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ADMINISTRATIVE INFORMATION

This is a final report on the intermodulation interference testing of candidate composite materials for the Advanced Enclosed Mast/Sensor (AEM/S) System. This work has been conducted by the Applied Electromagnetics Branch, Code 822, of the Naval Command, Control and Ocean Surveillance Center (NCCOSC), RDT&E Division, San Diego, California 92152–5001, under the sponsorship of the Office of Naval Research (ONR), 800 North Quincy Street, Arlington, Virginia 22717–5000.

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CONTENTS

FIGURES

TABLE

INTRODUCTION

With the possibility of the large-scale use of graphite-bearing composites for topside structures and masts, some concern has been expressed as to whether these materials might be intermodulation interference (IMI) generators. To resolve this question, tests were performed to compare the relative signal levels of intermodulation generated by two graphite fiber composite material samples to a steel sample and to a brass sample. The graphite fiber composite material samples were representative of the materials that will be used in the Advanced Enclosed Mast/Sensor (AEM/S) System. The results of these tests were evaluated in terms of the potential of graphite-loaded composite structures to be significant generators of IMI on board Navy ships.

The AEM/S System is a low-cost, lightweight hybrid composite platform designed for replacement of the all-metallic mast of a surface combatant. The AEM/S System will fully enclose the current radar and communication antennas, which will substantially reduce metallic mast blockage, virtually eliminate the ravages of weather and wind loading on antennas, and provide a significant improvement in signature control. The key to achieving these characteristics is the hybrid composite material system of the side walls, composed of dielectric materials and frequency-selective surface (FSS) layers. The FSS allows the ship radar and communication signals to pass through unattenuated while rejecting enemy radar signals over select threat frequency bands. Non-FSS composite walls use graphite fiber composite material systems. Signature control is done by appropriate exterior shaping. The AEM/S system represents an enabling technology that is the basis for a revolutionary approach to the topside integration of electromagnetic systems and that will promote the development of next-generation solid state multifunction antenna systems.

BACKGROUND

Successful reception of incoming traffic (signals) on a small platform can be hindered by interference that is independent of the care taken in the design of communications equipment and the systems they comprise (reference 1). Protection of the receivers from local transmissions, purification of radiated signals, and careful choice of receive-transmit frequency separations are all important and necessary means of avoiding interference. However, these controls do not guarantee unhampered reception during times of collocated transmissions.

In the Navy, severe interference problems have been observed aboard a number of ships. It was discovered that the major sources of this interference were nonlinear items inherent in the immediate surroundings of the receiver or transmit antenna packages (reference 2). Metallic lifelines were found to be major sources of interference. Expansion joints and mooring or anchor chains, used to secure the ship at the pier, were found to be significant nonlinearities. Other items found to be nonlinear contributors to interference include ladders, life raft hangers, guard rails, antenna guying wires, booms, and similar structures.

Natural (environmental) nonlinearities have a voltage-current characteristic curve closely resembling the curve for a pair of parallel front-to-back diodes. Figure 1 shows a typical nonlinearity voltage-current characteristic curve. This nonlinear characteristic causes intermodulation (mixing), producing sum and difference products during transmissions involving two or more signals of different frequencies. For example, if two frequencies are transmitted, intermodulation products formed and then radiated from a nonlinear element can be computed by substitution of a signal of the form

$$x = E_\omega \cos \omega t + E_\varrho \cos \varrho t$$

into a finite power series form

$$y = a_0 + a_1 x + a_2 x^2 + a_3 x^x + a_4 x^4 + \ldots + a_n x^n$$

where the finite power series is representative of the nonlinear curve of figure 1. The results of such computations yield the various intermodulation products of the form

$$\cos (m\omega \pm n\varrho)t$$

where m and n are integers and the "order" of the product is the sum, $m + n$. For transmissions from one transmitter only, $n = 0$ and the intermodulation products assume the form cos $m\omega t$. These signal source intermodulation products are known as harmonics of the fundamental transmitted signal,cos μt.

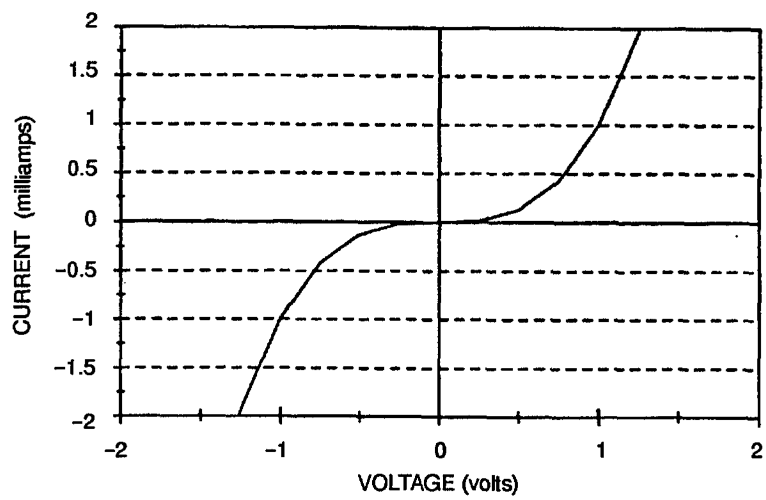

Figure 1. "Typical" nonlinear voltage-current characteristic curve.

Computations have been made relating the number of generated intermodulation frequencies to the number of transmitted frequencies as a function of order $(m + n)$. From these computations, it can be seen that with 10 signals being radiated, approximately 100 second-order, 800 third-order, 2400 fourth-order, and 10,400 fifth-order products are generated. As the number of transmitters is increased, the number of intermodulation products generated rises rapidly.

Due to the symmetrical nature of a typical natural nonlinearity voltage-current characteristic curve, odd-order intermodulation products and harmonics are much more pronounced than even order. Therefore, the third-order intermodulation products and the third harmonic are normally the strongest interference signals generated by environmental nonlinearities. It is generally the third-order intermodulation product that is representative of a given nonlinearity. Thus it is the determination of the magnitude of a third-order product from a given nonlinearity produced by two transmitted frequencies that is used to characterize a given nonlinearity.

Radio frequency (RF) currents that flow through the topside structures and deck equipment on board naval vessels can cause the generation of IMI products when they flow through interfaces and junctions that are electrically nonlinear. This phenomenon is often referred to as the "rusty bolt" problem, because the corrosion resulting from the moist sea-salt environment can create the offending nonlinear junction. When multiple high-powered, high-frequency (HF, 2 to 30 MHz) radio transmitters are operated simultaneously, the resultant IMI products can significantly degrade HF receiver performance, thus impacting the ship's ability to communicate. To deal with this problem, topside junctions and joints are repeatedly cleaned, tightened, and given preservation treatments. However, for a large composite structure, these mitigating techniques would not be appropriate.

EXPERIMENTAL APPROACH

To resolve whether graphite fiber composites are significant generators of IMI, tests were performed to compare the relative levels of IMI generated by two samples of graphite fiber composite materials to a steel sample and to a brass sample. Again, the graphite fiber composite materials were representative of the materials that will be used in the composite mast. The fibers in both samples are PAN-based graphite fibers. One sample, which will be referred to from here on as the "mat sample," was composed of a chopped graphite fiber mat consisting of a random dispersion of short, nominally 1-inch long, fibers impregnated with a brominated vinylester resin. The other was made of a continuous strand, graphite fiber, plain weave fabric also impregnated with a brominated vinylester resin and which will be referred to as the "fabric sample." Both graphite samples were fabricated by rolling a sheet of the mat or fabric to form a small diameter rod. These dry fiber rods were placed in a circular mold that was first evacuated, and then the vinylester resin was infused into the mold cavity, impregnating the dry fiber rods. The resulting rods had a high fiber content and low void content comparable to that anticipated for their application in the AEM/S. The steel sample was HY80, commonly used in decks. A brass sample was chosen as an IMI-free baseline reference to examine IMI inherent in the test setup. The test setup is shown in figures 2 and 3.

The sample test fixture, as shown in figure 4, consisted of a 1-inch coaxial cable connector in which the center pin had been cut off and replaced by the test sample. The samples were equipped with a small threaded brass stud that could be screwed into the face of the remaining portion of the center pin to make electrical contact and retain the sample in place.

A two-tone test was performed to determine the magnitude of the intermodulation product generated in the test materials. As displayed in figure 2, two AN/URT-23 1000-watt HF transmitters were driven by two Fluke model 6039A frequency synthesizers to create the two-tone test at frequencies F_1 and F_2. The transmitter output levels were monitored by Hewlett-Packard (HP) model 410B vacuum-tube voltmeters connected to the 50-ohm line by means of HP 11042A tee-probes. From a power level standpoint, a shipboard nonlinearity (i.e., "rusty bolt") can be anywhere between the transmitter and receiver. From a worst-case analysis, a

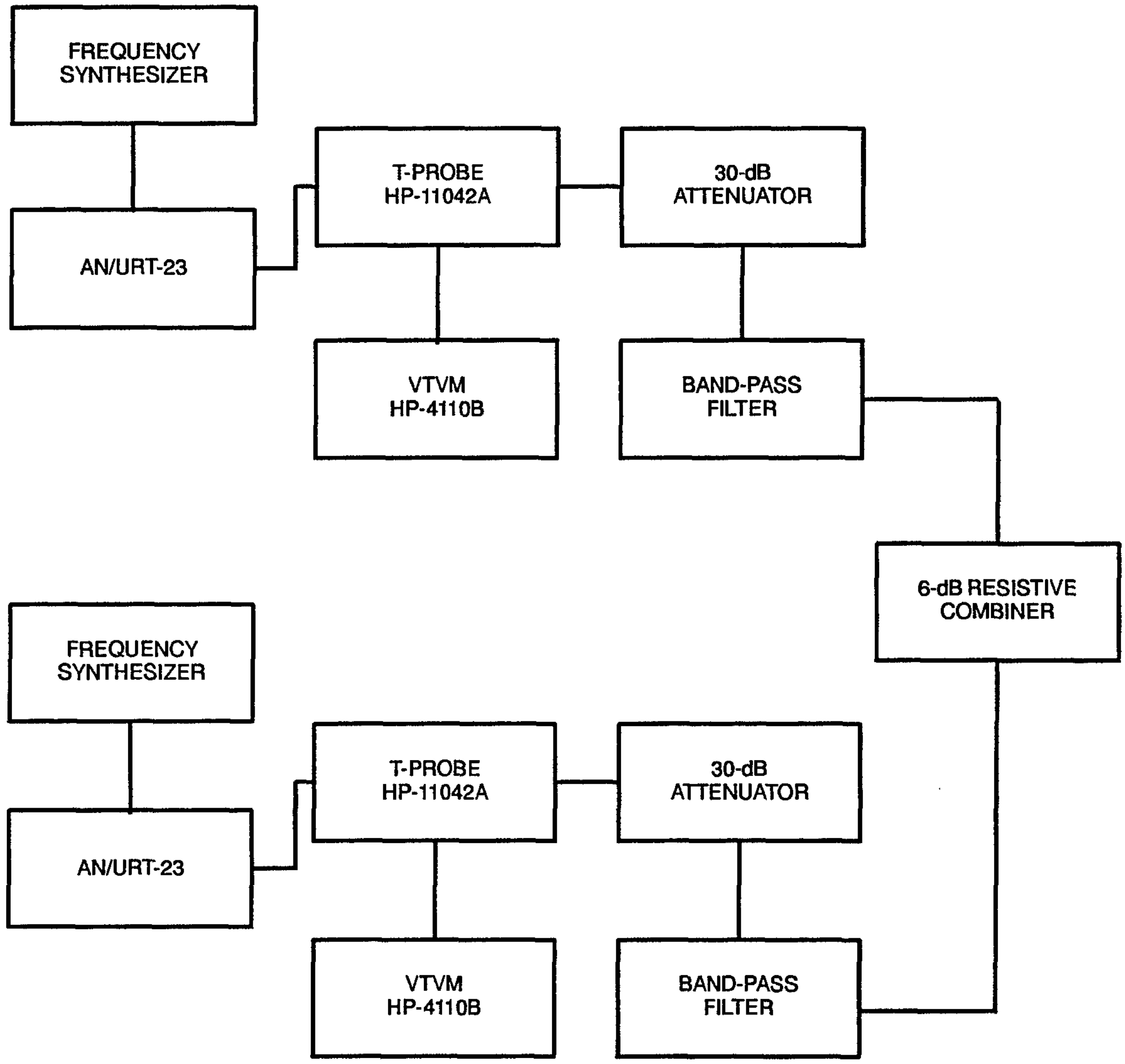

Figure 2. Test setup for measurement of IMI amplitude.

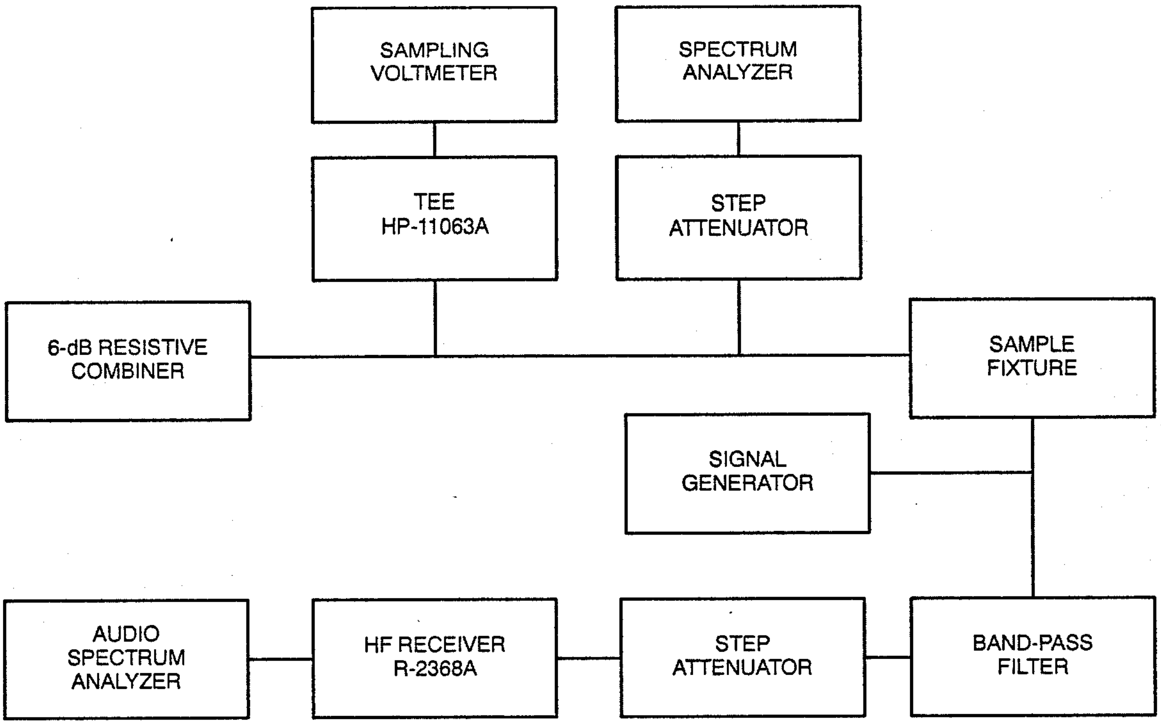

Figure 3. Test setup for measurement of IMI amplitude, continued.

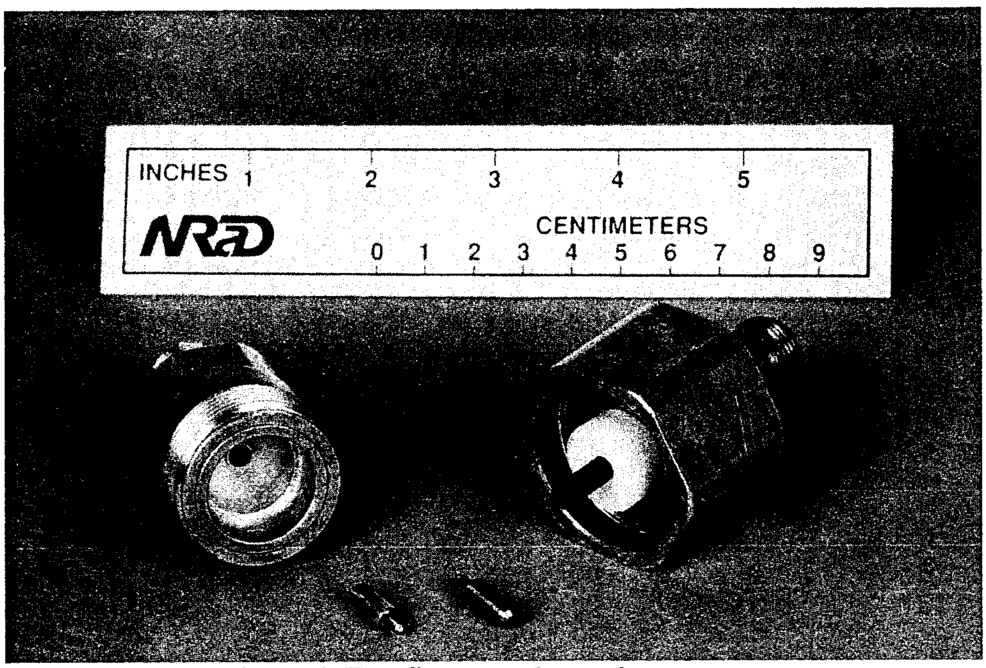

Figure 4. Test fixture and samples.

30-dB minimum loss can be assumed between the transmitter antenna terminals and the nonlinearity (reference 2). Thus the transmitter outputs were each attenuated by 30 dB. The outputs were then passed through tunable two-mesh linear filters tuned appropriately to F_1 and F_2. This output was then applied to a 6-dB linear resistive combiner.

As displayed in figure 3, the combiner output is then applied to the sample via the test fixture, figure 4. The combiner output was alternately applied to a spectrum analyzer to check equality of the two test tones and facilitate filter tuning, and then to an HP 3406A broadband sampling voltmeter equipped with a 50-ohm tee-probe/termination to measure tone amplitude. Tone amplitude was measured for one tone at a time by unkeying the other transmitter. The level of the applied tones varied from 65 mW to 80 mW per tone, depending on test frequencies.

Again in figure 3, the output of the sample test fixture was supplied to a tunable two-mesh linear filter that had been previously tuned to the third-order IMI product frequency. An example third-order IMI product frequency is $2 F_2 - F_1$. The output of the filter was first applied to a step-attenuator set and then to the antenna terminals of a high-performance HF radio receiver. The radio receiver was operated at maximum gain with its automatic gain control (AGC) off. The step attenuator in the antenna lead was used to maintain the level of the IMI signal applied to the receiver. The audio output of the receiver was supplied to an HP model 3580A audio spectrum analyzer to monitor the amplitude of the detected third-order intermodulation product. The receiver was operated in the carrier-wave (CW) mode with a 150-Hz intermediate frequency (IF) filter bandwidth. The beat-frequency oscillator (BFO) was adjusted so that the detected audio fell at approximately 1000 Hz. An arbitrary audio reference level was chosen to yield a response that was approximately 10 dB above the noise level as measured on the audio spectrum analyzer. This is considered a minimum detectable response usable for CW communications. An input level of −123 dBm was sufficient to produce this response. Using the earphones, an input signal as low as −135 dBm yielded a tone that could be distinguished from the background noise.

If a third-order intermodulation product was detected at the HF receiver, the attenuator on the antenna input was adjusted until the audio response was at the reference level. A signal generator output from an HP model 8640B signal generator was then substituted for the output from the test fixture and adjusted in amplitude to yield the same audio response. The signal generator output as read from its output meter was then considered the amplitude of the third-order intermodulation product from the sample.

RESULTS

The results of the measurements are shown in table 1. Two runs were made at three sets of test-tone frequencies, F_1 and F_2. The three sets of frequencies were 2.2 and 4.65 MHz, 9.81 and 16.3 MHz, and 11.43 and 29.8 MHz. In the first set of frequencies, F_1 and F_2, the measured, third-order intermodulation frequency was $(2 F_2 - F_1)$ or 7.1 MHz. In the second set of frequencies, the measured, third-order intermodulation frequency was $(2 F_1 - F_2)$ or 3.32 MHz. Finally, in the third set of frequencies, the measured, third-order intermodulation frequency was $(F_2 - 2 F_1)$ or 6.94 MHz. In all measurement runs, both the composite sample and the graphite sample yielded a third-order intermodulation product well above the reference level, whereas the steel and brass samples did not produce a detectable third-order intermodulation product. The amplitudes of the third-order intermodulation product for the graphite and composite samples were variable between the two runs. This is probably the result of the very low amplitude levels involved and also due to the change in electrical contact area as the samples were changed in the fixture.

Table 1. Third-order intermodulation interference measurements.

Material	F_1 MHz	F_2 MHz	F_{IMI} MHz	Run #1 P_{IMI}, dBM	Run #2 P_{IMI}, dBM
Graphite	2.2	4.65	7.1	−101	−108
Composite				−111	−130
Steel				<−135	<−135
Brass				<−135	<−135
Graphite	9.81	16.3	3.32	−110	−117
Composite				−122	−118
Steel				<−135	<−135
Brass				<−135	<−135
Graphite	11.43	29.8	6.94	−116	−96
Composite				−111	−118
Steel				<−135	<−135
Brass				<−135	<−135

In the shipboard environment, the design goal at HF is to have communication reception be limited by ambient noise rather than by interference (reference 3). References 4 and 5 recommend that quasi-minimum atmospheric noise represents a reasonable lower bound estimate of mean noise levels aboard Navy ships. Quasi-minimum noise (QMN) is depicted in figure 5. QMN describes a minimum atmospheric noise condition that is contaminated with some background noise. The design goal is to have the third-order intermodulation power below QMN. Ideally, the IMI should be reduced to the level of the noise (QMN). This ensures that the shipboard receive system is noise-limited rather than IMI limited.

The results in table 1 are plotted along with the QMN curve in figures 4 and 5. The results of Run #1 are given in figure 4 and the results of Run #2 are given in figure 5. On Navy ships, typical third-order IMI levels at the receive antenna are −59 dBm (reference 6). The third-order IMI levels of the graphite and composite materials are considerably less than −59 dBm. Except for one anomalous measurement for the graphite material in Run #2, all intermodulation interference levels for the graphite and composite materials are less than QMN. This analysis does not take into account that there may be some loss between the source of the IMI and the HF receiver.

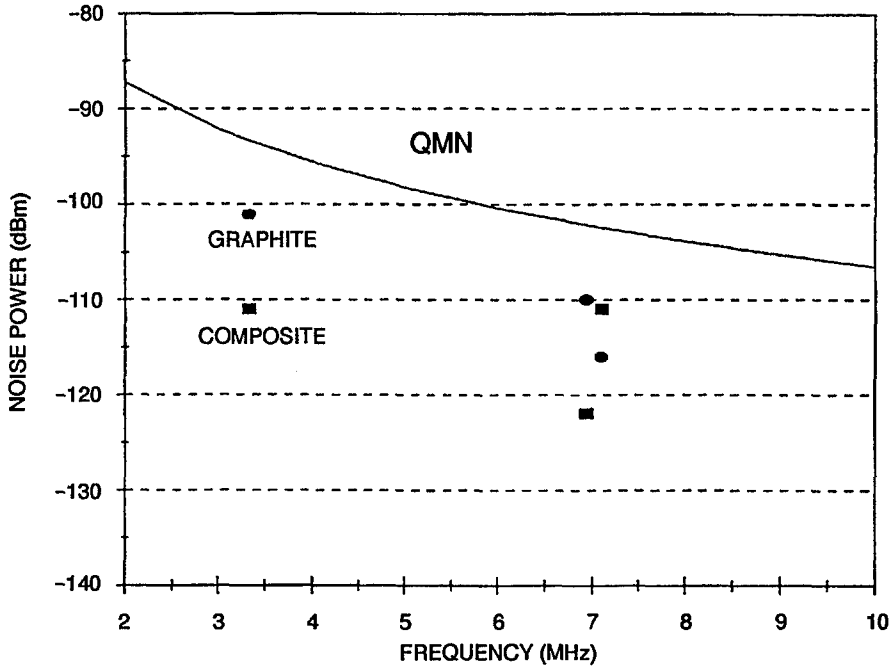

Figure 5. Noise power results for measurement run #1.

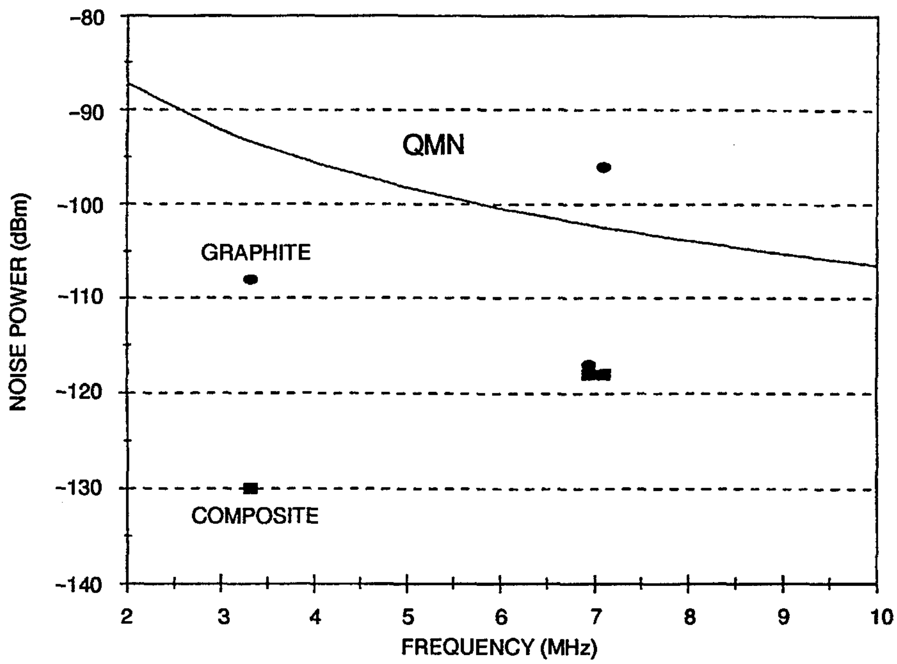

Figure 6. Noise power results for measurement run #2.

CONCLUSIONS

The graphite fiber composite samples do indeed produce intermodulation products, but at a much lower level than is typically found on Navy ships. On Navy ships, typical third-order IMI levels at the receive antenna are –59 dBm. The third-order IMI levels of the graphite fiber composite material samples are less than –100 dBm (except for one test case at –96 dBm). In fact, the IMI levels developed in the composite samples are generally below quasi-minimum noise, the shipboard design threshold for communications systems. Hence, the graphite fiber composites are unlikely to degrade shipboard communications.

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