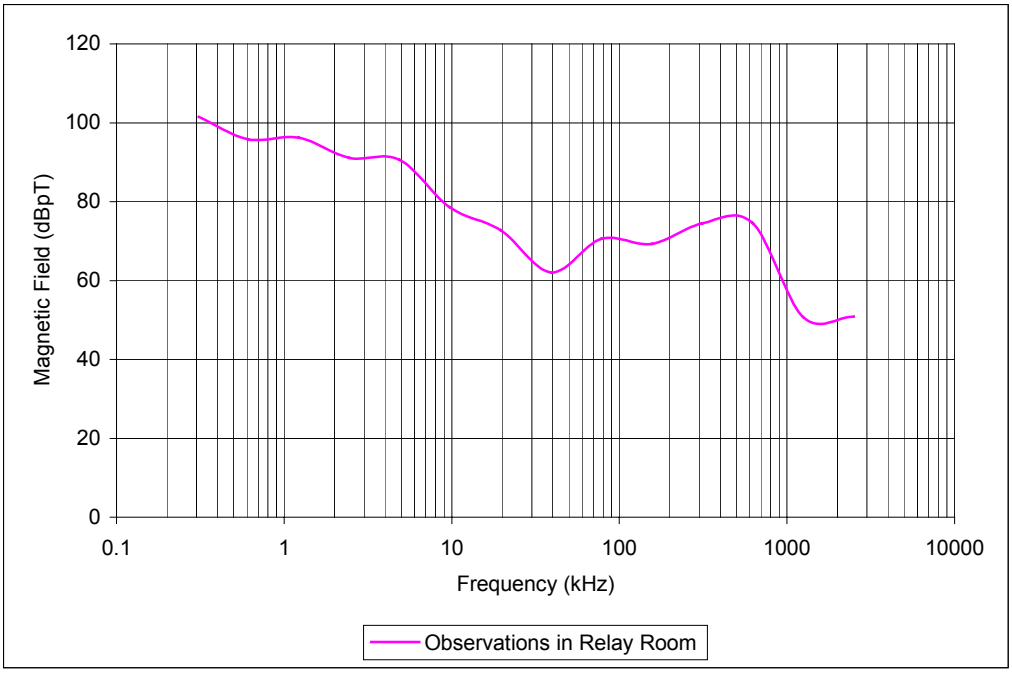

Fig. 2.6. Maximum radiated magnetic field observations in relay room.

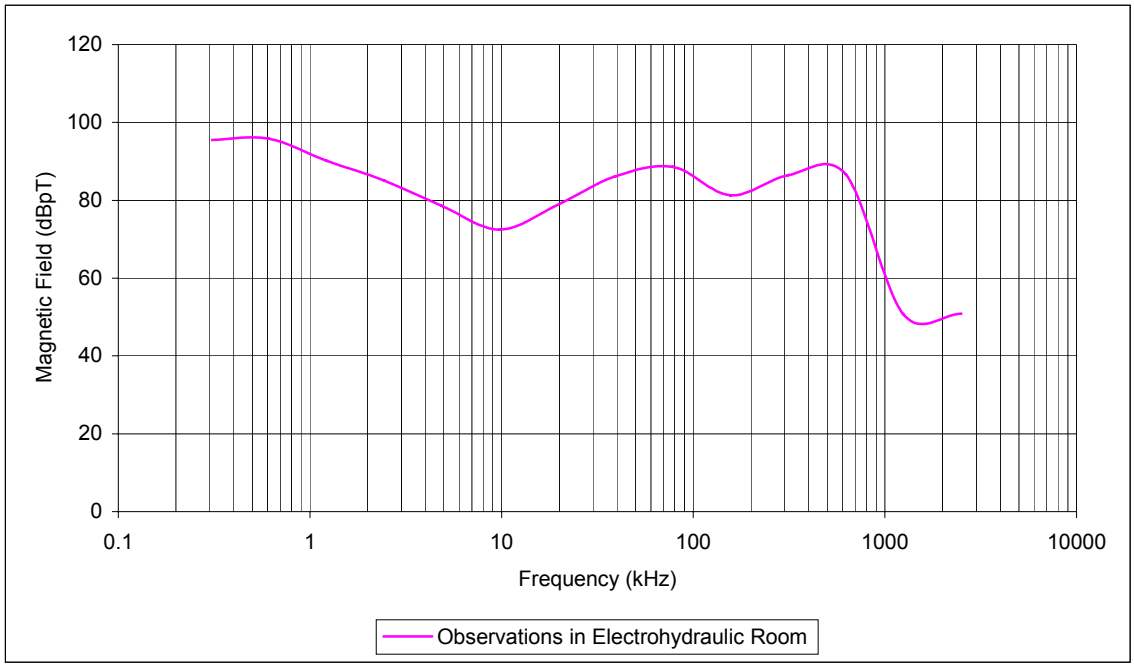

Fig. 2.7 Maximum radiated magnetic field observations in electrohydraulic room

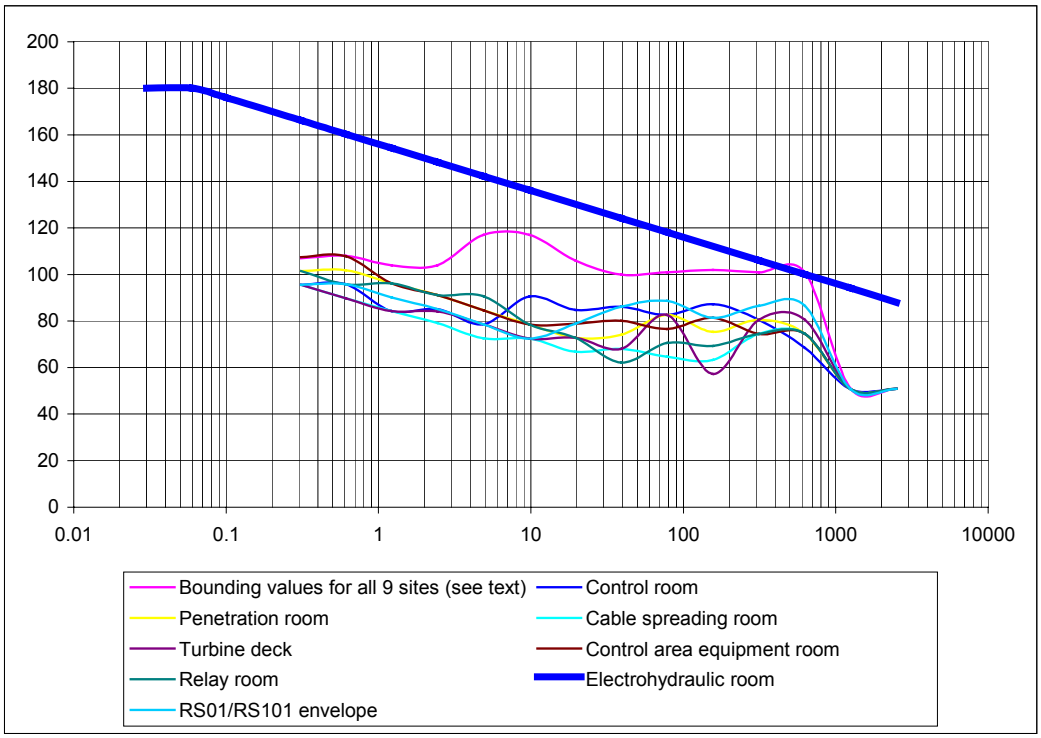

Fig. 2.8 Observed radiated magnetic fields by location compared to bounding envelope for all 9 sites (see text) and RS01/RS101 operating envelope.

2.2 TYPICAL RADIATED MAGNETIC FIELDS

The preceding analyses showed the bounding envelope of the radiated magnetic field levels in each of the eight locations examined to be below the recommended operating envelope suggested in NUREG/CR-6431 [identical to RS01/RS101 operating envelope in MIL-STD 461D].

Recall that in the preceding analyses, the bounding strength bin was the highest strength bin in which at most one count occurred in at least two data blocks or frames (recall that data was accumulated in 6-h frames or data blocks). Since in almost all cases examined, there was at most one count in only three or less frames, and lower strength bins in the relevant frequency bin always contained more than one count, this is similar to saying that the bounding strength bin was the highest bin in which the fewest frames contained counts. The bounding envelope frequency is the frequency for which the fewest frames have events in the highest strength bin.

While the bounding envelope is important for comparing to set criteria, it is also significant that in all the cases examined, the "typical" magnetic field levels were far below the bounding envelope. The majority of counts occurred within the receiver noise floor.

Table 2.2 shows the highest field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below. The table rows are frequency bins. For radiated magnetic fields, the frequency bins are in octaves. Bin 1 is 305-610 Hz; Bin 14 is 2.5-5MHz. The table columns are strength bins. Bin 1 is the receiver noise floor and contains the overwhelming majority of counts. It is noted that no counts were recorded above the receiver noise floor for frequencies greater than 1.25 MHz. Fig. 2.9 shows a plot of the data in Table 2.2.

2.3 BOUNDING ENVELOPES FOR RADIATED ELECTRIC FIELDS BY LOCATION

The observed radiated electric field data was analyzed by location and the maximum observed fields are indicated in Table 2.3. The corresponding plots are shown in figures 2.10 through 2.16. Fig. 2.17 shows these 7 separate plots, compared to the operating envelope suggested in NUREG/CR-6431 [identical to RS03/RS103 operating envelope in MIL-STD 461D]. As for Fig. 2.8 for the radiated magnetic fields, Fig. 2.17 also includes a plot of the overall bounding values for radiated electric fields for all 9 measurement sites in the NUREG/CR-6436 study. Again, as in the case of the magnetic field plot, this plot also appears higher than any of the locations because (1) data for **both** magnetic and electric fields were recorded for only 7 out of the 9 measurement sites (Table 1.1) in the NUREG/CR-6436 study. Thus, only these 7 measurement sites are analyzed in this report; (2) unlike the plots for the 7 locations, there is no restriction in the NUREG/CR-6436 plot of having at least two data blocks with at most one count in the same strength bin. Thus the overall bounding values encompass all events captured by the electric spectral receiver, including bins that may have had only one count throughout the observation period.

The maximum observed strength value for each frequency bin was calculated by determining the maximum bin in which a count occurred, and then calculating the equivalent strength (in dBμV/m) for that bin. For the electric field data, the total number of counts for all observations was 643,519, in contrast with the approximately 35.7 million observations for the magnetic field data. For the electric field data, a "count" is the result of a single spectral analysis performed by the electric spectral receiver and thus represents a little over 30s of elapsed (settling plus observation) time.

Table 2.2 Highest magnetic field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below.

Strength bin	Lower Freq. Bound (kHz) →	**0.3**	**0.61**	**1.22**	**2.44**	**4.88**	**9.77**	**19.53**	**39.06**	**78.12**	**156.25**	**312.5**	**625**	**1250**	**2500**
	Corresponding Bin Number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
		Noise floor													
1															
2			95.8	90.2	85.1										
3						84.6									
4															
5							90.5	84.8		76.6			74.5		
6									86.1		81.3	80.5			
7															
8															

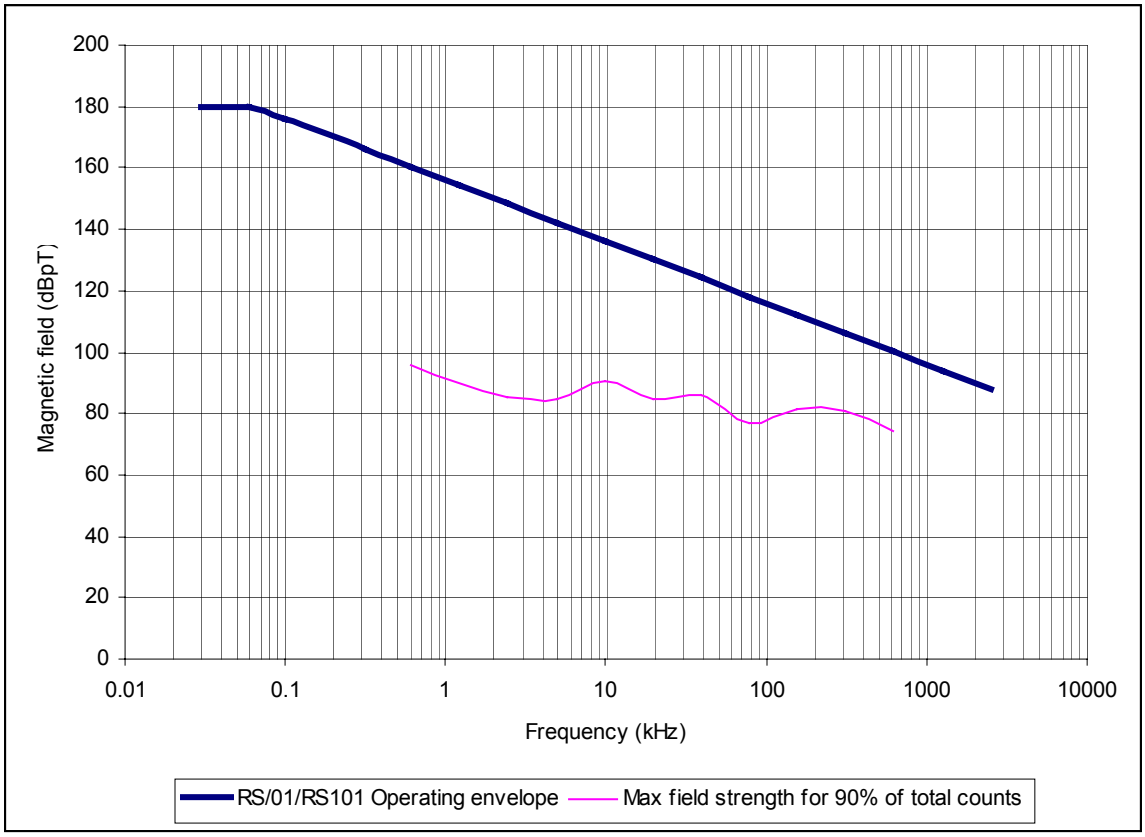

Fig. 2.9 Plot of highest magnetic field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below.

In this analysis, counts in a strength bin was considered statistically significant if at most one count occurred in a particular bin in at least two data blocks.3 Since the total number of counts for all observations was 643,519, two counts constitutes about 3 parts per million. This threshold was arbitrarily set with the objective of increasing confidence in the observed count(s) as being true signals, and not spurious ones.

The following observations may be made from the plots:

1. All the seven locations analyzed have levels within about 30dB of each other.
2. As for the magnetic field data, levels in all the seven locations examined are below the recommended operating envelope suggested in NUREG/CR-6431 [identical to RS03/RS103 operating envelope in MIL-STD 461D].
3. For radioactive electric fields, the quietest location for the plants analyzed is apparently the penetration room.
4. The control room has the relatively highest emissions of all the locations analyzed.
5. The highest observations in each frequency

c The original data was organized in blocks of 6h duration each.

5. The highest observations in each frequency band were used for each of the locations plotted. Therefore each of the plots envelops the worst case level. As noted in (2), these levels are well below the recommended operating envelope. The data therefore does not suggest that more than one set of recommended electromagnetic operating envelopes should be developed

2.4 TYPICAL RADIATED ELECTRIC FIELDS

The preceding analyses showed the bounding envelope of the radiated electric field levels in each of the eight locations examined to be below the recommended operating envelope suggested in NUREG/CR-6431 [identical to RS01/RS101 operating envelope in MIL-STD 461D]. As in the case of the magnetic field data, the bounding strength bin was the highest bin in which the fewest frames contained counts. The bounding envelope frequency is the frequency for which the fewest frames have events in the highest strength bin.

While the bounding envelope is important for comparing to set criteria, it is also significant that in all the cases examined, the "typical" electric field levels were below the bounding envelope. Table 2.4 shows the highest field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below. The corresponding plot is shown in Fig. 2.19. Again, as in the case of the magnetic field data, the majority of counts occurred within the receiver noise floor, although that is not obvious in the plot.

Table 2.3 Maximum Radiated Electric Fields by Location

Location	Freq. Band (MHz) →	5 - 100	100 - 200	200 - 300	300 - 400	400 - 500	500 - 600	600 - 700	700 - 800	800 - 900	900 - 1000
Control Room Maximum field (dBμV/m)		136.5	124.4	101.6	95.9	118.3	106.4	108.5	120	99.7	115.4
Penetration Room Maximum field (dBμV/m)		115.1	97.6	97.2	95.9	93.1	93.5	95.5	98.6	99.7	106.9
Cable Spreading Room Maximum field (dBμV/m)		115.1	106.1	97.2	95.9	110.3	97.9	95.5	98.6	99.7	106.9
Turbine Deck Maximum field (dBμV/m)		136.5	97.6	97.2	95.9	93.1	106.4	95.5	120	99.7	106.9
Control Area Equipment Room Maximum field (dBμV/m)		119.5	106.1	101.6	95.9	118.3	102	95.5	98.6	99.7	106.9
Relay Room Maximum field (dBμV/m)		123.7	102	97.2	95.9	106	106.4	95.5	98.6	99.7	106.9
Electrohydraulic Room Maximum field (dBμV/m)		119.5	106.1	101.6	95.9	118.3	102	95.5	98.6	99.7	106.9

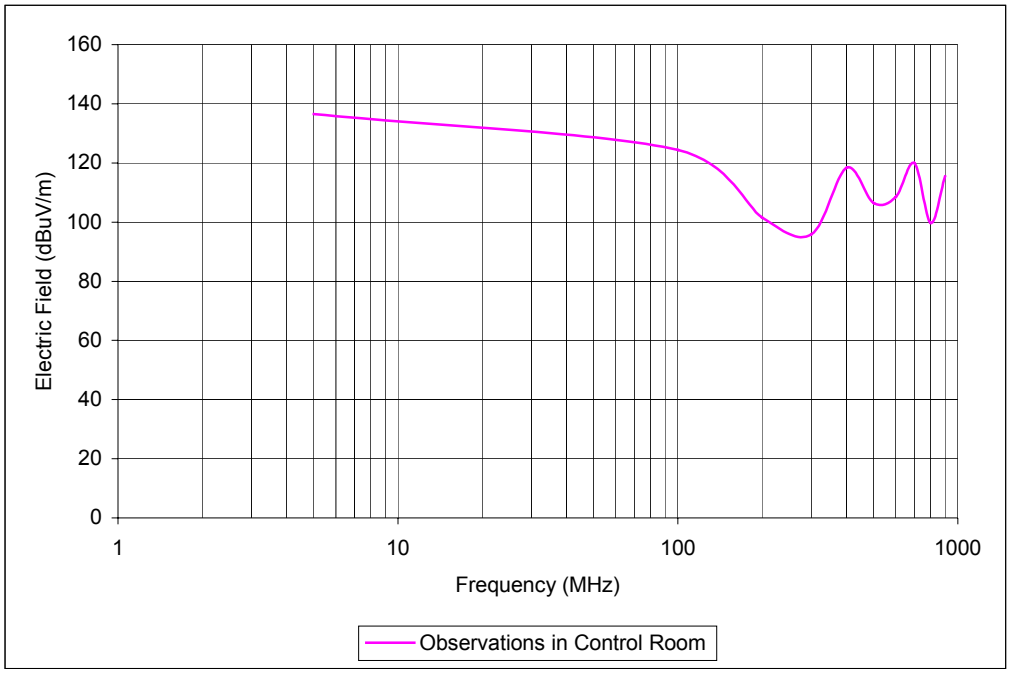

Fig. 2.10 Maximum radiated electric field observations in control room.

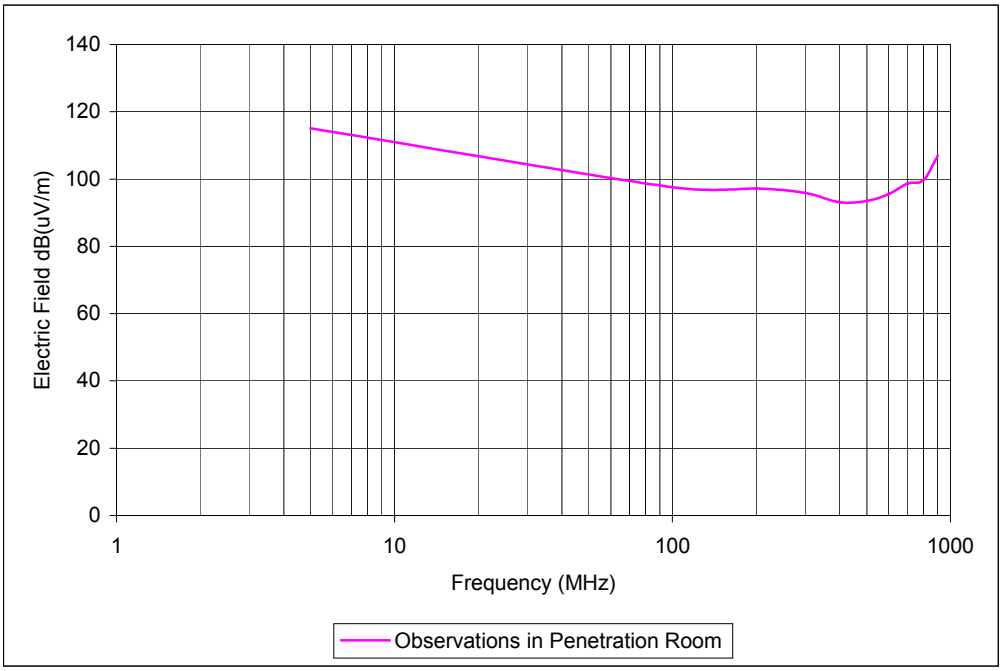

Fig. 2.11 Maximum radiated electric field observations in penetration room.

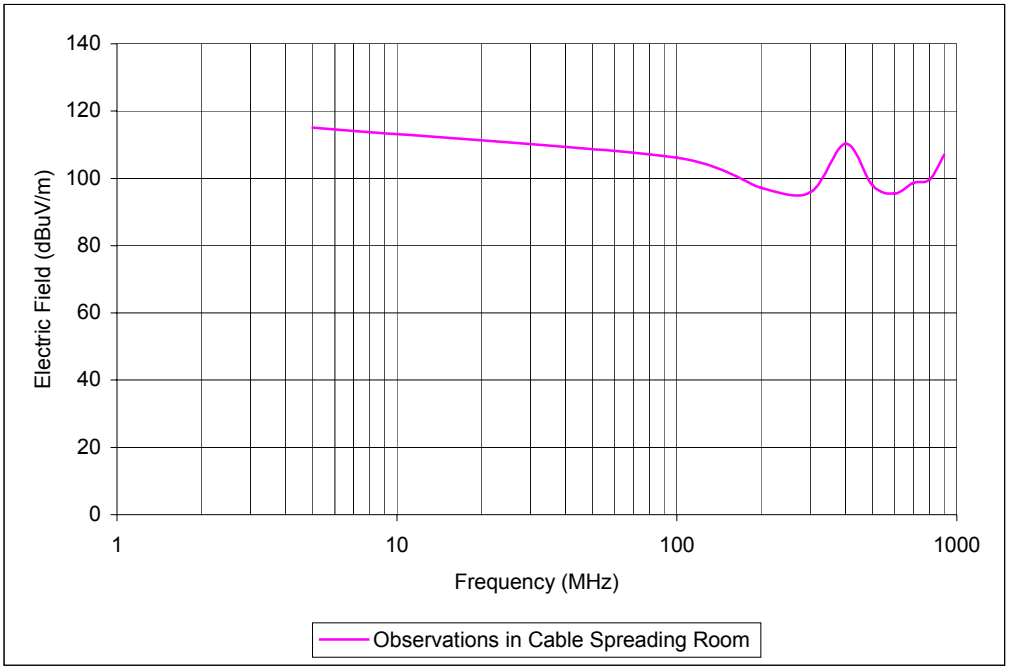

Fig. 2.12 Maximum radiated electric field observations in cable spreading room.

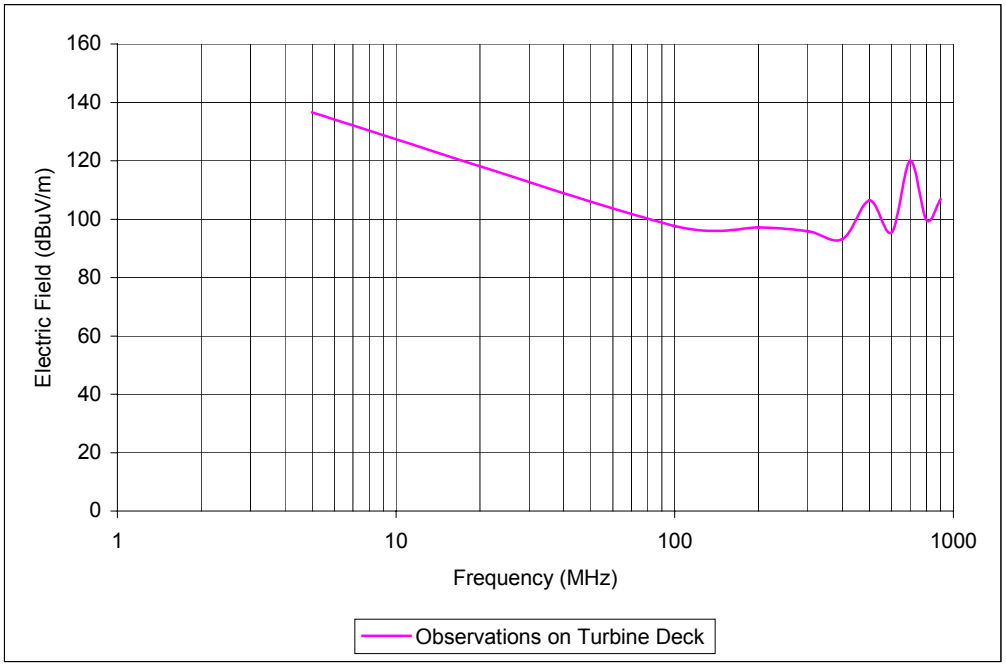

Fig. 2.13 Maximum radiated electric field observations in the turbine deck.

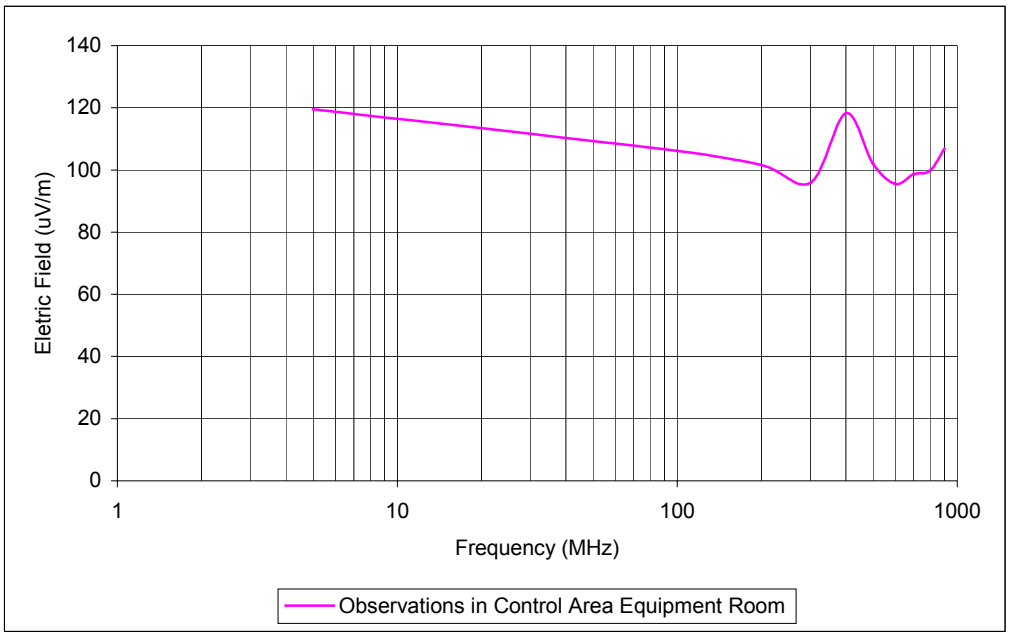

Fig. 2.14 Maximum radiated electric field observations in control area equipment room.

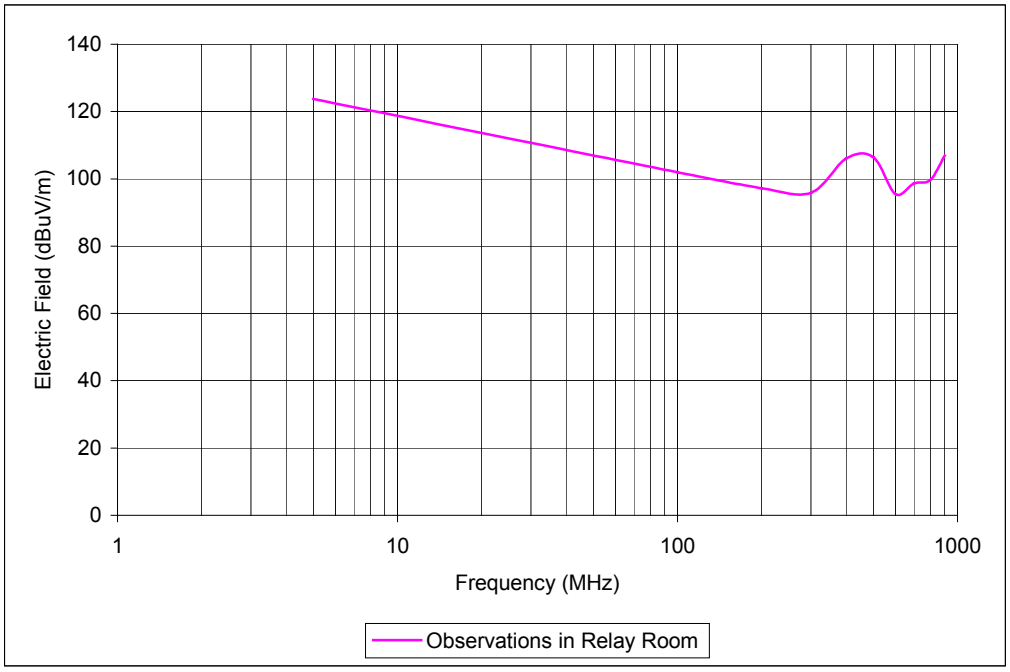

Fig. 2.15 Maximum radiated electric field observations in the relay room.

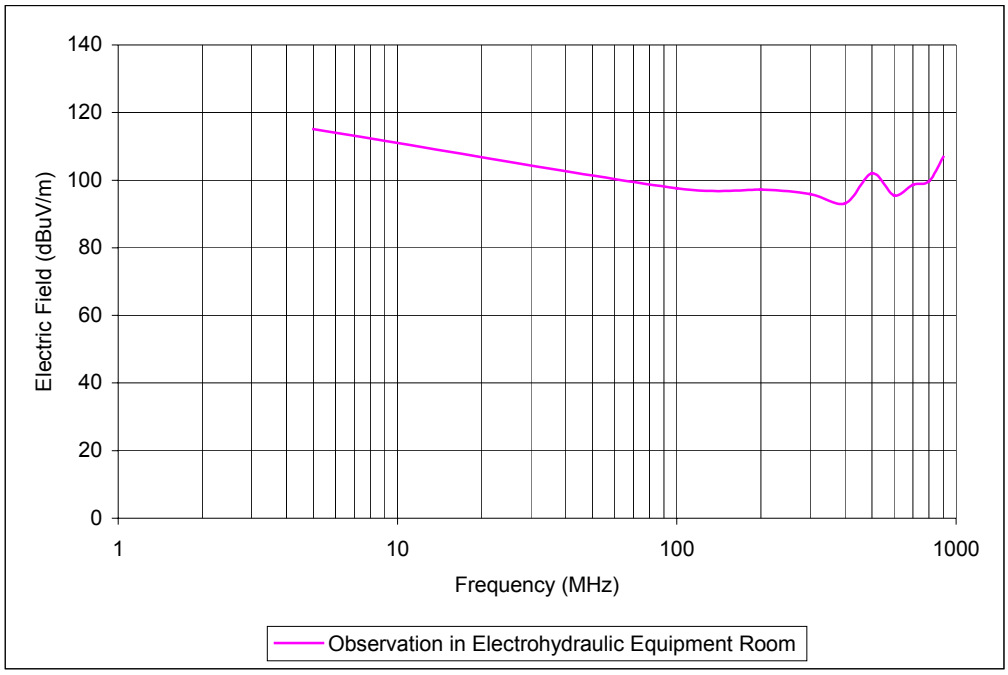

Fig. 2.16 Maximum radiated electric field observations in electrohydraulic room.

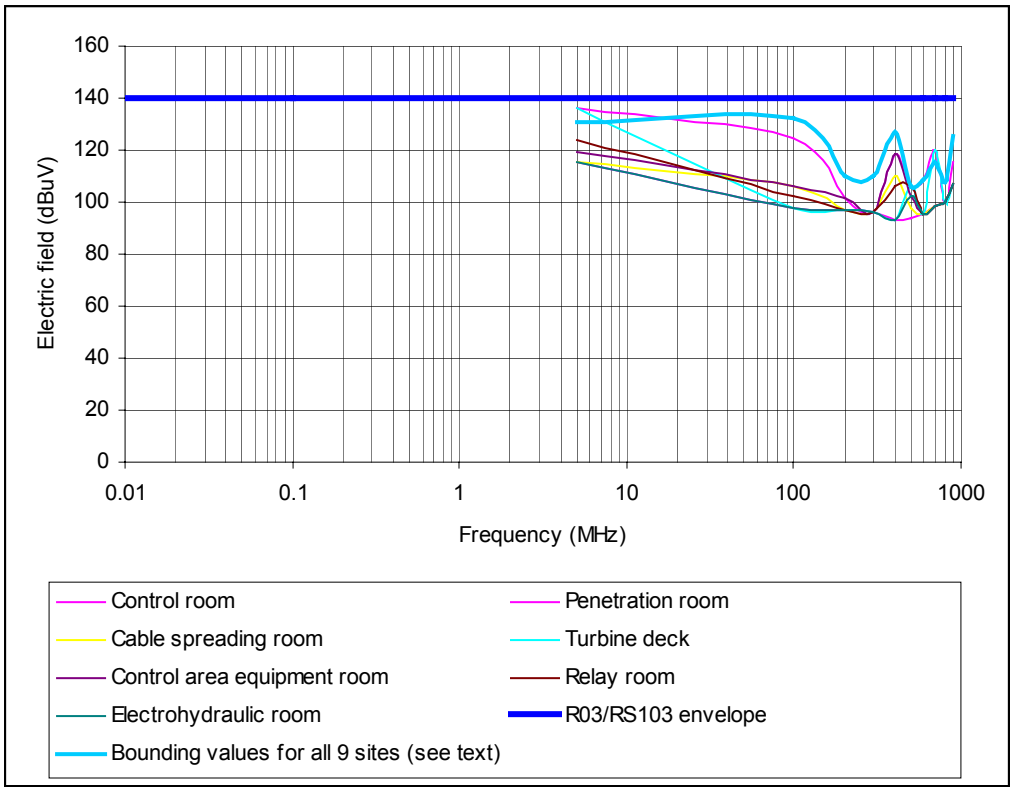

Fig. 2.17 Observed radiated electric fields by location

Table 2.4 Highest electric field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below.

Strength bin	Freq. Band (MHz) →	5 - 100	100 - 200	200 - 300	300 - 400	400 - 500	500 - 600	600 - 700	700 - 800	800 - 900	900 - 1000
1			97.6	97.2	95.9	93.1		95.5	98.6	99.7	106.9
2											
3		123.7									
4							106.4				
5											
6											
7											
8											
9											

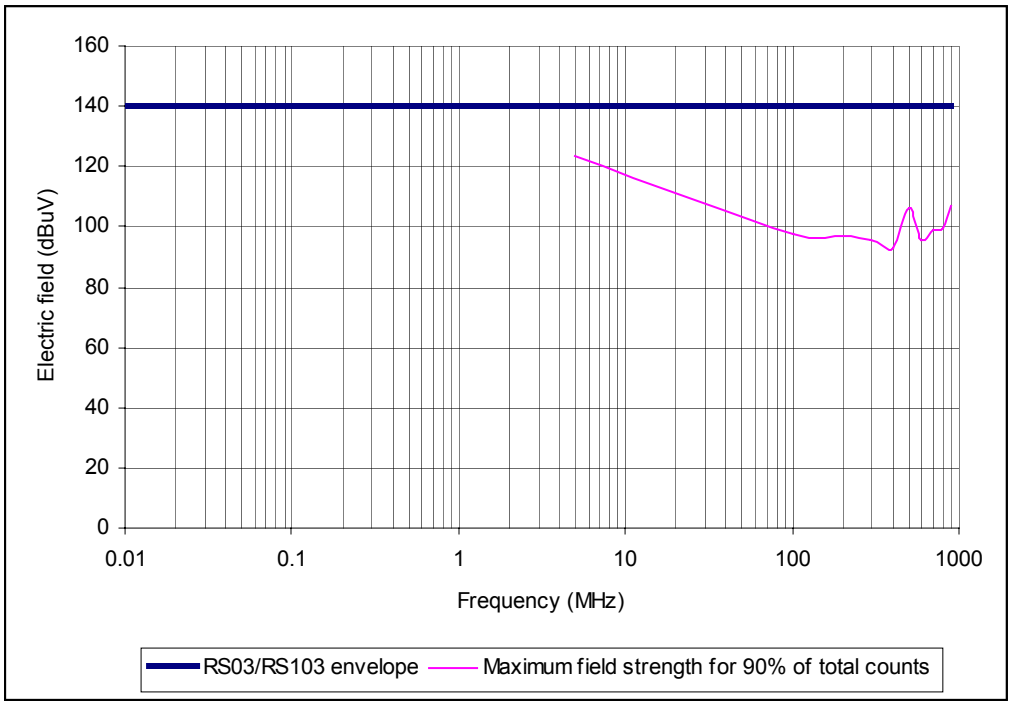

Fig. 2.18 Plot of highest electric field strength for which 90% of all counts in the corresponding frequency bin fell in that strength bin or below.

3. CONCLUSIONS

The objective of this report is to try to answer one question based on further analysis of EMI/RFI data collected and documented in NUREG/CR-6436: *Are the electromagnetic envelopes recommended in NUREG/CR-6436, which is based on data reported in NUREG/CR-6436, too severe for certain locations in the nuclear power plant and if so, is there is a need for plant-specific operating envelops?* To answer this question, the data obtained from the EMI/RFI surveys and documented in NUREG/CR-6436 were further analyzed primarily location, and compared with each other as well as with the envelopes suggested in NUREG/CR-6431. Seven sites were analyzed, out of a total of 9 sites surveyed and reported in NUREG/CR-6436. These seven sites are those for which both magnetic as well as electric field data were available. For the other two sites only magnetic field data, or only electric field data, was available. The locations analyzed were without regard to plant type. For example, all control rooms in all PWRs and BWRs surveyed were analyzed together, all cable spreading rooms in all plant types were analyzed together, etc. The most significant conclusions of relevance to answering the question posed in this report are the following (these conclusions are true for both electric and magnetic field data).

- While there is some variation in the electromagnetic ambient levels among the various locations examined, all the levels were within about 30 dB of each other.

- The levels in all the seven locations examined are well below the recommended operating envelope suggested in NUREG/CR-6431.

- The plot of overall bounding values, which encompasses <u>all</u> the locations surveyed in NUREG/CR-6436, is also within the recommended operating envelope. However, the bounding envelope is rather close to the recommended operating envelope in the frequency window of 400 MHz - 700 MHz.

- The majority of counts for all frequency ranges, as recorded by the magnetic and electric spectral receivers, were within the noise floor for all the plants monitored. This is significant because it suggests that typical electromagnetic fields at power plants may be "quieter" than anticipated.

We conclude from these results that information to date on ambient electromagnetic fields in nuclear power plants support the recommendation of only one set of operating envelopes for all nuclear power plants. Furthermore, the electromagnetic envelopes recommended in NUREG/CR-6436, which is based on data reported in NUREG/CR-6436, are not too severe, and there is no need for location-specific or plant-specific operating envelopes.

APPENDIX A

Portions of actual data files stored during operation of the electric and magnetic field spectral receivers.

BLOCK	BIN	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	32	0	0	0	0	0	0	0	0	0
	2	171	0	0	0	0	0	0	0	0	0	183	0	0	0	0	0	0	0	0	0
	1	279	450	450	450	450	450	450	450	450	450	235	450	450	450	450	450	450	450	450	450
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	56	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	394	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450	450

Fig. A.1 Electric field spectra data file.

BLOCK	BIN		1	2	3	4	5	6	7	8	9	10	11	12	13	14
	9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	8		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	7		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	6		0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	5		0	0	0	0	0	0	0	0	0	0	0	0	0	0
	4		0	0	0	0	0	0	0	0	0	8	0	0	0	0
	3		0	0	0	0	0	0	0	0	1	60	22	0	0	0
	2		0	11	0	3	6	1	29	30	97	22047	1110	7792	0	0
	1		36072	36061	36072	36069	36066	36071	36043	36042	35974	13957	34940	28280	36072	36072

Fig. A.2 Magnetic field spectra data file.

APPENDIX B

CALIBRATION OF THE ORNL ELECTRIC AND MAGNETIC SPECTRAL RECEIVERS

Calibration of the electric and magnetic spectral receivers involves determining the electric and magnetic field amplitudes, respectively, corresponding to amplitude bin boundaries, for each frequency bin.

The spectral receivers were originally calibrated in 1994 during their development and recalibrated over the period 1998 October 26 to 30 at the ORNL Gigahertz Transverse Electromagnetic (GTEM) calibration facility. The facility includes a signal generator, power amplifiers, an EMCO GTEM 5305 transverse electromagnetic (TEM) cell, and an isotropic field probe set (EMCO 7121 Isotropic Probe Set, SN1399). The item to be calibrated was placed within the uniform field volume of the TEM cell. The applied field was controlled by adjusting the output level of the signal generator and measured using a calibrated isotropic field probe (placed within the uniform-field volume near the test item). The ORNL GTEM calibration facility is limited to frequencies above 10 kHz, so it was not possible to recalibrate the first 5 frequency bins for the magnetic spectral receiver. The original calibration is used for the first 5 frequency bins. This was not a concern as there had been very little change in the calibration for the other frequency bins.

The general procedure that should be followed in establishing the calibration of each instrument is as given below:

1. Set up the spectral receiver in a facility where the frequency and amplitude of the field (electric field or magnetic field, as appropriate) applied to the receiver may be controlled and measured.
2. Connect the VGA monitor and keyboard to the receiver so that the signal amplitude in each frequency bin may be read from the monitor screen.
3. Apply a field of known frequency and amplitude to the receiver and record the signal amplitude displayed on the monitor screen for the corresponding frequency bin.

   Note: The displayed value is related to the detected-signal amplitude in the corresponding frequency bin. The detected-signal values corresponding to amplitude bin boundaries are as listed in Tables B.1 and B.2, for the electric and magnetic spectral receivers, respectively. The recorded data include the signal generator frequency and output level (dBm), the electric field indicated by the isotropic field probe (V/m) and the detected-signal amplitude displayed on the monitor.
4. Repeat step 3 for several values of the applied field, such that the signal amplitude values span the measurement range (i.e., the range of values listed in Table B.1 and B.2, as appropriate).
5. Repeat steps 3 and 4 for at least one frequency in each frequency bin.
6. For each frequency bin, analyse the recorded data to determine the field values at amplitude bin boundaries. Where results are available for more than a single frequency within a bin, take the maximum available value as the field value at the amplitude bin boundary.

Precision and Uncertainty

Amplitude-frequency bin structures for the electric and magnetic spectral receivers are given in Figures B.1 and B.2, respectively. Similar information is given in Figures B.3 and B.4. In these figures, however, the upper bound amplitude bin strengths are given, and the frequencies are given in terms of bin numbers. Figures B.3 and B.4 are what one would normally use to interpret the data files such as those shown in Fig. A.1 and A.2.

In Figures B.1 and B.2, the bin limits are defined as the upper bounds on the possible values of the peak electric field or magnetic flux in a given strength bin for a given frequency band. It should be noted that the upper bounds for some strength bins are frequency dependent but all the bounds are shown as constant in the figure to enhance the clarity of the illustrations.

The precision of the output values of both receivers is limited by the resolution of the A/D converters (see chapter 1). The magnetic spectral receiver uses 8-bit conversion with I bit reserved for the sign. This yields 2^7 possible absolute values. Consequently, the decimal values of strengths computed from the A/D converter output are accurate to only three significant figures at best. The electric spectral receiver- uses 12-bit conversion with I bit reserved for the sign. This yields 2^{11} possible absolute values; consequently, the decimal values of strengths computed from the A/D converters are only accurate to four significant figures at best.

The precision of the output values of both receivers is limited by the resolution of the A/D converters. The magnetic spectral receiver uses 8-bit conversion with I bit reserved for the sign. This yields 2' possible absolute values. Consequently, the decimal values of strengths computed from the A/D converter output are accurate to only three significant figures at best. The electric spectral receiver- uses 12-bit conversion with I bit reserved for the sign. This yields 21' possible absolute values; consequently, the decimal values of strengths computed from the A/D converters are only accurate to four significant figures at best. Hence, the tables in the following chapters show the electric receiver values rounded to four significant figures and the magnetic spectral receiver values rounded to three significant figures.

The bin structures illustrated in the figures are based on the rms values of the upper bounds of the strength bins in each frequency band. However, they do not account for measurement uncertainty. It is necessary to consider the measurement uncertainty with the bin structure in establishing a realistic bounding envelope for the measurements.

The observation uncertainty for the results of this electromagnetic survey characterizes the dispersion of the values that could reasonably be attributed to the measurand, which is the electromagnetic phenomenon subject to measurement (i.e., radiated fields). It accounts for the combined effect of the representation uncertainty or bin width (i.e., the spread of values about the measurement result. within which the value of the measurand can be expected to be found) and the measurement uncertainty (i.e., the possible error in the value of the measurand as provided by the measurement result). The observation uncertainty is determined by calculating the combined standard uncertainty for the highest strength value in each frequency band. This computation uses the law of propagation of errors (i.e., the square-root of the sum of the squares) to combine the two uncorrelated uncertainties.

In calculating the combined standard uncertainty for the electromagnetic survey results, probability distributions for the uncertainty components must be established or assumed. For the measurement uncertainty contribution, a normal distribution is used because the measurement standard deviation for each spectral receiver was determined through calibration testing of the individual components and the completed receiver. The measurement standard deviation for the electric spectral receiver is ±1.53 dB and the measurement uncertainty for the magnetic spectral receiver is +1.75 dB. The bounding measurement uncertainty for the spectral receiver pair is defined in terms of the expanded uncertainty An expanded uncertainty defines a range about the measurement result in which measured values of the measurand can be expected to lie with high confidence. As is typical, the expanded uncertainty represents a 95% confidence that the measurand is within the uncertainty span. This span is determined by using twice the standard deviation for the measurement. The expanded uncertainty (95% confidence level) is +3.1 dB for the electric spectral receiver and +3.5 dB for the magnetic receiver.

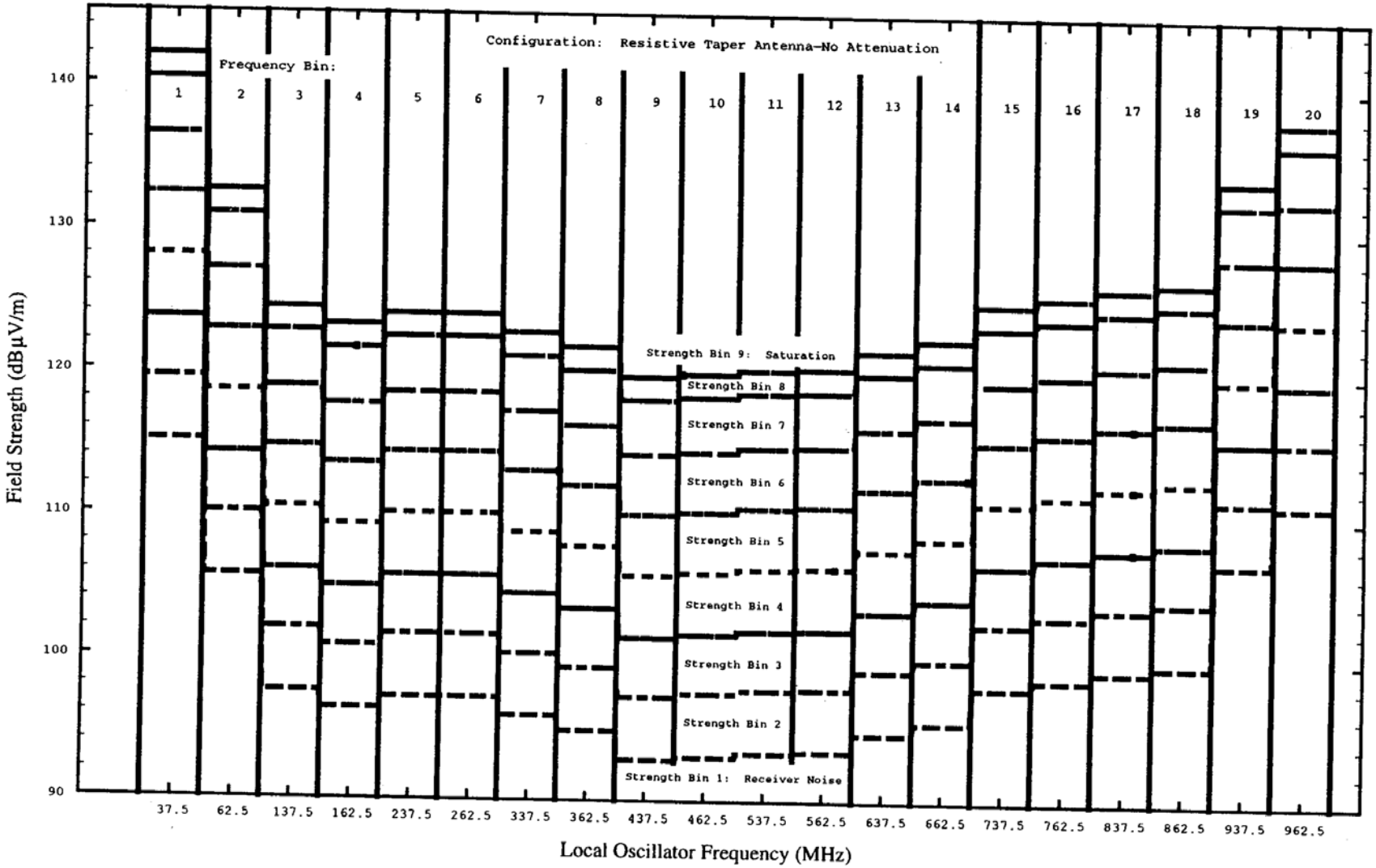

Figure B.1. Amplitude and frequency bin structure for the electric spectral receiver.

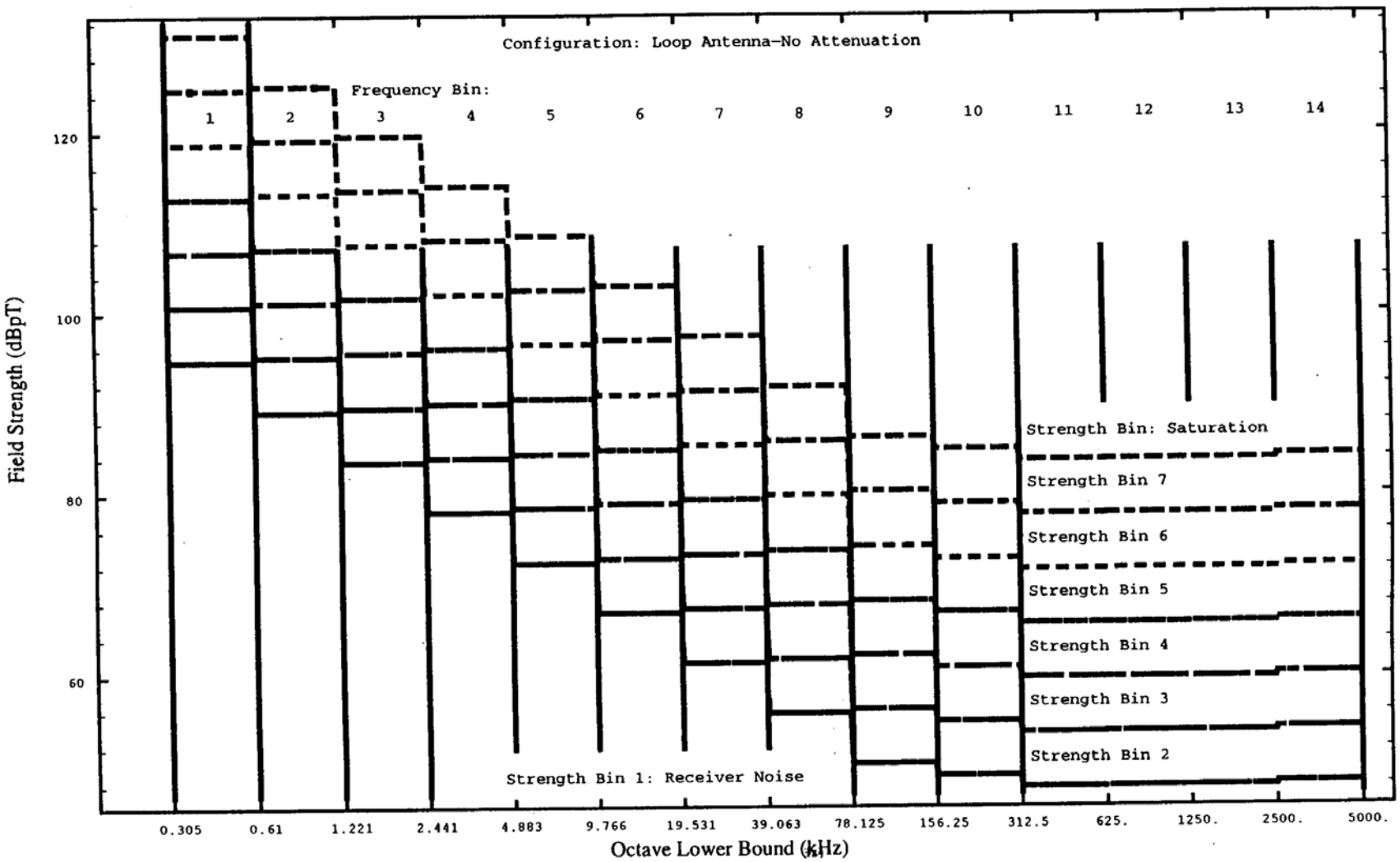

Figure B.2. Amplitude and frequency bin structure for the magnetic spectral receiver.

	Bin No→	1	2	3	4	5	6	7	8	9	10
9	Strength	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation
8	← Bin No	142	132.6	124	123.3	124	124	122.8	121.8	119.8	120
7		140.4	130.9	122.4	121.6	122.4	122.4	121.1	120.1	118.1	118.3
6		136.5	127.1	118.6	117.8	118.6	118.6	117.3	116.3	114.2	114.5
5	Upper Bound of Eletric Field Strength (dBuV/m)	132.3	122.9	114.4	113.6	114.4	114.4	113.1	112.1	110.1	110.3
4		128	118.6	110.1	109.3	110.1	110.1	108.8	107.8	105.8	106
3		123.7	114.2	105.7	104.9	105.7	105.7	104.5	103.5	101.5	101.6
2		119.5	110.1	101.6	100.8	101.8	101.6	100.3	99.3	97.3	97.5
1	→	115.1	105.7	97.2	94.6	97.2	97.2	95.9	94.9	92.9	93.1

	Bin No→	11	12	13	14	15	16	17	18	19	20
9	Strength	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation
8	← Bin No	120.2	120.3	121.6	122.4	124.9	125.5	126.1	126.5	133.7	
7		118.6	118.7	120	120.8	123.3	123.8	124.5	124.9	132.1	
6		114.7	114.8	116.1	116.9	119.4	120	120.6	121	128.2	
5	Upper Bound of Eletric Field Strength (dBuV/m)	110.6	110.7	111.9	112.7	115.2	115.8	116.4	116.9	124.1	
4		106.3	106.4	107.7	108.5	111	111.5	112.1	112.6	119.8	
3		101.9	102	103.3	104.1	106.6	107.2	107.8	108.2	115.4	
2		97.8	97.9	99.2	100	102.5	103	103.6	104.1	111.3	
1	→	93.4	93.5	94.7	95.5	98	98.6	99.2	99.7	106.9	

Fig. B.3. Amplitude and frequency bin structure for electric spectral receiver

	Bin No→	1	2	3	4	5	6	7
	Strength							
8	← Bin No	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation
7		131.5	125.8	120.2	115.1	108.6	102.5	96.8
6		125.5	119.8	114.2	109.1	102.6	96.5	90.8
5	Upper	119.5	113.8	108.2	103.1	96.6	90.5	84.8
4	Bound of	113.5	107.8	102.2	97.1	90.6	84.5	78.8
3	Eletric Field	107.5	101.8	96.2	91.1	84.6	78.5	72.8
2	Strength	101.5	95.8	90.2	85.1	78.6	72.5	66.8
1	(dBuV/m) →	95.5	89.8	84.2	79.1	72.6	66.5	60.8

	Bin No→	8	9	10	11	12	13	14
	Strength							
8	← Bin No	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation	Saturation
7		92.1	88.6	87.3	86.5	86.6	86.7	86.9
6		86.1	82.6	81.3	80.5	80.6	80.7	80.9
5	Upper	80.1	76.6	75.3	74.5	74.6	74.7	74.9
4	Bound of	74.1	70.6	69.3	68.5	68.6	68.7	68.9
3	Eletric Field	68.1	64.6	63.3	62.5	62.6	62.7	62.9
2	Strength	62.1	58.6	57.3	56.5	56.6	56.7	56.9
1	(dBuV/m) →	56.1	52.6	51.3	50.5	50.6	50.7	50.9

Fig. B.4. Amplitude and frequency bin structure for magnetic spectra