GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION
SPONSORED PROJECT INITIATION

Date: 2/1/80

Project Title: Analysis of Shipboard EM Radiation Levels Relative to Personnel Safety

Project No: A-2458

Project Director: J. C. Toler

Sponsor: Naval Underwater Systems Ctr.

Agreement Period: From 8/30/79 Until 2/28/80

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(thru OCA)

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SPONSORED PROJECT TERMINATION

Date: 9/23/80

Project Title: Analysis of Shipboard EM Radiation Levels Relative to Personnel Safety

Project No: A-2458

Project Director: J.C. Toler

Sponsor: Naval Underwater Systems Center

Effective Termination Date: 6/30/80

Clearance of Accounting Charges: 6/30/80

Grant/Contract Closeout Actions Remaining:

- X Final Invoice and ~~Closing Documents~~
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GEORGIA INSTITUTE OF TECHNOLOGY
ENGINEERING EXPERIMENT STATION
ATLANTA, GEORGIA 30332

FINAL ENGINEERING REPORT
Project A-2458

ANALYSIS OF SHIPBOARD ELECTROMAGNETIC RADIATION LEVELS RELATIVE TO PERSONNEL SAFETY

By
J. C. Toler

July 1980

Prepared for
NAVAL UNDERWATER SYSTEMS CENTER
NEW LONDON LABORATORY
NEW LONDON, CT 06320

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FOREWORD

The research study described in this report is the result of efforts undertaken by personnel in the Biomedical Research Branch of Georgia Tech's Engineering Experiment Station. The primary purpose of the study was to identify engineering and medical areas that can be used to guide comprehensive bioeffects programs yielding answers to Navy questions regarding the safety of personnel exposed to shipboard electromagnetic environments. The study was sponsored by the Naval Underwater Systems Center under Purchase Order No. N66604-79-M-7418. The period of performance was November 1979 through June 1980. Results of the study are in the form of recommendations regarding accurate synthesis of shipboard electromagnetic environments,facilities for generating multi-frequency exposure environments, quantifiable biological endpoints, and medical procedures for accessing the biological endpoints.

Respectfully submitted,

J. C. Toler
Project Director

Approved:

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Associate Director,
Electronics Technology Laboratory

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I. INTRODUCTION

Over the past several decades, sophisticated new electronic systems and devices have been developed and integrated into the military armamentarium. These systems and devices have tended to be physically small and have increasingly been computer-directed. They have also offered significantly increased technical capabilities relative to their predecessors. This has contributed appreciably to maintenance of a strong national security and a favorable balance of military strength. However, as is often the case, the use of these new systems and devices has not been without some attendant problems. One of these problems -- and the technical matter of concern during this study -- has been the fact that most new electronic systems and devices have either influenced, or been influenced by, operational electromagnetic environments. For transmitting systems and devices, this influence has been via reliance on the frequency spectrum for intended operation, and in many cases, undesired contributions of harmonic and spurious emissions to the frequency spectrum. The result has been futher congestion of a spectrum that, in many military operational situations, was overcrowded before the introduction of new systems and devices.

Further contributions to an already overcrowded frequency spectrum are of concern from several points-of-view. Obviously, electromagnetic compatibility is compromised as emissions from one system or device occur at response frequencies, and above susceptibility thresholds, of other systems and devices. This has necessarily been a matter of military concern for decades, and several generations of standards have been developed to impose electromagnetic compatibility requirements at all operational levels. More recently, tactical electromagnetic environments have become a matter of concern from the point-of-view of personnel safety [1,2]. In this case, the concern has been directed to the question of whether personnel exposure to electromagnetic environments can result in alterations to sensitive biological endpoints. If such alterations can be electromagnetically induced, the next level of concern is whether the alterations are deleterious. Clearly, if the operational frequency

is in the range of efficient coupling to biological materials, and if the power level is high enough, extremely undesirable effects can result from personnel exposure to electromagnetic environments. However, the probability of exposure to such high level environments is reduced because the danger is recognized and precautions are taken. Therefore, the primary concern has been directed to either

- personnel exposure to moderate-level environments for relatively short time periods and/or
- personnel exposure to low-level environments for relatively long time periods.

Over the past few years, an appreciable research effort has been undertaken to investigate the possibility of personnel hazards resulting from exposure to electromagnetic environments. In many cases, conclusions from these investigative efforts have suffered because of the lack of well conceived, thoroughly planned, and fully implemented bioeffects research programs. These research programs have too often provided

- fragmented results difficult to correlate with other studies,
- monitoring of inappropriate biological endpoints,
- inadequate definition of dosimetry, and
- insufficient attention to experimental designs.

This study was initiated with full knowledge of the above-described situation. Its purpose has been to define basic engineering and medical components of a bioeffects research program that would be suitable for adoption by the Navy. Therefore, major efforts were directed to identifying engineering and medical areas of research concern that can be used to guide a comprehensive bioeffects program yielding answers to Navy questions regarding the safety of personnel exposed to shipboard electromagnetic environments. Results of these efforts are presented in the following sections of this report.

II. ENVIRONMENT DEFINITION

The initial task in any effort concerned with shipboard electromagnetic environment levels and personnel safety is to characterize the exposure environment. This involves defining relevant parameters of the shipboard radiated environment at positions where personnel are located. Typical parameters of interest are frequency, output power level, modulation, antenna pattern, beamwidth, polarization, duty factor, etc. Personnel locations of interest are for the most part, those where persons are stationed for appreciable time periods during non-combat conditions. Additional analyses must be devised to assure that bioeffects concerns are satisfactorily considered in these situations.

Efforts to precisely define relevant parameters of the shipboard radiated environment are difficult because

- electromagnetic emitters vary from ship-to-ship within a class of ships, and from one ship class to another,
- topside structure designs influence radiated environments via scattering and vary from one ship class to another, and
- operational scenarios determine which emitters will be energized at any point in time.

These factors dictate that, in many instances, a worst-case environment be synthesized using coarse-cull techniques. Coarse-cull techniques can be either manual, automated, or a combination of the two, and they can be supplemented by data obtained during actual shipboard measurements. Manual coarse-cull techniques might utilize open literature listings that present transmitter types relative to ship classes. A consolidated listing extracted from several different open literature sources is shown in abbreviated form in Table I. The nomenclature designations for transmitter types (mobile telemetering, fire control, radar, navigation, etc.) can then be used to determine reasonably detailed operational parameters such as frequency, output power level, modulation, polarization, etc. For an automated synthesis of a worst-case radiated environment, the source of information for transmitter types relative to ship classes would be computer-based listings that are frequently up-dated in terms

TABLE I

ABBREVIATED LISTING OF TRANSMITTER TYPES RELATIVE TO SHIP CLASSES

JAN Nonenclature For Transmitters	CG	CGN	CV	CVN	DD	DDG	FF	FFG
MK1					X		X	
MK4						X		X
MK5					X			
MK6	X							
MK11						X		
MK13		X				X		X
MK14	X	X						
MK37					X			
MK56	X				X		X	X
MK63	X							
MK67						X		
MK68		X			X	X	X	
MK74	X	X				X		X
MK76	X	X				X		
MK77	X							
MK86		X			X	X		
MK91					X			
MK92								X
MK111					X	X		
MK114	X				X	X	X	X
MK115		X			X			
MK116		X			X			
NTDS	X	X	X	X		X	X	

Continued

TABLE I (Concluded)

ABBREVIATED LISTING OF TRANSMITTER TYPES RELATIVE TO SHIP CLASSES

JAN Nonenclature For Transmitters	CG	CGN	CV	CVN	DD	DDG	FF	FFG
SPG9					X			
SPG35					X		X	X
SPG4913	X							
SPG51C	X					X		X
SPG51D		X						
SPG53A		X			X	X	X	
SPG53B						X		
SPG55	X							
SPG55B		X				X		
SPG60		X			X			
SPN10			X					
SPN42				X				
SPN43				X				
SPN44				X				
SPQ9A		X						
SPS10	X	X		X	X	X	X	X
SPS30	X		X					
SPS37	X	X			X	X		
SPS39						X		
SPS40					X	X	X	
SPS40B		X						
SPS43			X					
SPS48	X	X	X	X		X		
SPS52	X		X	X				X
TACAN		X	X	X		X		

of both the transmitter compliment on a given ship and the operational characteristics of these transmitters.

At best, coarse-cull information obtained by either manual or automated means will provide listings of transmitters as a function of different ships and ship classes, plus data that define operational parameters of these transmitters. In using these listings and data to synthesize a worst-case shipboard environment, it is assumed that all transmitters are operated simultaneously and directed unobstructed toward personnel locations. Power densities resulting from each transmitter are then calculated, and these power densities are analyzed to determine the anticipated extent of their coupling to biological systems. Such coupling analyses involve frequency, polarization, duty factor, etc., considerations relative to a biological system that is assumed to be a homogeneous dielectric body.

Results of these analyses are worst-case predictions of the extent to which shipboard electromagnetic environments couple to personnel at their assigned duty stations. In highly obvious ways, these predictions are coarse and can provide little beyond a worst-case assessment of possible bioeffects; however, they offer two important advantages:

- they are relatively easy to prepare and
- they are conservative in that, if no hazard to personnel in indicated under these conditions, it is doubtful that hazards exist.

If the coarse-cull technique indicates that potentially hazardous conditions exist (a highly likely situation), a refined prediction technique will be necessary. From an environmental point-of-view, this technique will have to account for the topside performance of shipboard antennas, and must therefore rely heavily on analytical models that (1) assess effects of ship structure on antenna performance and (2) define in-band and out-of-band interactions between the large number of antennas that are installed in limited physical spaces. A considerable effort has been expended in the development of such models, and these models are useable in determining safety aspects of personnel exposure to shipboard

electromagnetic environments. Summaries of programs under which these models were developed are presented in the following paragraphs.

In one program [3], near-field antenna coupling in the presence of obstacles was studied experimentally and theoretically. Tests were conducted with C-band and X-band radar antennas at short near-field separations, both with and without obstacles in the near-field.

Additional capabilities for predicting shipboard electromagnetic environments were developed during a follow-on program [4]. In this program, tests were conducted with S-band, C-band, and X-band radar antennas at near-field separations, both with and without obstacles. The effects of flat plate, cylindrical masts, square columns, and finite vertical corner reflector obstacles on main beam-to-main beam coupling were measured. Data were obtained for antenna pairs having (1) coincident boresight axes and (2) vertically misaligned boresight axes. Empirical curves for estimating decoupling were derived, and methods of predicting clear-site coupling between misaligned antennas was presented. Also, measurements of the near-field aperture distribution of a radar antenna at out-of-band frequencies were used to predict out-of-band far-field antenna patterns.

This work was extended in a program [5] that further studied out-of-band near-field antenna coupling in the presence of blocking obstacles and derived statistical models for predicting the performance of phased array antennas at out-of-band frequencies. In the out-of-band antenna coupling studies, data were recorded using boresighted and misaligned antennas for two parallel-polarization senses and two cross-polarization senses. Also, empirical curves for decoupling as a function of obstacle distances between the antennas were derived for three sizes of cylindical masts, square columns, flat sheets, and corner reflectors. In the area of statistical models, a theoretical model was derived to describe the out-of-band antenna characteristics and predict median gains of phased array antennas. Statistical analyses of both linear and planar randomly-phased arrays were performed to derive equations for predicting and describing out-of-band characteristics of array antennas.

During another study [6], the effects on far-field antenna performance of obstacles located in the near-field of an antenna were analyzed and statistical models were derived for predicting the out-of-band performance of waveguide phased-array antennas. In the obstacle effects analysis, empirical data were recorded to determine the degrading effects of near-field blocking obstacles and reflecting objects on gain loss, beamshift, beamwidth, and sidelobe levels of microwave radar antennas. These data were recorded for two parallel-polarization senses. Empirical prediction curves were then derived as a function of the obstacle's radial distance and angular position relative to the antenna for

- three sizes of solid cylindrical metal masts, square columns, flat sheets, and corner reflectors,
- two sizes of open-mast metallic obstacles, and
- one size dielectric-coated metal cylinder.

An existing computer program for shipboard antenna siting was modified to predict antenna gain loss based on the derived empirical data. The statistical model efforts expanded the previously-derived theoretical model to include arrays of waveguide elements which randomly propagate higher-order modes. Statistical equations were derived to predict and describe the out-of-band radiation pattern characteristics and median gain as a function of the in-band scan angle of the array.

The culmination of these programs to develop models useful for predicting shipboard electromagnetic environments was an effort [7] during which the Plane Wave Spectrum scattering analysis algorithm was extensively modified to include the capability to analyze a large class of Navy directive antennas. This algorithm now permits the calculation of pattern and tracking effects of both metallic and dielectric ship structures for a selectable angular field-of-view. Measured data obtained during this program included

- mainbeam gain-loss data for a tripod open-mast,
- amplitude and phase patterns for pole, tripod, and quadrapod masts blocking an azimuth monopulse antenna, and
- planar near-field data describing the scattered spectrum of a tripod.

The five programs summarized above are representative of Navy efforts to develop a capability for predicting the performance of shipboard antennas. Performance prediction is difficult because close physical mountings often result in mutual interactions while topside structures modify both near-field and far-field patterns; however, the status of these performance prediction efforts is such that their collective outputs would be highly useful in synthesizing the electromagnetic environment at specific shipboard locations. Such a synthesized environment should be considerably more accurate than one obtained by coarse-cull techniques; therefore, more accurate assessments of personnel safety can be made.

III. EXPOSURE ENVIRONMENT

After coarse-cull and/or analytical prediction techniques have been used to define shipboard electromagnetic environments for bioeffects studies, it will be necessary to generate these environments under controlled conditions in a research laboratory. Therefore, consideration must be given to technical factors that govern how these environments are to be generated.

An initial consideration is whether the exposure environment should be single- or multi-frequency. Essentially all bioeffects research to date has involved single-frequency exposures. There is no published rationale for this other than the fact that single-frequency environments are easier to generate than multi-frequency environments. In spite of this fact, single frequencies are not representative of multi-frequency shipboard environments. Bioeffect studies using single-frequency exposure environments may therefore not yield the results necessary for accurately assessing shipboard personnel safety. Consequently,technical considerations must be given to facilities capable of generating multi-frequency exposure environments.

Several exposure facility concepts that find frequent useage in bioeffects research (for example, the circular waveguide and circular, parrallel-plate concepts) can not readily be used for multi-frequency exposures because their design is wavelength-dependent. However, in the compact range concept, a multi-frequency exposure environment can be generated with only minimal design limitation. In the compact range concept, plane wave exposure environments can be developed over a predictable volume in a region near the aperture of a full or cut parabolidal reflector [8,9]. Features of these environments which make them attractive for bioeffects studies include

- the ability to develop waves with planar fronts very near the reflector,
- the ability to collimate energy in the desired direction and thereby reduce reflection of energy, and
- the ability to provide power densities that are range-independent.

The range-independent power densities result from the fact that the collimated energy throughout the plane-wave volume remains constant as a function of distance; therefore, the power density is not range-dependent as it would be if the waves were divergent instead of collimated. The fact that the desired spatial distribution is generated near the reflector reduces the output power requirements on single sources and also significantly reduces the total space required for the exposure facility.

An understanding of the exposure environment generated by the compact range can be had by noting that, if a point source of electromagnetic energy is placed at the focal point of a paraboloidal reflector, a plane wave is produced immediately at the reflector aperture. As indicated in Figure 1, this wave will propagate parallel to the reflector axis as a good approximation of a plane wave for a distance corresponding to several reflector radii. An intuitive understanding of how the planar phase front is generated may be had by imagining a plane erected perpendicular to the axis of the paraboloid. The distance travelled by a ray from the focal point f to a reflection point R on the paraboloidal surface to the corresponding point P on the imaginary plane will be independent of the position of the reflection point. This means that the distance from f to R_1 to P_1 as shown in Figure 1 is equal to the distance from f to R_2 to P_2. Therefore, since the two rays start out from f in phase with one another, they reach points P_1 and P_2 in a plane of constant phase.

It is not sufficient that the wave illuminating the experimental animals be only planar. It should, in fact, be both planar and uniform. This means that it must be a plane wave of uniform amplitude.

Once a plane wave, either uniform or non-uniform, is generated, the amplitude profile is independent of position along the direction of propagation. That is to say, if the measurement plane were moved along the axis of the paraboloid to some new position, the amplitude of each ray would be the same as it was in the original position. However, referring again to Figure 1, one sees that, as the wave propagates from the focal point to the reflector surface, it diverges as a spherical wave. Thus, if Rays 1 and 2 were emitted from the focal point with

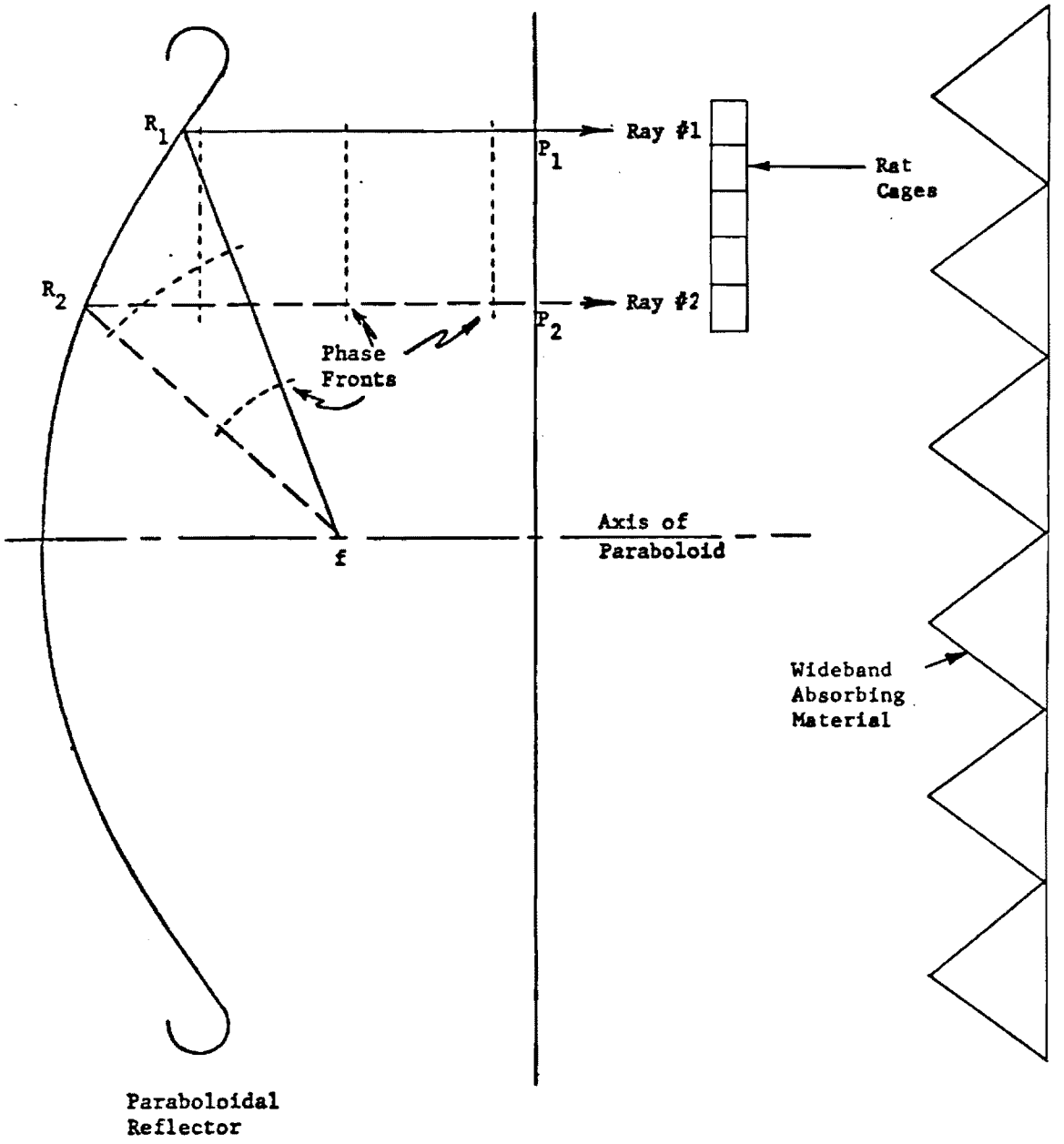


Figure 1. Principle of plane wave generation.

equal amplitudes, the ray at R_1 will have a smaller amplitude than the ray at R_2, simply because it has travelled a greater distance. This means that the ray at P_1 has a smaller amplitude than the ray at P_2, because the amplitude profile does not vary after the wave becomes a plane wave. In order for Rays 1 and 2 to have equal amplitudes as points P_1 and P_2, it is necessary that Ray 1 be initiated with a larger amplitude. Therefore, the amplitude pattern of the feed antenna at the focal point must be shaped to compensate for the fact that the different rays travel different distances to reach the reflector surface. In this way, a good approximation to a uniform plane wave can be achieved over a limited region above the axis of the paraboloid.

If the compact range is used as a multi-frequency exposure facility, solutions must be found to the problem of antennas to illuminate the reflector while generating the multi-frequency signals. At least two problems complicate the design of these antennas. One is that high-power, horn antennas are difficult to operate over more than approximately one octave of frequency. The other is the difficulty of coupling more than one high power signal source onto a single transmission line. These problems dictate the use of separate feed antennas with separate transmission lines. This, however, introduces the problem of how to locate multiple feeds at the single focal point of a compact range. Two methods of approach that appear feasible for this are identified in the following paragraphs, where it is assumed that dual (two) frequencies will be used for the exposure environment.

The first method of approach for generating a dual-frequency exposure environment on the compact range employs two separate horn antennas as illustrated in Figure 2. The smaller, high-band antenna could be located at, or just above, the focal point on the compact range. The larger, low-band antenna would then be located below the focal point where it will not block the aperture of the high-band antenna. When the feed antenna is located below (above) the focal point, the resulting collimated beam is tilted upward (downward), as illustrated in Figure 2. For small displacement, the beam tilt angle γ is given approximately by

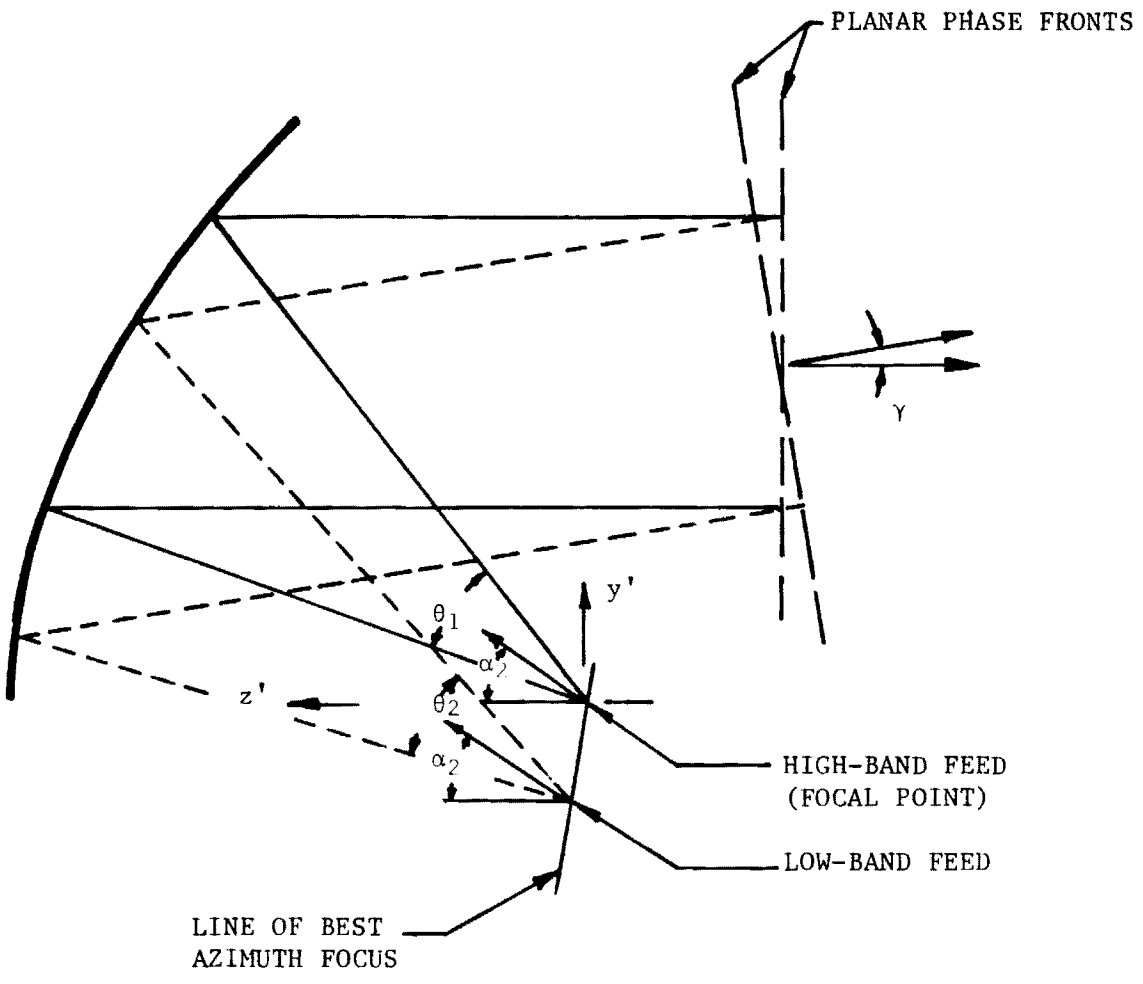


Figure 2. Elevation diagram of a two-horn feed configuration for the dual-frequency exposure facility.

$$\gamma \simeq - \arctan \frac{y'_f}{F} \quad , \tag{1}$$

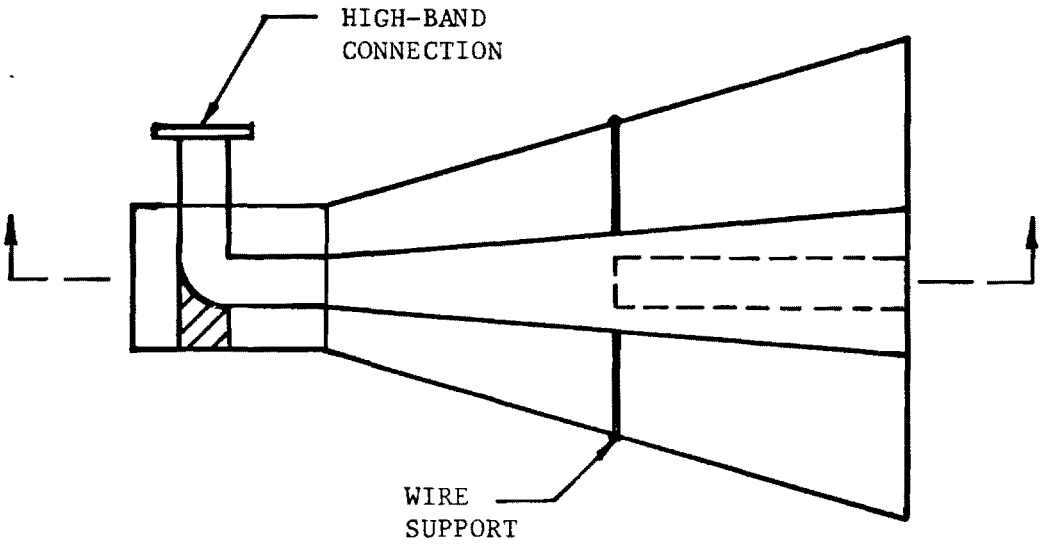
where y'_f is the y' coordinate of the feed antenna and F is the focal length of the reflector. As an example, a 450-MHz horn antenna would have an approximate beam tilt of 11 degrees. Azimuth focusing is generally best when a vertically displaced antenna is moved along the line

$$z'_f = \frac{y'_f y'_m}{2F} \quad , \tag{2}$$

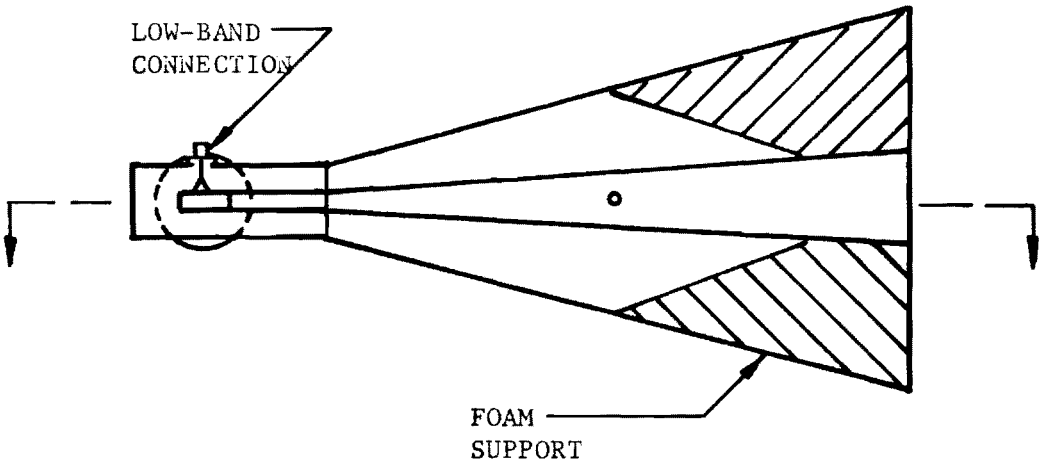
where y'_m is the y' coordinate of the point on the reflector at which the antenna is aimed. A discussion of some of the focusing characteristics of paraboloidal reflectors with displaced feed antennas is available in the open literature [10].

The second method of approach that appears feasible for generating dual-frequency exposure environments involves the use of an arrangement of concentric-horn antennas. Antennas of this general type have been used for other purposes, and some of their design considerations are discussed in the literature [11,12]. The design concept that may prove feasible for bioeffects studies on a compact range is shown in Figure 3. In this concept, a small high-band horn is placed inside a larger, low-band horn. It is assumed that the transmission lines are waveguide for the high-band antenna and coaxial cable for the low-band antenna. The unique aspect of this design is the integration of a "T-bar" coax-to-waveguide adapter [13] for the low-band antenna and a waveguide connection for the high-band antenna. It may be possible to support the high-band antenna inside the low-band horn by tension wires placed in the H-plane and by foam blocks placed in the E-plane. The phase centers of the two horns will have to be precisely co-located to preclude serious defocusing of the exposure field.

The initial design concepts for a concentric-horn for dual-frequency exposure can begin with the design procedures [14,15] used for pyramidal horn antennas. Figure 4 shows the basic geometrical parameters that will have to be determined. The aperture dimensions A_h and A_e have

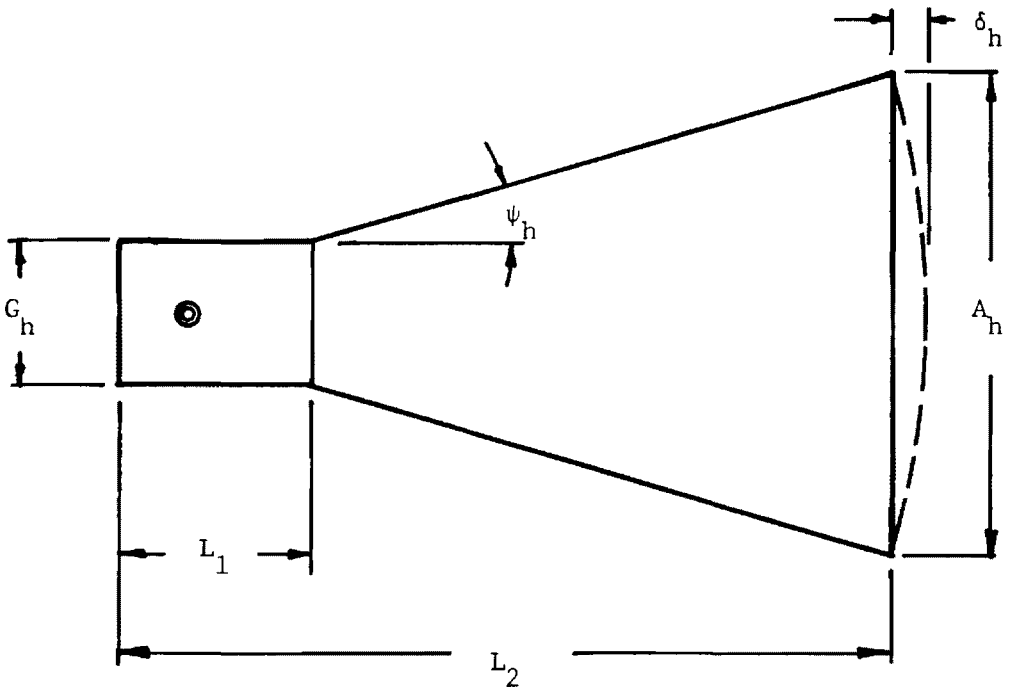


(a) H-plane View

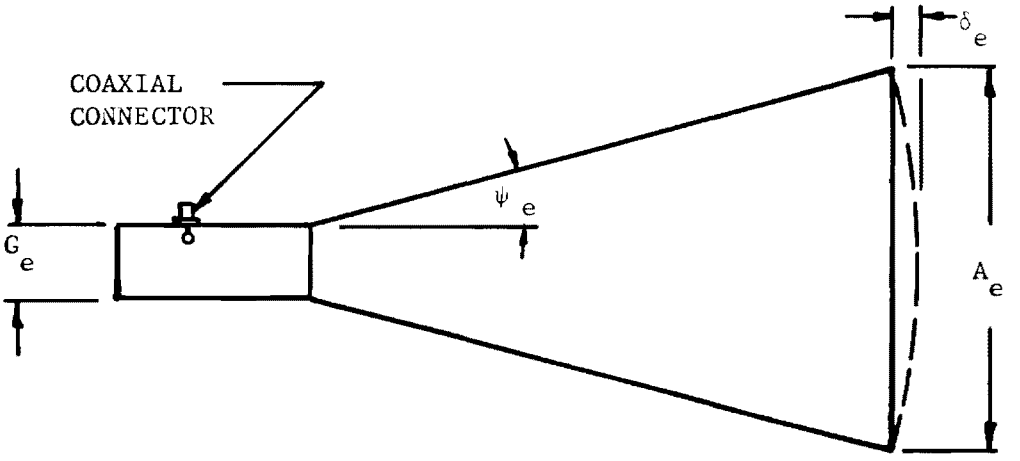


(b) E-plane View

Figure 3. Diagram of the concentric horn.



(a) H-plane View



(b) E-plane View

Figure 4. Diagram of a conventional pyramidal horn.

principal control of the pattern beamwidth. For the simplest model, and when a TE_{10} mode is assumed in the aperture, these dimensions are given by [14]

$$A_h = 68.7 \frac{\lambda}{\theta_h} \quad , \tag{3}$$

and

$$A_e = 50.4 \frac{\lambda}{\theta_e} \quad , \tag{4}$$

where θ_h and θ_e are the desired half-power beamwidths in degrees in the H- and E-planes and λ is the wavelength. The waveguide dimensions G_h and G_e must be chosen to permit propagation of only the TE_{10} mode. The following guidelines are used in making this choice for standard pyramidal horn antennas:

$$\frac{\lambda}{2} < G_h < \lambda \tag{5}$$

and

$$\frac{\lambda}{4} < G_e < \frac{\lambda}{2} \quad . \tag{6}$$

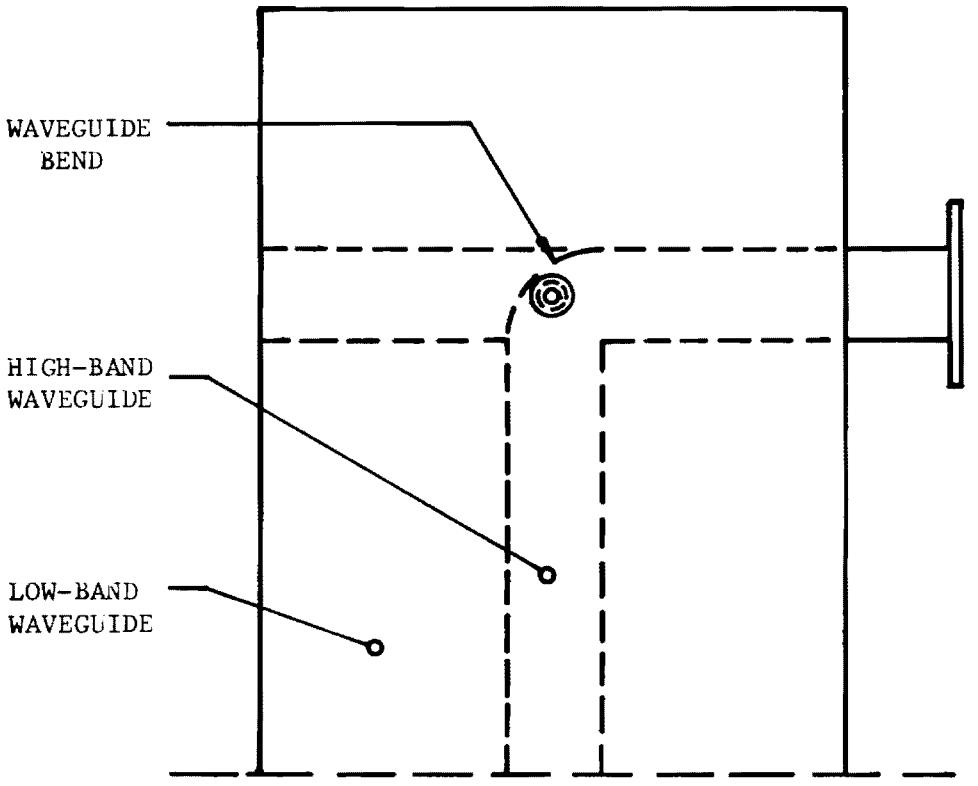
Variations of these equations will have to be identified for the concentric-horn design.

When the coax-to-waveguide is properly matched, the length L is not critical, but should be greater than $\lambda/2$ to ensure that higher-order modes are attenuated before the start of the flare.

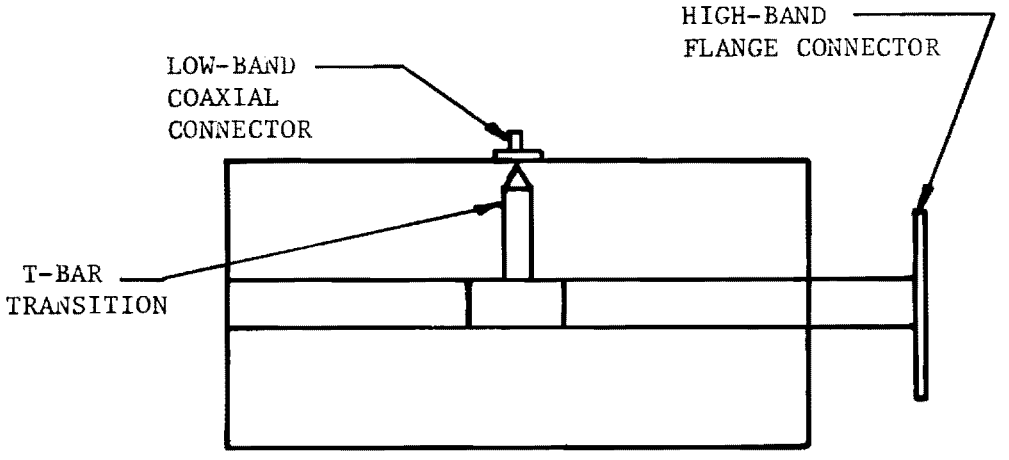
The flare angles ψ_h and ψ_3 are primarily constrained by the phase error that can be tolerated at the aperture. Cylindrically-bowed phase fronts are indicated by dashed lines in Figure 4, and the H- and E-plane phase errors are indicated by the deviations δ_h and δ_e from planar phase fronts. The performance of conventional horn antennas begins to deteriorate when the phase error $\Delta\phi = 360\ \delta/\lambda$ exceeds 90 degress ($\lambda < \lambda/4$). Also, when the phase error is less than 90 degrees, beamwidths may be predicted with resonable accuracy using Equations (3) and (4). For the concentric-

horn concept, an acceptable range of phase error will need to be identified, and beamwidths as a function of phase error will have to be determined.

In any attempt to use the concentric-horn concept for dual-frequency irradiation, the low-band horn will no doubt suffer the gain loss and increased sidelobe levels that are common in cases of aperture blockage. The extent of this gain loss and increased sidelobe levels will have to be determined for the specific concentric-horn design. A design problem of considerably more concern is the low-band coax-to-waveguide adapter. One possible design for this adapter is shown in Figure 5. It is noted that, if the longitudinal section of the high-band waveguide were removed from this design, the low-band adapter would become a conventional adapter with a "T-bar" design [16,17]. More detailed research efforts will have to be undertaken in order to determine the feasibility of the concentric-horn antenna in terms of its power handling capabilities, the interaction between the high-band and low-band waveguide, the tendency to alter the frequencies at which cutoff occurs, etc.



(a) H-plane view



(b) Front View

Figure 5. Diagram of the concentric waveguide adapter section.

IV. SELECTION OF BIOLOGICAL ENDPOINTS

Systematic research into biological effects resulting from exposure to non-ionizing electromagnetic environments is a relatively embryonic field; therefore, biological endpoints specifically relatable to electromagnetic parameters have not been precisely identified. Consequently, when establishing experimental designs for bioeffects research, it is necessary to either (1) use biological endpoints that have been shown to be sensitive to other environmental insults or (2) use established biological endpoints that are recognized as providing indepth knowledge regarding the status of vital biological functions. In conversations with medical professionals, it was noted that, for many vital biological functions, standardized protocols have been developed and demonstrated to yield repeatable data. Also, many of the endpoints associated with other environmental insults are subjective in nature, and therefore difficult to reliably quantitate. For these reasons, it is recommended that bioeffects research programs monitor those established endpoints that yield quantitable data defining the status of vital biological functions. When these endpoints are used and an indication of a bioeffect is observed, other endpoints with specially-developed analysis protocols can then be monitored to more precisely define the extent and nature of the effect. For all endpoints, it is important to note that there are ranges of normal biological variability. For some endpoints, this variability is quite large; therefore, they are not suited for bioeffects research in which the effect may be small and subtle. If these endpoints were used, their normal variability would likely mask out or obscure any effect resulting from exposure to the electromagnetic environment.

Established endpoints recognized as providing indepth knowledge regarding the status of vital biological functions are numerous. However, one group of endpoints well suited for bioeffects monitoring are those medically termed as "a blood series" or "a complete blood count". This series generally consists of measurements of hemoglobin, hematocrit, white blood cell count, differentials, and red blood cell count. The series is an excellent screening procedure and the available blood can be used for other analyses.

Detailed procedures for conducting measurements that constitute the complete blood count are widely documented in medical publications [18,19], so there is no requirement to present those details in this report. Instead, the overall purpose of representative measurements is presented as follows:

- Hemoglobin -- a resonably accurate measurement useful as an indicator of anemias.
- Hematocrit -- an accurate and reproducible measurement that defines that fraction of the total centrifuged blood volume occupied by packed red blood cells.
- White blood cell count -- an accurate measurement useful as an indicator of infection and to follow the progress of certain diseases.
- Red blood cell count -- an accurate measurement that defines the number of red blood cells in a prescribed volume of whole blood.
- Differential cell count -- an accurate measurement used to determine the relative number of each type of white cell present in the blood.

The ability to accurately measure the above endpoints using standardized protocols means that a large range of important and sensitive biological functions can be observed to determine the nature and extent of any bioeffect resulting from exposure to shipboard electromagnetic environments. For example, the measurement of hemoglobin provides a means by which changes in the number of erythrocytes per unit volume can be monitored. Changes in erythrocyte number can be an indication of disturbances in the blood production system that manifest themselves as any of approximately 100 separately-defined anemias. Similarly, changes in white blood cell count are routinely used as a sensitive indicator of infection-related abnormalities and as sensitive means of tracing changes in pathological states. The white blood cell count, as well as the hematocrit, red blood cell count, and differential cell count, are useful as sensitive indicators of disturbances in the blood production system. Therefore,

analyses of peripheral blood can provide insight into the possibility that biological system exposure to electromagnetic environments perturbs formation of the various types of blood cells. This blood cell formation occurs primarily in bone marrow and is generally considered to be highly sensitive to environmental insults.

The above discussion clearly indicates the many advantages of a complete blood count as a screening procedure for electromagnetically-induced bioeffects. However, the usefullness of the series in determined in part by how the blood is obtained. For example, if experimental animals used in research investigations are anesthetized to permit blood to be drawn, the anethesia itself may introduce undersired changes in biological functioning. Similarly, physical restraint of the animal to permit blood to be drawn can cause trauma that also introduces undesired changes in biological functioning. These changes in biological function can make interpretation of the analysis results more difficult and/or completely obscure the bioeffect caused by exposure to the electromagnetic field. Needed, then, is a procedure by which circulating blood can be drawn from experimental animals without the probable introduction of changes in biological functioning. Fortunately, Dr. Vojin Popovic of the Emory University School of medicine has developed such a procedure [20,21]. The procedure involves the implantation of a fine cannula in the aorta of the animal and it has been developed for mice, rats, squirrel monkeys, etc. This cannula exists the body in the back near the neck, and remains in place for the animal's lifetime. Adverse effects of cannulation have never been described and there is no published criticism of the technique. To date, Dr. Popovic estimates that 15,000 animals have been cannulated in his laboratory at Emory University.

As noted above, the cannulation procedure allows ready access to circulating blood in undisturbed, resting, and unanesthetized animals. Blood sampling is made possible by the fact that the plastic cannula extends out of the animal's body a few inches, and is heat-sealed. At the time of blood sampling, the heat-sealed tip is cut off, and the arterial pressure forces small amounts of blood out the exteriorized end of the cannula. The initial blood is removed by a gauze sponge, and

blood samples are then collected for hematological examinations. After sampling, blood remaining in the cannula is forced into circulation by injecting a small amount of saline (slightly more than the volume of the cannula), and the cannula tip is heat-sealed again.

V. RECOMMENDATIONS

The preceeding sections have discussed several engineering and biomedical areas of fundamental importance to research efforts concerned with the safety of Navy personnel exposed to shipboard electromagnetic environments. In essentially every case, the areas discussed are those which current and past research programs have inadequately considered. In this section, key engineering and biomedical aspects of these areas are summarized as recommendations. It is hoped that these recommendations will be adopted by the Navy. The recommendations are presented below.

Recommendations No. 1

It is not possible to make even a semi-valid analysis of personnel safety relative to shipboard electromagnetic radiation levels without reasonably accurate characterizations of the shipboard electromagnetic environment. Analytical tools developed over the past few years now make it possible to predict the performance of typical antenna systems for a wide range of shipboard mountings. These tools, combined with results from measurement programs and knowledge of transmitter operational parameters, represent a capability for defining shipboard electromagnetic environments that has not existed earlier. Consequently, it is recommended that this capability be used to more accurately and efficiently characterize the environments to which Navy personnel are exposed.

Recommendation No. 2

In order to investigate the extent to which shipboard electromagnetic environments are safe for Navy personnel, it will be necessary to generate these environments under controlled conditions. The facility for generating these environments should provide multi-frequency, calibrated, plane wave fields with uniform amplitudes over an area large enough to expose statistically significant numbers of experimental animals. Exposure to an environment comprised of uniform plane waves simplifies tremendously dosimetry determinations. Multi-frequency exposures represent a large step toward simulating actual shipboard environments, and, if the number of experimental animals is not sufficiently large, the results will be inconclusive. The compact range is a facility concept capable of providing

the needed features in an exposure facility. It is, therefore, recommended that this facility concept be used to generate simulated shipboard electromagnetic environments.

Recommendation No. 3

It is almost a certainty that biological effects resulting from exposure of Navy personnel to shipboard electromagnetic environments will be subtle and difficult to reliably detect. Therefore, the biological endpoints assayed to determine whether exposure levels are safe must yield highly accurate and quantifiable data. These data should define the status of vital biological functions and should result from standandized protocols. Consequently, it is recommended that a standard blood series be used as the biological endpoint. This series is an excellent screening procedure, and it provides insight regarding the status of many important biological functions.

Recommendation No. 4

In order for the blood series to serve as a satisfactory biological endpoint, it is necessary that blood be obtained from animals in a way that introduces no artifactual changes in biological function. The cannulation technique developed by Dr. V. Popovic of the Emory University School of Medicine permits blood to be obtained in a highly satisfactory way; therefore, it is recommended that this technique be used in Navy bioeffects research programs.

If these engineering and medical recommendations are adopted, cannulated experimental animals will be used to provide quantifiable data describing the biological effects of exposure to multi-frequency environments that reliably simulate actual electromagnetic conditions. Research of this type will be necessary in order to assess the safety of Navy personnel relative to shipboard electromagnetic environments.

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