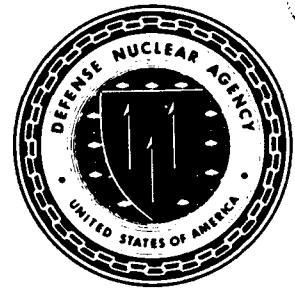


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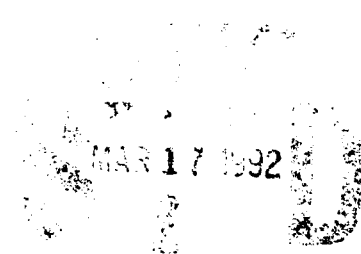


DNA-TR-91-105

**High-Altitude Nuclear Electromagnetic Pulse (HEMP)
Environment Simulation
Public Health and Safety Considerations**

**JAYCOR
P.O. Box 85154
San Diego, CA 92186-5154**

March 1992



Technical Report

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13. ABSTRACT (Maximum 200 words) The existence of electromagnetic fields external to the working volumes of high-altitude nuclear electromagnetic pulse (HEMP) environment simulators has raised both environmental and public-health concerns regarding the safety of HEMP environment simulator operations. This report contains a review of what HEMP is, what its effects on defense systems are, and why and how HEMP environment simulation testing is conducted. The state of present knowledge concerning the external simulator fields and their possible effects on biological and electronic systems is summarized. Research initiatives are identified to aid in answering the most important questions regarding the continued environmental safety of HEMP simulator operations. These initiatives are intended to support (1) development of options for modification and/or relocation of HEMP environment simulator facilities and (2) determination of safe exposure levels for biological and electronic systems. Recommendations for specific DoD actions are given.				
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EXECUTIVE SUMMARY

The electromagnetic pulse produced by a high-altitude nuclear detonation (the high-altitude electromagnetic pulse, or HEMP) can cause malfunctions in, or damage to, unprotected electronic systems and is thus a matter of concern for US defense planners. Testing of critical defense systems to simulated HEMP environments is an important and valuable tool for evaluating system hardness against HEMP effects and for identifying defects in HEMP hardness design and implementation. Simulated HEMP environment testing thus contributes in a vital way to the national defense and deterrence posture.

HEMP environment simulators are designed to create electromagnetic fields similar to the HEMP (that is, to create a HEMP-like electromagnetic environment) over working volumes large enough to be useful for system testing. Systems tested using HEMP environment simulators include missiles, aircraft, ships, and ground-based systems. The fields produced by these simulators are not strictly confined to their working volumes, but they decrease rapidly with increasing distance from a given simulator.

The existence of these “external” fields has raised both environmental and public health and safety concerns. The principal issues are:

- The potential effects on human health and on plant and animal life which may arise from exposure to the external fields of HEMP environment simulators; and
- The potential safety hazards to “fly-by-wire” commercial aircraft which may arise from such exposure.

Occupational safety concerns have also arisen. We do not, however, address the occupational safety issue in this paper except insofar as we recommend that all relevant occupational exposure standards continue to be adhered to in HEMP environment simulator operations. We confine our attention to the issues relevant to the general public.

The concerns noted above have led to a lawsuit brought against the Department of Defense by the Foundation on Economic Trends. This suit, which illustrates the public

health concern, alleged that field levels away from HEMP environment simulators were hazardous. It has led to the Army's decision to suspend HEMP environment simulator operations at its Harry Diamond Laboratory in Woodbridge, Virginia. Another suit, brought by an employee of the Boeing Aerospace Corporation against that company, alleges that the plaintiff's leukemia is a consequence of his participation in HEMP testing. This lawsuit, which has recently been settled out of court, is based on an occupational safety issue. If the safety of HEMP simulator operations cannot be demonstrated, further legal and political actions could eventually lead to the cessation of such operations nationwide, at substantial risk to the national defense posture.

In view of these developments, it is incumbent upon the Department of Defense to formulate a strategy for accommodating both the legitimate defense needs of the United States, which require HEMP environment simulation testing of critical defense systems, and the equally legitimate health and safety concerns of the American public. The issues are complex—it is extremely difficult to prove or to disprove a connection between low-level electromagnetic field exposure and health risks, whether one is considering the external fields of HEMP simulators or power lines, microwaves, or some other form of electromagnetic radiation—but the problem remains.

In order to support DoD efforts to formulate an appropriate strategy, the Defense Nuclear Agency initiated an effort to summarize the issues and identify relevant research initiatives. In this report we review what HEMP is, what its effects on defense systems are, and why and how HEMP environment simulation testing is performed. We summarize the state of knowledge concerning the external simulator fields (that is, the fields away from, and outside the working volumes of, HEMP environment simulators) and their possible effects on biosystems and electronic systems. We identify specific research initiatives for consideration by the DoD in expanding the relevant technology bases, aiding the development of new exposure and compatibility standards, and continuing to carry out its mission in ensuring the HEMP hardness and survivability of critical defense systems. A summary of the body of the report is given in the remainder of this section.

HEMP and its Effects on Defense Systems.

Detonation of a nuclear weapon at an altitude above about 40 kilometers will produce, through well-understood physical mechanisms, a pulse of electromagnetic energy which propagates downward from the burst and which illuminates a broad area of the Earth's surface. The early-time portion of this "high-altitude electromagnetic pulse" or HEMP comprises an electromagnetic field whose electric field strength rises to a peak value of some tens of kilovolts per meter (kV/m) in a few nanoseconds (ns) and then decays over the next 100 ns or so. An approximation to this field, which is the portion of the total HEMP environment posing the greatest threat to the largest number of defense systems, is produced in the working volumes of HEMP environment simulators.

It is well known from the results of simulated HEMP tests on military systems that HEMP poses a risk to such systems when they have not been specifically hardened to HEMP effects and tested to verify this hardness. The risk ranges from mission degradation to mission failure. Moreover, because of the wide area coverage of the HEMP, many systems can simultaneously be placed at risk (a detonation at an altitude of a few hundred kilometers, for example, could illuminate the entire continental United States). It is recognized within the Department of Defense that protection of critical defense systems is necessary in order to mitigate potentially adverse HEMP effects.

HEMP Environment Simulation Testing.

The HEMP hardness of critical systems cannot be determined by analysis alone, because the complexity of the systems under study does not allow calculations of HEMP-induced responses to be performed with sufficient accuracy and in sufficient detail to reliably predict system behavior in the HEMP environment. Testing is therefore necessary in order to determine the adequacy of hardening designs and implementations, to establish baseline data for hardness assurance, and to monitor the continued hardness of a given system over its life cycle.

Simulated HEMP stresses can be applied to systems under test by several means, as appropriate to the specific purpose of a given test. Full-system testing to near-threat level fields—the most reliable form of HEMP testing—can only be performed using HEMP environment simulators which provide high-level pulsed field illumination of the entire system. Other forms of testing, which do not involve generation of HEMP-like fields over large volumes, are useful only under restricted circumstances.

A HEMP environment simulator comprises a pulsed electric power source which drives an antenna or wave-guiding structure to produce a HEMP-like electromagnetic field within the simulator's working volume. The test object is placed within this volume and subjected to HEMP-like electromagnetic stresses, and its electrical and functional responses are observed. Based on these responses, inferences are drawn regarding the HEMP hardness of the test object.

It is important to distinguish between the electromagnetic fields within the working volumes of HEMP environment simulators and the fields external to these simulators. The fields within the working volumes approximate those of the HEMP threat itself; they are known to be able to adversely affect the functioning of unprotected electronics. The environmental and public-health issues with which we are concerned arise from the fields outside the working volumes and away from the simulators themselves, where non-occupational exposures may occur. These "external" fields decrease as the reciprocal of the distance from the simulator, for observers well above the ground. They decrease even more rapidly for observers on or near the ground. The external field intensity at a distance of one kilometer from a high-level simulator is less than ten percent of the level within the working volume and less than three percent of the present occupational exposure standard for personnel.

External-Field Effects on Biosystems.

Claims of the existence of adverse effects of the electromagnetic fields associated with the operation of HEMP environment simulators have been made by individuals and organizations. A review conducted in 1988 by the Oak Ridge National Laboratory concluded, however, that "Evidence from the available database does not establish that

[H]EMPs represent either an occupational or a public health hazard” [1]. A fundamental fact concerning the possible public-health effects of simulated HEMP-like fields is that *no adverse effect has been found in the general public in over 25 years of HEMP environment simulator operation.*

At the same time, it must be noted that the evidence does not definitely establish that exposure to the external fields of HEMP environment simulators is risk-free. No studies have been made of the biological effects, if any, of HEMP-like fields on the general public. There is a large body of literature dealing with studies of the biological effects of some types of electromagnetic field (particularly microwaves and power-line fields), but very few studies of the biological effects of brief, transient electromagnetic fields have been conducted.

There does exist some evidence to support a position that certain low-level electromagnetic fields can affect biological systems. This evidence involves fields which are different in important ways from the external fields of HEMP environment simulators. In addition, the existing evidence is not conclusive for the fields studied. The uncertainties associated with the observed effects are large, and the experimental findings are often not repeatable.

There are reasons to believe that the external fields of HEMP environment simulators are far less stressing than the fields which have been implicated in the studies referred to above. We note that HEMP simulator field levels, even within the working volumes, are minuscule when measured against existing thermal (power-deposition-based) exposure standards such as that of the American National Standards Institute (ANSI). Such standards may, however, be irrelevant to phenomena involving very short pulsed intense electromagnetic fields, which can induce substantial (but very brief) internal fields and currents and whose interactions with biological systems would most probably involve nonthermal effects.

External-Field Effects on Electronic Systems.

While much is known about the effects of near-threat-level, HEMP-like fields on military electronic systems, relatively little is known about the effects on these systems, or on civilian systems, of the much less intense external fields from HEMP environment simulators.

The electronic systems of primary concern are those associated with commercial aircraft. Operation of HEMP environment simulator facilities over the past twenty-five years by the Air Force Weapons Laboratory (now the Phillips Laboratory) and the Defense Nuclear Agency at Kirtland Air Force Base near Albuquerque, New Mexico—which shares runway facilities with Albuquerque International Airport—has yielded no report of adverse effects on aircraft resulting from these operations.

The present aircraft-related concern deals primarily with “fly-by-wire” aircraft, which rely solely on electronic rather than mechanical or hydraulic systems for many flight control functions. Such aircraft may be more susceptible to electromagnetic interference effects than present commercial and military aircraft; but this increased susceptibility is, at present, only conjectured.

Research Initiatives.

Research initiatives which would aid in answering the most important questions regarding the environmental safety of HEMP simulator operations have been identified. These initiatives are intended to support two principal objectives:

- Development of options for the modification and/or relocation of HEMP environment simulator facilities; and
- Determination of safe exposure levels for biological and electronic systems.

Specific recommendations for DoD actions based on these identified research initiatives are given in the Appendix to the report.

PREFACE

This document was prepared by several authors in order to assist the Defense Nuclear Agency and the Department of Defense in formulating policy to deal with public concerns which have arisen regarding the electromagnetic fields produced by HEMP environment simulators. The authors and their affiliations are listed below:

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The Appendix, which contains specific recommendations for action by the Department of Defense, was written by Joan Ma Pierre of the Defense Nuclear Agency.

The authors are grateful to the following reviewers, who contributed critical comments, suggestions for improvement, and useful advice while the effort was in progress:

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- Eugene L. Patrick, Harry Diamond Laboratory
- Lt. Col. Richard F. Rapids, USAF, Office of the Assistant to the Secretary of Defense (Atomic Energy)
- MG Gerald G. Watson, USA, Director, Defense Nuclear Agency

CONVERSION TABLE

Conversion factors for U.S. Customary to metric (SI) units of measurement

MULTIPLY → TO GET ←	BY → ← BY	→ TO GET ← DIVIDE
angstrom	10^{-10}	meters (m)
British thermal unit (thermochemical)	1.054×10^3	joule (J)
calorie (thermochemical)	4.184	joule (J)
degree (angle)	1.745×10^{-2}	radian (rad)
electron volt	1.602×10^{-19}	joule (J)
erg	10^{-7}	joule (J)
erg/second	10^{-7}	watt (W)
foot	3.048×10^{-1}	meter (m)
inch	2.540×10^{-2}	meter (m)
micron	10^{-6}	meter (m)
mil	2.540×10^{-5}	meter (m)
mile (international)	1.609×10^3	meter (m)
statcoulombs	$1/3 \times 10^{-9}$	coulombs
statcoulombs/cm ³	$1/3 \times 10^{-3}$	coulombs/meter ³
statamperes	$1/3 \times 10^{-9}$	amperes (A)
statamperes/cm ²	$1/3 \times 10^{-5}$	amperes/meter ²
statvolts/cm	3×10^4	volts/meter
statvolts	300	volts (V)
gauss cm ²	10^{-8}	webers
gauss	10^{-4}	tesla
oersted	$1/4\pi \times 10^3$	amp-turn/meter
maxwell	10^{-8}	webers

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SECTION 1

INTRODUCTION

Realistic scenarios of nuclear conflict include the possibility of nuclear detonations at high altitudes (i.e., altitudes above about 40 kilometers). These nuclear events may occur in the context of strategic defense against missile attack, or they may be offensive in nature, intended to attack power and communication systems or other "electronic" targets. Each such detonation will produce a concomitant "high-altitude electromagnetic pulse" or HEMP which propagates downward from the burst and illuminates a broad area on the Earth's surface. The HEMP can adversely affect civil and military systems. It is thus considered to be an important part of the total threat posed by nuclear weapons.

Research into the nature of the HEMP threat, and on methods for protecting critical systems against its effects, has been ongoing for over a quarter century. A valuable asset in this endeavor has been our ability to simulate the HEMP environment and to observe the response of defense systems to HEMP-like electromagnetic stresses. This form of system testing is performed using *HEMP environment simulators*, devices which combine a source of pulsed electrical energy and a radiating structure to produce simulated HEMP fields over a limited region of space (the *working volume*). Nontechnical and unclassified reviews of HEMP research can be found in [2] and [3].

Public attention has been directed to the possible effects on the environment and on public health and safety which might arise as a consequence of HEMP environment simulator operations. These concerns have arisen because the electromagnetic fields created by HEMP environment simulators are not strictly confined to their working volumes, where the field intensity is high and where system testing is actually conducted. Lower-level "external" fields are present outside the simulators themselves, and it is these external fields which have come under scrutiny. The principal issues are:

- The potential effects on human health and on plant and animal life which may arise from exposure to the external fields of HEMP environment simulators; and

- The potential safety hazards to "fly-by-wire" commercial aircraft¹ which may arise from such exposure.

These and other closely related concerns have led to a lawsuit brought against the Department of Defense (DoD) by the Foundation on Economic Trends, alleging that electromagnetic field levels in the vicinity of HEMP environment simulators were hazardous [4]. The settlement of that suit has led to the Army's decision to suspend HEMP environment simulator operations at Harry Diamond Laboratory. In another case, an employee of the Boeing Aerospace Corporation has sued that company, claiming that his occupational involvement in HEMP testing led to his contracting a form of leukemia² [5]. This lawsuit has recently been settled out of court. These lawsuits have raised public awareness concerning the possible effects of HEMP environment simulator operations on health and the environment, and have brought pressure on the DoD to demonstrate the safety of continued simulator operations. If the safety of these operations cannot be demonstrated, further legal and political actions could eventually lead to the cessation of such operations nationwide, at substantial risk to the national defense posture.

HEMP environment simulation testing has received a large amount of recent media attention, largely as a result of the lawsuit by the Foundation on Economic Trends. Examples of claims which have recently appeared in print, and brief replies thereto by the authors of this Position Paper, are listed below.

- "The Foundation on Economic Trends ...alleges that electromagnetic pulse testing could harm human health, as well as disrupt the civilian operation of nuclear power plants, telephones, computers, ships and automobiles." (Albuquerque *Journal*, 15 May 1988). [Studies to date have not established any correlation between health problems and exposure to HEMP-like fields within

¹Aircraft are either military or civilian; the latter category includes both commercial and private aircraft. We are principally interested here in commercial aircraft.

² We note that the form of testing involved in the Boeing lawsuit did not involve exposure to the electromagnetic field of a HEMP environment simulator. Rather, current injection testing, where a test object is driven by an electric current source, was involved.

simulator test volumes. Some civilian electronic systems have been damaged or caused to malfunction in the intense electromagnetic environments within simulator test volumes, as would be expected; but off-site effects have not been reported or observed over the period of 25 years in which HEMP simulators have been in operation. One case in point is the location and operation of high-level simulators adjacent to the runways of the Albuquerque International Airport with no deleterious effects on airport or aircraft operations reported over the period from 1964 to the present.]

- "...environmentalists and others say the [HEMP] tests are a threat to wildlife, marine life, and possibly human health in adjacent areas, chiefly because the electromagnetic fields might disrupt electrical balances in the body." (New York *Times*, 7 June 1988). [The research performed to date does not establish that HEMP testing adversely affects man or the biota near the simulators. No disruption of "electrical balances" has been reported in the literature.]
- "Environmentalists say that electromagnetic pulse testing could have ill effects on pregnant women." (Washington *Post*, 15 April 1988). [Animal experiments have yielded no evidence that reproductive function is impaired by exposure to pulsed electromagnetic fields.]

In view of these concerns, it is clear that action must be taken if the national capability to conduct HEMP environment simulation testing of critical defense systems is to continue. The issues are complex. There exists no evidence of any correlation between exposure to the external fields of any existing HEMP simulator and incidence of health problems. Existing data which relate to HEMP-like exposures of laboratory animals have not established that such exposure is in any way harmful. At the same time, the data to support a conclusion that exposure to HEMP-like fields is risk-free are also not conclusive, and conclusive data are not likely even to be obtainable in the absence of a long-term biomedical effects research program. It is extremely difficult (and may be impossible) to prove or disprove a connection between low-level electromagnetic field exposure and health risks, no matter what the source of the field—but the problem remains.

In the following sections of this report we discuss the nature of the HEMP environment and we review what is known about HEMP effects on defense systems. We review the need for, and the use of, HEMP environment simulation and describe the fields which are expected outside the working volume, but in the vicinity, of a HEMP environment simulator. We discuss what is known about the effects of low-level external simulator fields on biosystems and on electronic systems, and we identify research initiatives by which more may be learned about these effects.

We discuss methods which may be employed for controlling and reducing the external simulator fields and thus for further reducing potential inadvertent exposures. Recommendations for DoD action are given in the Appendix.

SECTION 2

HEMP AND ITS EFFECTS ON DEFENSE SYSTEMS

In this section we review the nature of the HEMP itself and its similarities to, and differences from, other natural and man-made electromagnetic fields. We discuss the DoD Standard description of the environment. Finally, we review some of the evidence concerning the effects of simulated HEMP environments on military systems.

2.1 WHAT IS HEMP?

A small fraction (less than one percent) of the energy released in a nuclear detonation is emitted in the form of gamma radiation. When the detonation takes place in the atmosphere, gamma-ray photons interact with the air, knocking electrons off their parent air molecules. The motion of the freed "Compton" electrons constitutes an electric current. This current, like that in the antenna of a radio transmitting station, can radiate an electromagnetic field. The character and intensity of this field depend upon a number of factors. One of the most important is the detonation altitude.

When the detonation occurs at a high altitude (that is, at or above approximately 40 kilometers), the downward-propagating gamma radiation from the burst produces an electron current which is initially directed radially outward from the burst point. These electrons experience a force in the transverse direction (perpendicular both to their direction of motion and to the Earth's magnetic field). The resulting initial transverse motion of the electrons produces the electromagnetic field referred to as the *high-altitude electromagnetic pulse* or HEMP, which propagates downward and outward from the burst point. This process is illustrated in Figure 1. The HEMP appears, to an observer on the ground, to come from the location of the burst. It is actually generated at lower altitudes within the upper atmosphere, over the approximate altitude range from 20 to 40 kilometers.³ [6].

³At higher altitudes, the density of the atmosphere is too low for the production of many electrons by the weapon's gamma radiation. At lower altitudes, the electrons produced are mostly absorbed in the atmosphere before they are able to turn significantly.

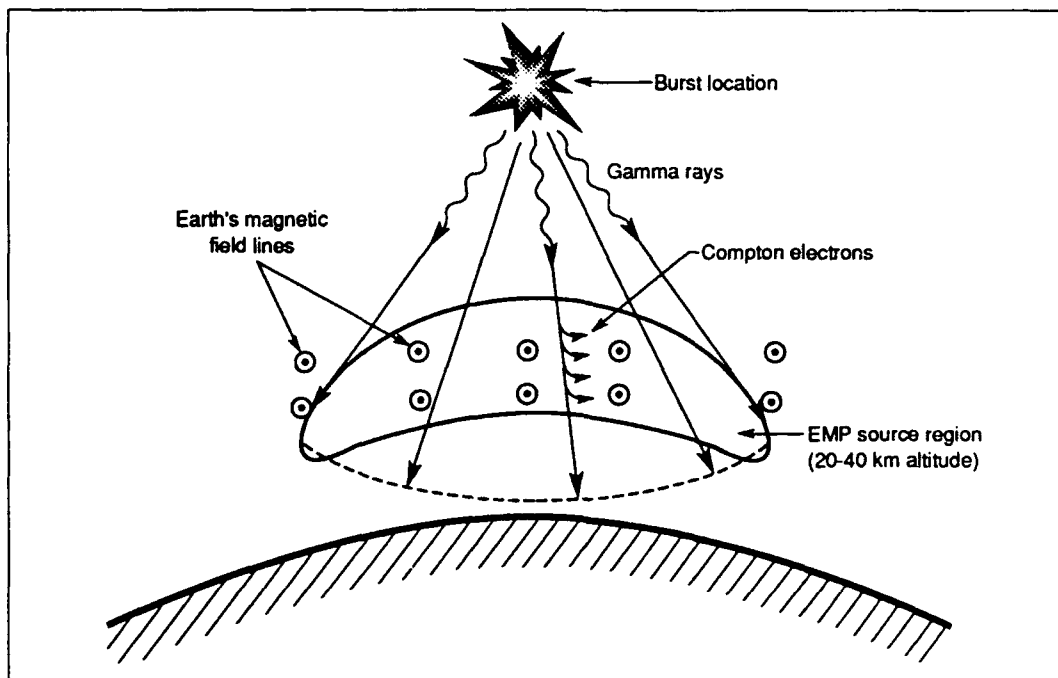


Figure 1. The generation of the early-time portion of the high-altitude nuclear electromagnetic pulse. In this figure, the geomagnetic field is taken to be horizontal.

We now briefly consider the character of the HEMP environment and how it compares to other electromagnetic fields which may be more familiar. It is critical to note that HEMP is not a form of ionizing radiation like x-rays or gamma rays. HEMP does not induce radioactivity in materials exposed to it. HEMP environment simulators are essentially radio broadcast antennas connected to special electrical generators: they have no nuclear components and produce no radioactivity. HEMP is an electromagnetic field, just as are the fields radiated by radio and television stations and emitted by lightning strokes (often heard as static interference with radio transmission). While radio and television signals are of very low intensity and very long duration, the HEMP signal is the opposite: it is very intense (the fields are about a million times as strong as "typical" radio wave fields) and of very short duration (the intense early-time HEMP field lasts only about one ten-millionth of a second). The peak electric field reaches several tens of kilovolts per meter (kV/m) in a few nanoseconds (ns) and then decays

over the next 100 ns or so. No electromagnetic environment similar to the HEMP in all important physical respects occurs in nature or in the peacetime man-made environment.

Some naturally occurring fields have similarities to the HEMP, although there are also important differences. One such field is that associated with electrostatic discharge. The “shock” which one can experience on a dry day results from the transfer of electric charge between a person and a grounded structure. The electromagnetic field created by this charge flow (or electric current) has a pulse shape similar to that of the HEMP, but its amplitude (and, of course, its spatial extent) is much smaller. Another example is lightning. During a lightning flash, many electromagnetic pulses are emitted from electrical processes in the clouds and a pulse is emitted from the large lightning return stroke. The pulse shapes radiated by the cloud processes are similar to that of the HEMP, but their amplitudes are much smaller at ranges beyond a few kilometers. The lightning return-stroke pulse has a peak intensity similar to that of the HEMP at ranges relatively close to the return stroke, but the rise time and the duration of the lightning pulse are substantially longer than those of the HEMP.

Most man-made electromagnetic fields are very dissimilar to the HEMP. We have noted above that radio and television signals differ from the HEMP. These signals are continuous waves, rather than pulses. They oscillate at nearly a single frequency and their intensities are very low—a small fraction of one volt per meter (V/m) in a home environment, for example. Microwave signals used for communications, radar, and cooking are continuous-wave fields at frequencies much higher than those associated with the HEMP. Finally, the electromagnetic fields occurring around power lines are also dissimilar to the HEMP. Although the fields below high-tension lines can be quite intense—approaching levels associated with the HEMP—they are continuous-wave fields at a very low frequency (60 Hz), rather than pulses.

The high-altitude nuclear electromagnetic pulse represents a unique aspect of the nuclear threat because of its intensity and its broad area coverage. It is sufficiently intense to cause malfunctions and damage in unprotected electronic systems, circuits, and

components. Its breadth of coverage is such that a single nuclear detonation at an altitude of 300 km or more over the central United States could expose the entire continental US to substantial HEMP fields. It is recognized within the Department of Defense that protection must be provided for critical defense systems in order to mitigate potentially adverse HEMP effects. HEMP survivability is an important component of nuclear survivability; and nuclear survivability of critical defense systems is mandated by DoD policy [7].

The standard description of the HEMP environment, developed for use in the protection of military systems upon which HEMP survivability requirements have been imposed, is contained in Department of Defense Standard DoD-STD-2169A, "High-Altitude Nuclear Electromagnetic Pulse (EMP) Environment". This Standard was designed to account for any realistic HEMP environment which an adversary could impose on US assets. A system which can tolerate the electromagnetic stresses encompassed by the standard environment is expected to function acceptably upon exposure to any actual nuclear HEMP.

The electromagnetic field prescribed by the Standard comprises three temporal components or phases. The early-time phase is the most intense. Its electric field rises in a few nanoseconds to a peak value of several tens of kilovolts per meter (kV/m), and then decays exponentially over the next hundred nanoseconds (approximately). The later-time phases are of much smaller amplitude and longer duration. These later-time phases of the HEMP are of principal importance in coupling to systems with extended components, such as power or communication systems or systems with low-frequency antennas; they do not substantially affect systems of smaller size such as missiles, aircraft without long trailing-wire antennas, and ships at sea. We confine our attention to the early-time phase in this report, as it is this component of the HEMP which poses the greatest potential threat to the largest number of systems and which is simulated in HEMP environment simulators.

2.2 HEMP EFFECTS ON DEFENSE SYSTEMS.

Electromagnetic fields interact with metallic and other conducting materials by inducing currents to flow in these materials. The minuscule current induced in a receiving antenna by a radio wave, for example, produces the information-bearing signal at the receiver. The large current induced by a HEMP field on the same antenna, although its duration would be very short, could cause the receiver to malfunction or even to be damaged.

When enough electromagnetic energy couples to the interior of any potentially vulnerable system, it can cause a variety of adverse effects. These effects include transient, resettable, or permanent upset of digital logic circuits, and performance degradation or burnout of electronic components. It is well known from the results of simulated HEMP tests on military systems that HEMP can harm such systems when they have not been specifically hardened to HEMP effects and tested to verify this hardness. Some examples of system anomalies which have been observed in simulated-HEMP tests at relatively high field levels are listed below:

- **Aircraft:** upset of onboard computers and weapon launch control systems; garbled messages; permanent damage to electronics; high-frequency coupling through shields, filters, and isolation devices; arcing across filters and isolation devices; failure of terminal protection devices.
- **Ground-Based Systems:** communication equipment failures (upsets in, and permanent damage to, integrated circuits); false fault indications; telephone handset failures; printer failures; power supply failures; vehicle ignition system failures; damage to power grid distribution components (transformers, generators, relays, insulators); locomotive control system and transformer failures.
- **Missiles:** catastrophic logic upset; permanent damage of discrete semiconductors and integrated circuits; capacitor and resistor damage; premature firing of electroexplosive devices.

Similar effects have also been observed in simulated-HEMP testing of Navy ships.

The Nation's deterrence-oriented defense policy requires that critical defense systems be able to function reliably under HEMP-induced stresses. A single well-placed high-altitude nuclear detonation would subject almost all the electronic systems within the continental United States to HEMP and could, if critical systems were not protected, have a major effect on our ability to respond to an attack. Understanding HEMP effects and hardening critical communications and other electronic systems are therefore key factors in deterring nuclear war.

SECTION 3

HEMP ENVIRONMENT SIMULATION TESTING

Testing plays a vital role in the initial validation and the continued monitoring of system hardness to HEMP, and thereby in minimizing the risk of system failure under HEMP stress. A system's hardness will tend to degrade in the course of its operational lifetime, as a result of modifications, routine operations and maintenance, or damage. Periodic monitoring of the system's HEMP hardness (hardness surveillance), and performance of hardness maintenance, are therefore required to ensure the continued survivability of the system to a HEMP threat. HEMP environment simulation testing of systems and components is also an indispensable part of HEMP research and development activity.

In addition to its role in research and development, system testing in simulated HEMP environments is performed for three principal purposes:

- Determining the adequacy of the system's HEMP hardening design (a part of the Developmental Test and Evaluation process);
- Determining the adequacy of the hardening implementation (a part of the Operational Test and Evaluation process); and
- Providing baseline data for use in hardness assurance (production quality control) and hardness surveillance (monitoring of hardness throughout the operational life of the system).

HEMP environment simulation testing is necessary to determine the hardness of critical systems. This hardness cannot be determined by analysis alone, because the complexity of the systems under study does not allow calculations of HEMP-induced responses to be performed with sufficient accuracy and in sufficient detail to predict system behavior in the HEMP environment.

In any form of HEMP testing, an electromagnetic stress is applied to the system under test and its functional and/or electrical responses are observed and measured. Inferences regarding the HEMP hardness of the test object are then drawn from the observed

system responses. The tools available for application of electromagnetic stresses to systems under test include: 1) high-level pulsed field illumination of the entire system (HEMP environment simulation); 2) low-level pulsed or continuous-wave (cw) field illumination; 3) localized electromagnetic field excitation of specific points on the system; and 4) direct injection of electric currents at line penetrations of the system shield or into the system electronics.⁴ Only HEMP environment simulation provides the capability to perform full-system testing to near-threat level fields. It is this most vital form of testing which is of immediate concern to the DoD and to the public.

We next discuss the HEMP environment simulators themselves and the electromagnetic fields which they create, both within and outside their working volumes.

3.1 HEMP ENVIRONMENT SIMULATORS.

HEMP environment simulation consists in illuminating the system under test with an electromagnetic field which resembles a desired HEMP field as closely as possible. A HEMP environment simulator is a device whose purpose is to create a HEMP-like electromagnetic field over a region which is referred to as the *working volume*. Its two principal components are an electrical energy source and a radiating structure or antenna. The energy source provides pulsed electric power to the antenna, which produces the electromagnetic field at the test object. These simulators are of three basic types.

A *radiating* simulator is one in which the electromagnetic field is allowed to propagate freely away from the simulator antenna. The test object is placed in the vicinity of the antenna and is illuminated by the field as it propagates past the object. An example of a radiating simulator is the Vertically Polarized Dipole (VPD-II) simulator shown in Figure 2. This simulator, located at Kirtland Air Force Base in New Mexico, comprises a vertical monocone antenna atop a pulsed power source and a ground plane. The ground

⁴This is the form of HEMP testing which was involved in the Boeing lawsuit.

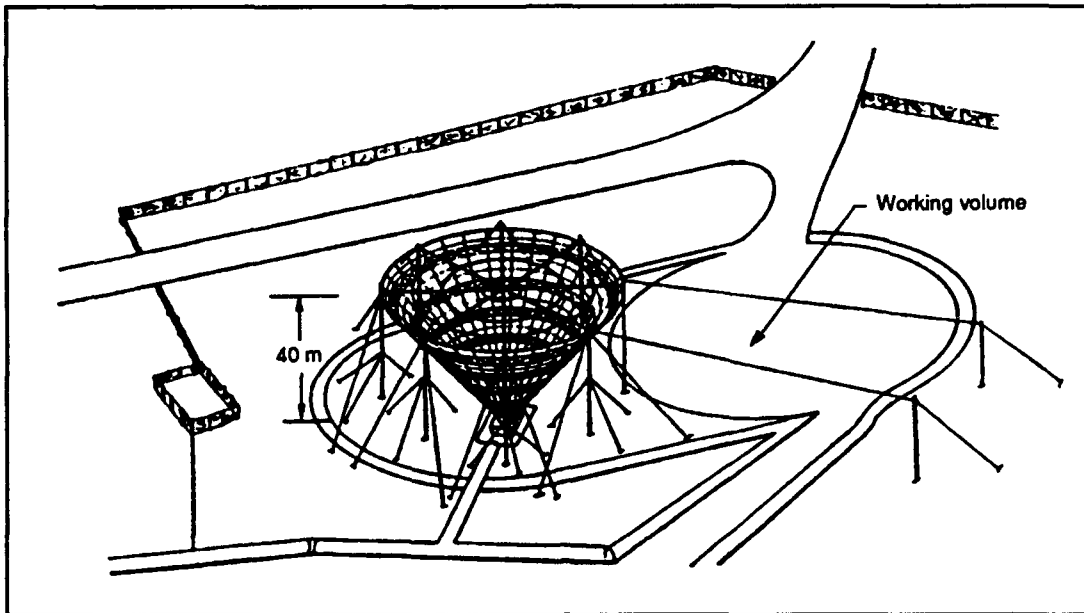


Figure 2. The Vertically Polarized Dipole (VPD-II) HEMP environment simulator.

plane extends to a radius of approximately forty meters from the base of the antenna. An additional section extends beneath the working volume, which is centered 100 meters from the base of the antenna. The peak electric-field amplitude in the working volume of the VPD-II simulator is approximately 35 kV/m. The electromagnetic field radiated by VPD-II is not confined; it simply propagates away from the antenna, its amplitude decreasing with distance from the simulator.

In a *bounded-wave* simulator such as the TRESTLE facility shown in Figure 3, the field is partially confined between a pair of parallel conducting wire meshes. Confinement of the fields is intended to compensate for the decrease in field strength with propagation distance within the working volume which is characteristic of radiating simulators. The working volume is situated between the mesh “walls”. The meshes do not, however, completely confine the field energy to the region between them, so that there does exist an external field outside the working volume.

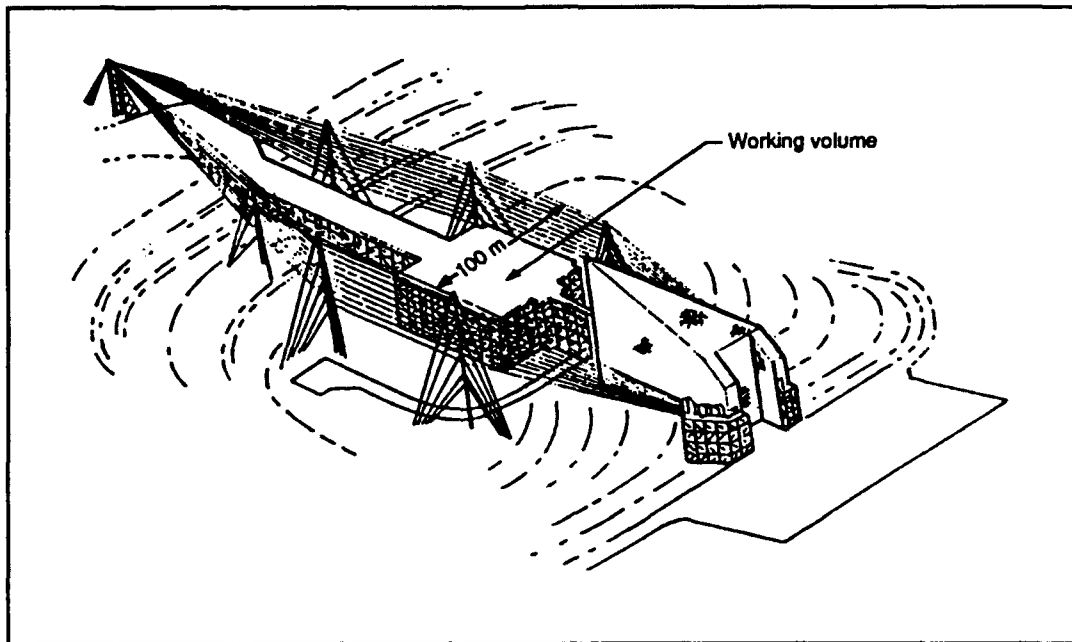


Figure 3. The TRESTLE HEMP environment simulator.

The third type of HEMP environment simulator is termed *hybrid*, because it possesses characteristics common to both radiating and bounded-wave simulators. The Horizontally Polarized Dipole (HPD), a hybrid simulator located at Kirtland AFB, is shown in Figure 4. The pulser and main radiating element are located at the top of an elliptical arch. The working volume of this simulator is located beneath the pulser. The field is essentially unconfined; its amplitude decreases with increasing distance as it propagates away from the simulator.

Each of the specific simulators described above was designed, and is most often used, for aircraft testing. Other simulators intended primarily for testing of missiles and spacecraft include ARES (Advanced Research EMP Simulator) and ALECS (AFWL/ Los Alamos EMP Calibration and Simulation), bounded-wave simulators at Kirtland AFB. Simulators such as EMPRESS-II (EMP Radiation Environment Simulator for

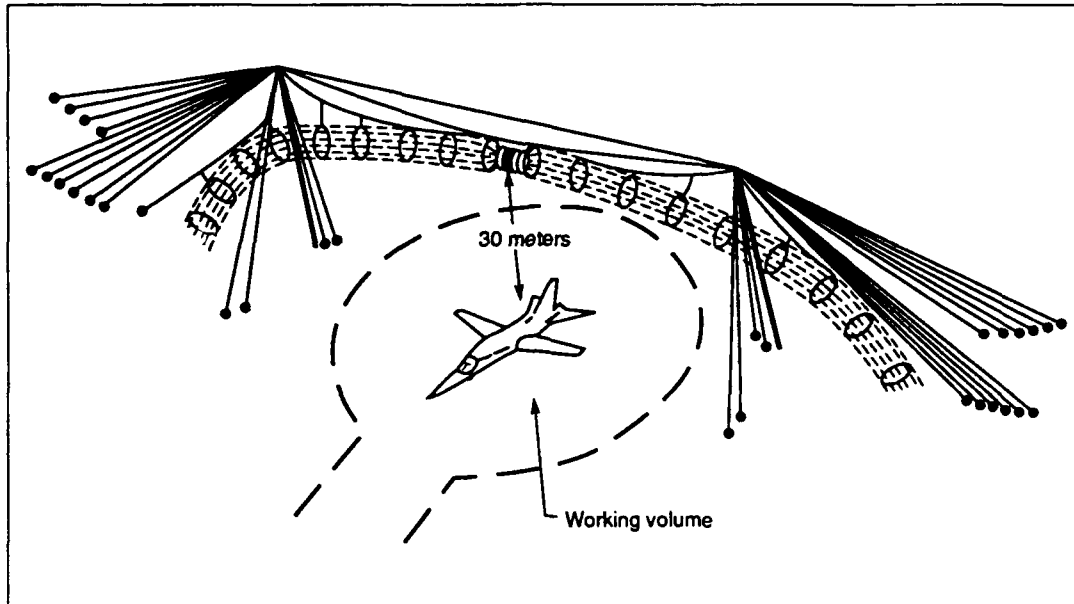


Figure 4. The Horizontally Polarized Dipole (HPD) HEMP environment simulator.

Ships) and AESOP⁵ (Army EMP Simulator Operation) are intended for application to other types of systems, including ships and ground-based systems and facilities. Table 1 lists a number of HEMP simulators and indicates their type and intended application.

3.2 HEMP ENVIRONMENT SIMULATOR FIELDS.

The electromagnetic fields produced within the working volumes of HEMP environment simulators are intended to reproduce, within practical limitations, the physical characteristics of the early-time phase of an actual HEMP. The working-volume electric field rises to a peak value of some tens of kilovolts per meter within several nanoseconds, and then decays over the next hundred nanoseconds or so. Typical pulse rates during the conduct of a test range from one to ten pulses per hour.

⁵AESOP, a hybrid HEMP environment simulator like HPD, is located at the Army's Harry Diamond Laboratory in Woodbridge, Virginia. High-level testing with this simulator has been suspended by direction of the Army, following the Foundation on Economic Trends lawsuit referred to earlier in this paper.

TABLE 1. HEMP Environment Simulators. Other HEMP test facilities (for use in testing smaller objects) are also operated by various DoD agencies and industrial concerns.

Simulator Name	Operating Agency; Simulator Location	Type and Polarization	Remarks
AESOP (Army EMP Simulator Operation)	US Army; HDL, Woodbridge, VA	Hybrid; horizontal polarization	High-level testing suspended by legal action
ARES (Advanced Research EMP Simulator)	Defense Nuclear Agency; Kirtland AFB, NM	Bounded wave; vertical polarization	Accommodates missiles and small ground systems
ALECS (AFWL/Los Alamos EMP Calibration and Simulation)	US Air Force; Kirtland AFB, NM	Bounded wave; vertical polarization	Accommodates small to medium sized ground systems and missiles
EMPRESS-II (EMP Radiation Environment Simulator for Ships)	US Navy; based at NSWC, Solomons, MD	Barge-mounted vertical monocone; vertical polarization	Barge-mounted, transportable; intended for ship testing
HPD (Horizontally Polarized Dipole)	US Air Force; Kirtland AFB, NM	Hybrid; horizontal polarization	Primarily intended for aircraft testing
TRESTLE	US Air Force; Kirtland AFB, NM	Bounded wave; horizontal polarization	Intended for aircraft testing (simulated in-flight)
VDP-II (Vertically Polarized Dipole)	US Air Force; Kirtland AFB, NM	Vertical monocone; vertical polarization	Primarily intended for aircraft testing, including aircraft in flight (fly-by)
WESTA (White Sands EMP Systems Test Array)	US Army; White Sands Missile Range, NM	Bounded wave	Intended for testing of ground systems
FEMPS (Fast-rise EMP Simulator)	Defense Nuclear Agency; Physics International San Leandro, CA	Vertical monocone; vertical polarization	Capable of testing smaller objects (8m x 3m x 4m working volume) to faster pulses; environmentally shielded

Of immediate concern to the public and to the DoD are not the fields in the working volumes—which are known to be able to induce malfunctions or damage in sensitive electronic systems—but rather the much less intense external simulator fields which are propagated outside the working volumes. These fields can be characterized in detail for any given simulator through a combination of theoretical analysis and experimental field mapping. Such characterization programs have been conducted for some simulators, and work along these lines is presently in progress; however, more remains to be done before a truly complete picture of the external simulator environments will emerge.

It is not at all difficult to estimate the field levels expected at various distances from HEMP environment simulators. The electromagnetic fields decay as the reciprocal of the distance from the simulator for observers well above the air-earth interface, and even more rapidly near this interface. The electric-field levels expected at ranges of order one kilometer from these devices are of order one kV/m near the ground and three kV/m in the air (see, e.g., [8]). These field levels are less than ten percent of those in the working volume and from one to three percent of the present occupational exposure standard for personnel (100 kV/m for single-pulse exposures).

Similar field levels are encountered at distances of two or three kilometers from lightning discharges, although the pulse duration and shape of the lightning signals differ from those of the external HEMP simulator environment. Over the continental United States, each square mile will experience, on average, 3.5 lightning strokes per year. Some areas, such as south-central Florida, experience a much higher incidence of lightning. Thus military and civilian personnel and equipment are typically subjected to lightning fields of amplitudes up to five kV/m several times a year. We note again, however, that the pulse characteristics of the lightning field are not identical to those of the simulator external fields, so that the two fields are not totally comparable on bases other than peak amplitude.

3.3 HEMP SIMULATION TESTING: SUMMARY.

We have reviewed certain aspects of HEMP system testing in this section. Testing is absolutely necessary for gaining high confidence in system performance under HEMP

stress, because the modeling tools now available and foreseeable cannot predict the HEMP-induced system stresses or responses in sufficient detail to enable reliable hardness-related conclusions to be drawn on the basis of analysis alone. The importance of HEMP environment simulation testing at the system level to threat-like environments for purposes of hardening validation cannot be overstated. Such testing represents the only opportunity for exposing a complete system to HEMP-like stresses and observing its responses to those stresses.

Public concern regarding the safety of HEMP environment simulator operations is focused on the possible effects on biological and electronic systems of the external fields of HEMP environment simulators. These fields are much less intense than those created within the working volume. The possible effects of the external fields are discussed in the following sections.

SECTION 4

HEMP SIMULATOR EXTERNAL FIELDS: EFFECTS ON BIOSYSTEMS

Concern over possible adverse effects on man and the environment has been a focal point in the public discussion of HEMP environment simulator operations. Media coverage of these simulators, of the Boeing lawsuit in which a link between HEMP testing using direct current injection and leukemia is alleged, and of the Foundation on Economic Trends lawsuit in which possible dangers of HEMP simulators to the environment were cited, has focused on the possible biological effects. This coverage follows numerous recent reports in the press of possible health hazards from other sources of electromagnetic fields.

A review of the limited scientific literature which is relevant to the interaction of transient electromagnetic fields with biological material has uncovered some facts which bear on these concerns. It is important to note the following points:

- The only HEMP-specific biological-effects testing which has been conducted was carried out in the late 1960's and in the 1970's on animals (primarily rats and dogs).
- Occupational safety and public health factors are each important at the present time. We concentrate in this paper on the public-health aspect of the issue. The HEMP-related biological-effects testing which has been conducted was done for occupational-safety reasons.
- Field levels to which the general public may be exposed are far below (by a factor of 100 or more) present occupational safety exposure standards. Further, the repetition rate of the pulses is very low (at most, some tens of pulses per day), resulting in a small cumulative exposure.

We find that although the biological effects of these fields are not completely understood, the existing data do not support the claim that HEMP simulator fields pose a risk to human health or to the natural environment. In Section 4.1 we identify several

important aspects of the interaction between transient electromagnetic fields and biological systems.

The present guidelines for electromagnetic exposure of biological systems do not adequately address HEMP-like fields. Since HEMP simulator testing is vital to the national interest and must therefore continue, there is a need to increase our understanding of the interaction of transient electromagnetic fields with biological systems, and to define levels of exposure which are safe beyond any reasonable doubt. In Section 4.2 we identify research initiatives which are directed toward the definition of an exposure threshold for transient electromagnetic fields in general and HEMP environment simulator fields in particular.

We then comment in Section 4.3 on some options for minimizing the public's exposure to HEMP simulator fields. Specifically, we address the topics of relocation of the simulators and reduction of their external fields through shielding.

4.1 HEMP-BIOSYSTEM INTERACTION.

While the biological effects of transient electromagnetic fields are central to our discussion, a detailed review of these effects is beyond the scope of this paper. A review of the relevant biological aspects of HEMP environment-simulator and related electromagnetic fields has been compiled and is available as a separate document [9]. For the purposes of the present discussion it is sufficient to call attention to the following facts:

First, we note that because the HEMP waveform is a pulsed rather than a continuous electromagnetic field, the energy deposited by a HEMP-like field in biological material is actually very small. In addition, it is difficult to correctly infer a health risk in a HEMP-like field on the basis of a health risk in another type of electromagnetic field. In particular, we note that the dominant physical effect⁶ of most radio frequency (RF)

⁶We distinguish between "physical" and "biological" effects. Physical effects are those directly related to the energy deposited in a biological system by the electromagnetic field: thermal heating would be an example. Biological effects are the (often unknown) consequences of this electromagnetic energy deposition on life, health, or progeny.

sources operating at high levels is a heating of the exposed tissue and, concomitantly, that the current American National Standards Institute (ANSI) standard for electromagnetic exposure is based on the concept of an acute thermal dose [10]. In contrast, the energy deposited in a human body by a HEMP-like field, or even by repeated exposures to such fields, is insignificant when compared with normal human metabolic output (and with the ANSI standard), so that the biological effects of exposure to transient electromagnetic fields, if any, are most probably non-thermal.

In examining the relevant biological effects data, one must distinguish between the HEMP-like fields encountered in occupational exposure, and the much lower field strengths which may be encountered by the general public. We are concerned in this report with field levels to which the general public may be exposed, and do not consider the occupational-safety issue directly. The available experimental and epidemiological data on HEMP-like field exposure are relevant only to occupational exposure levels. No studies of the effects of non-occupational exposures have been reported, and there have been no reports of adverse effects in the general public. The Boeing lawsuit noted previously deals with the effects of occupational exposure.

The most extensive experimental investigation of the subject to date was done in a series of three experiments at the Armed Forces Radiobiology Research Institute (AFRRI) during the 1970's. In the first study, 370 rats were exposed to 10^8 pulses of peak intensity in excess of 400 kV/m over a period of 38 weeks⁷ [11]. Non-exposed control populations of equal size were maintained in this investigation and in the studies which followed. Examinations of numerous aspects of the animals' health detected no differences between exposed and nonexposed animals, with the exception of some variation in the numbers of two types of blood cells (immature red blood cells and platelets). The variations observed were within normal physiological limits. Fifty

⁷This number of pulse exposures is immense: it is approximately one hundred thousand times larger than the total number of pulses generated in a typical test of a large system. This field strength is also ten times larger than the peak field in a simulator's working volume and over one hundred times larger than the external field which might be encountered within one kilometer of a HEMP environment simulator.

leukemia-prone mice were also exposed in this study. These animals did not experience either an increased tendency to develop leukemia or an earlier onset of the disease as a result of exposure.

In the second study of the series, 340 rats were exposed to 2.5×10^8 pulses over 94 weeks (essentially the entire adult life of the animal) in an effort to detect long-term hazards [12]. Again, examinations of numerous biological indicators failed to detect any significant abnormalities, although the variations in blood cell counts noted in the first experiment were evident.

In the final study, 13 dogs were exposed in an attempt to better detect potential blood-related hazards in man [13]. Although extrapolation of results gained from tests on one species to inferences regarding effects on another species is difficult at best, dogs are more appropriate animals than rats for such tests since the production, distribution and function of blood cells in dogs is similar to that in man. In addition, the use of a physically larger animal results in electromagnetic-field coupling which more closely approximates that experienced by humans. No adverse effects were detected in the dogs following exposure to 5.8×10^6 pulses over a period of 45 days. In particular, the blood cell variations noted above for rats were not observed in the dogs. We note, however, that these results cannot be considered conclusive because of the small number of animals utilized in the study.

The effects of HEMP simulator fields on ecological systems have not been extensively investigated. Several studies dealing with marine and avian life have appeared in the EMPRESS-II environmental impact statement [14], and indicate that the risk to this portion of the biosphere is negligible. No studies involving terrestrial ecosystems have been identified.

Inferences regarding the effects of HEMP-like fields on man have been drawn from the health records of occupationally exposed workers. Between 1970 and 1976 the health records of 300 HEMP workers at Boeing were reviewed. No adverse health effects

attributable to HEMP-like fields were identified, but in the same time period two⁸ cases of leukemia and one case of lymphoma were reported. In 1977 the Lovelace Biomedical and Environmental Research Institute examined the health records of some 600 workers exposed to simulated HEMP fields (among them the Boeing employees⁹) and found no adverse effects which could be attributed to exposure to HEMP-like fields [15]. In the period from 1977 to 1987 the health records of 56 Boeing HEMP workers were monitored in a study conducted by Boeing. During this time an additional case of leukemia was reported among the exposed group. The occurrence of three cases of leukemia among the Boeing employees is larger than expected for the general population, but the number of affected individuals is not statistically meaningful. A causal relationship to exposure to simulated HEMP fields can therefore be neither confirmed nor disproved. In fact, causality cannot be demonstrated using epidemiological studies alone.

A 1988 review of the available data by Oak Ridge National Laboratory concluded that "Evidence from the available database does not establish that [H]EMPs represent either an occupational or a public health hazard." [1]. A review performed by the Office of Technology Assessment (OTA) of the health effects of the EMPRESS-II simulator reported "It is not clear that [H]EMP, at levels produced at EMPRESS II, has any health effects at all, although there is a possibility that some effects might occur for repeated, long-term exposures at electric field levels of hundreds of kilovolts per meter (kV/m)..." [17]. A fundamental fact concerning the effects of simulated HEMP-like fields on biological systems is that *no adverse effect has been found in the general public in over 25 years of HEMP simulator operation.*

It must be acknowledged that although no adverse effects have been identified, the interaction of simulated HEMP fields with the human body is imperfectly understood. (A similar statement can be made for electromagnetic fields in general.) The existing

⁸There is disagreement within the Boeing work as to whether one or two cases of leukemia were detected [16].

⁹The Lovelace work [15] indicates that 400 Boeing employees were exposed to HEMP-like fields, while a total of only 300 workers is reported by Boeing [16].

information is fragmentary and inconclusive [1, 9,17]. Further, given the complexity of most biological systems, there is no reason to expect that our level of understanding will change radically in the near future. The available evidence does not, therefore, conclusively establish that exposure to the external fields of HEMP environment simulators is risk-free.

4.2 BIOLOGICAL RESEARCH INITIATIVES.

It is generally acknowledged that the biological effects of non-ionizing electromagnetic radiation are imperfectly understood, in spite of the appearance of several thousand papers on the subject within the last ten years. Our knowledge of the effects of HEMP-like fields is even more limited (only some tens of reports dealing with the effects of such fields exist).

Since HEMP simulator operations are considered vital to the national interest, there is a need to establish levels of exposure which are safe beyond any reasonable doubt. As we discussed earlier, those electromagnetic radiation exposure standards based on power deposition and thermal heating which are presently in effect are well above levels that would be produced by the external fields of HEMP environment simulators. At the same time, these measures (that is, power deposition and thermal heating) may not adequately characterize HEMP-like fields because of differences in the waveforms involved. Additional thresholds for simulated HEMP fields have been established, but these standards were developed for occupational safety reasons and do not address the concerns recently brought to the public's attention. Also, the peak field thresholds were determined before the possibility of an association between exposure to HEMP-like fields and leukemia was suggested.

It is not realistic to expect that the non-thermal effects of HEMP-like fields on biological systems will be completely understood within the near future, but specific questions can be identified which are amenable to immediate investigation and which may help to better establish safe levels for general and occupational exposures to transient electromagnetic fields. These issues are discussed in subsection 4.2.1.

In defining acceptable levels of simulated HEMP fields for both occupational and public exposure, two problems are encountered. First, we have already noted that our knowledge of the interaction between transient electromagnetic fields and biosystems is limited. As a result, it is difficult to identify the important biophysical mechanisms to be considered in establishing a standard. As was mentioned earlier, these mechanisms are likely to be non-thermal in nature. A second problem encountered in defining an exposure level is that although we are constantly exposed to electromagnetic radiation from natural and artificial sources, this ambient radiation is generally quite different from HEMP. The electromagnetic sources which contribute to the ambient fields (primarily power lines and communications) tend to be continuous-wave sources of modest power, while HEMP simulator fields are very brief but intense pulses. In addition, there is some evidence that some forms of electromagnetic radiation, although very different from HEMP environment simulator fields, may in fact pose a hazard. It is therefore difficult to establish a safe exposure level based only on ambient electromagnetic field levels.

In subsections 4.2.2 and 4.2.3 below, we discuss two methods of defining an exposure threshold, the first emphasizing an experimental study of the interaction phenomenology, and the second following the paradigm of the current ANSI exposure standard. Advantages and drawbacks of both approaches are discussed.

4.2.1 Research Topics.

A starting point for investigations into the biological effects of simulated HEMP should be a quantitative determination of the fields produced inside biological systems by a HEMP-like illumination. At present, these field levels are largely unknown, although simple analytical models suggest that they may be appreciable in comparison to naturally occurring field levels [1, 9]. An estimate of the internal fields can be used to guide future experimental research by providing a reference level for the exposure of tissues. In addition, a comparison of HEMP simulator-induced fields with those arising from natural sources is of interest.

Another important question to be answered deals with the biological response of the body to very brief electromagnetic stimuli. It is known that most natural biological processes are relatively slow in comparison with HEMP (typical macroscopic bioelectric processes occur within a time period of 10 milliseconds or more, while the HEMP pulse is essentially complete within 100 nanoseconds). Experimental investigations are required to identify what biological mechanisms, if any, are affected by electromagnetic phenomena of short duration, and what the effects of multiple-pulse exposure—whether a short burst of pulses or only a few pulses per day over a longer period—may be.

There is also a need to address the possibility of an association between HEMP fields and leukemia. Whether or not such an association in fact exists, any suggestion of a link between HEMP simulator fields and cancer is disconcerting; other sources of electromagnetic exposure (specifically high voltage power lines) have been linked to leukemia. For this reason, the relation of HEMP to leukemia has received special attention both in the press and in this discussion. The leukemia issue was addressed previously in the AFFRI experiment [11] with a finding of no effect, but there have been no reported attempts to verify this result. Furthermore, no attempt was made to quantify the internal field strengths or absorbed electromagnetic energy. This information is needed to relate any effects observed in laboratory animals to potential effects in other species. The experimental investigations can and should be repeated using a larger animal population for statistical purposes, and with better control of the electromagnetic dosimetry.

Some attempts have also been made to examine the leukemia link through epidemiological means [1,15] but the statistical information resulting from these studies is relatively weak. Previous studies of leukemia (unrelated to HEMP-like field exposure) have shown that this affliction can occur in geographical clusters. The possible existence of a leukemia cluster independent of HEMP-like field exposure among the Boeing cohort should be investigated.

4.2.2 Experimental Investigation of Exposure Thresholds.

One approach to the definition of an exposure standard for HEMP fields is through an experimental study of laboratory animals. The AFRRI experiments noted earlier [11,12,13] are examples of the type of investigations required. These experiments involve the exposure of relatively large populations of animals followed by examinations of various aspects of the animals' physical condition. The limitations of this experimental approach and the difficulties associated with extrapolation of the results to other species are well recognized. However, animal experimentation is a valuable tool and is widely used in biological-effects research. We note that research into genetic effects requires experimentation to be conducted over several generations of the experimental animal.

Experimental observation of biological phenomena is presently our only means of detecting responses to electromagnetic fields. However, it is difficult to obtain conclusive experimental data on effects that have proven to be rare. Some topics which are appropriate for experimental investigation have been noted in [9].

4.2.3 Internal-Field Based Investigation of Exposure Thresholds.

A second method of defining a safe HEMP exposure level is based on the concept of a biologically insignificant exposure [9]. It is well known that animate biological material generates internal bioelectric fields. In man, these fields form the basis for several common medical diagnostic tools including the electroencephalogram (EEG) and the electrocardiogram (ECG or EKG). (Note, however, that EEG and ECG signals are macroscopic averages of phenomena occurring at the cellular level. In the following discussion, it is the bioelectric fields present at the cellular level which are important.) Although we may not know the specific origin or function of these natural phenomena, we can often measure or model them with accuracy.

The primary physical effect of exposure to a HEMP-like field is the creation of additional internal fields and currents which are superimposed on the naturally

occurring quantities. If the induced effects are constrained to be small in relation to the naturally occurring phenomena, then the potential for adverse effects would seem to be correspondingly small.

There exists a precedent for this approach. The existing ANSI standard (ANSI C95.1-1982 [10]) limits human electromagnetic field exposure to power levels and durations which result in a small energy deposition in comparison with the body's natural metabolic output. In effect, the standard uses a knowledge of the internal electromagnetic fields (obtained from modeling work), and constrains the power deposition to be small in comparison with naturally occurring power levels. The approach to protection defined above attempts to constrain HEMP-induced internal fields to levels below those identified as occurring naturally.

The major drawback of this approach is the difficulty in estimating the naturally occurring and HEMP-induced internal fields. At this time some estimates for naturally occurring bioelectric phenomena have been presented in the literature but, as discussed in subsection 4.3.1, the HEMP-induced fields are virtually unknown at the present time and further work in this area is needed. Additional discussion of this approach appears in [9].

4.3 MINIMIZING HEMP-BIOSYSTEM INTERACTION.

From the standpoint of our limited knowledge, it is prudent to minimize the exposure of biological systems to simulated HEMP fields. Several methods of accomplishing this can be identified. These include the following:

- Use of field containment or redirection structures to control and reduce the external fields of HEMP environment simulators.
- Relocation of HEMP environment simulators to remote areas.

These measures are discussed more fully in the following.

One approach to the problem of minimizing the public's exposure to HEMP simulator fields is to limit simulator emanations outside the working volume through the use of

various field containment or redirection structures. The idea of total containment of the HEMP fields is appealing, but it involves some difficult technical issues dealing with the reflections from the shielding walls. To illustrate these issues, we note that an important factor in HEMP simulation is the length of time over which the simulated signal replicates the true HEMP waveform. When the reflections from the walls of the structure reach the test object the fidelity of the simulation will be lost. If we take one microsecond as a desirable period for the simulation, then the radius of the shield must be at least 150 m, which defines a hemisphere of considerable size. The inner surface of the shield should also be constructed of a material which minimizes the reflection of electromagnetic radiation. Clearly, the most desirable shield is one which is anechoic (i.e., one which produces no reflections) but achieving this ideal may be impossible given the broadband nature of HEMP and the state of current technology.

Progress along these lines has, however, been made. The external field of the FEMPS simulator (see Table 1) has been successfully contained without adversely affecting simulation fidelity. This (relatively small) simulator is located within a shielded metal building outside which the leakage field level is exceedingly small. Reflections from the inner walls are reduced to acceptable levels by a "curtain" of flexible, conductor-impregnated mesh positioned outside the working volume but inside the facility wall. The working volume of this simulator is not large (although an object the size of a two-ton truck can be tested), but FEMPS demonstrates that the technical means are available for acceptable operation of HEMP environment simulators within shielded enclosures. Application of these means may also be possible on a large scale.

A less ambitious option in reducing HEMP simulator emanations is to redirect the external fields through the use of "fences" and other obstacles of limited vertical extent located along the perimeter of the test volume. Using shaping and impedance loading techniques, it may be possible to design a fence which significantly reduces the external fields in the region outside the fence. Further analysis is required to define the limitations of this approach.

In the absence of readily available technology for eliminating external HEMP environment simulator fields, the most practical way to accommodate the concerns of the general public may be to locate new simulators at remote sites where the nearby population is very small. In the case of existing simulators, relocation to a remote site will involve a number of logistical problems, both with respect to test objects and with regard to on-site personnel, which will have to be addressed in order to evaluate this option.

For all of the options discussed in this section we find that further technical investigation is required before a definite plan of action can be recommended. For the near term, the fields in the vicinity of HEMP simulators could be measured to determine the limits of a "safe zone", within which the external fields meet all applicable standards dealing with electromagnetic field exposure for the general public. Simulator outputs could then be limited as necessary to ensure that their fields in regions accessible to the general public are in compliance with these standards.

SECTION 5

HEMP SIMULATOR EXTERNAL FIELDS: EFFECTS ON ELECTRONIC SYSTEMS

While much is known about the effects of threat-level, simulated HEMP fields on electronic systems, relatively little is known about the effects of the much less intense external simulator fields on these systems. Clearly there is no effect at zero field, but the threshold level for malfunction or damage (if one exists) is not usually known.

Except for military and critical civil defense systems, the electronic system which has been most thoroughly studied to determine its response to transient electromagnetic fields is the cardiac pacemaker. Pacemakers were investigated in studies conducted by DNA and the Air Force in order to establish safe exposure levels for individuals equipped with these devices. In the DNA experiments, for example, 40 pacemakers of different models were individually mounted in phantoms and exposed to HEMP-like fields of peak amplitudes near 50 kV/m. The responses of the pacemakers were observed to note induced perturbations in output (added or dropped pulses) [18]. A safe peak exposure level for isolated pulses was determined to be 100 kV/m; the safe level established for repetitive pulse exposure was 300 V/m [19]. Other implanted or externally-worn medical electronic devices have not yet been tested, although the importance of such testing is now recognized.

The electronic systems of primary concern in this paper are those associated with commercial aircraft. Operation of HEMP environment simulator facilities over the past twenty-five years by the Air Force Weapons Laboratory and the Defense Nuclear Agency at Kirtland Air Force Base near Albuquerque, New Mexico—which shares runway facilities with Albuquerque International Airport—has yielded no evidence or report of adverse effects on aircraft resulting from simulator operations. Procedures which are employed at Kirtland ensure that no commercial aircraft will be exposed to peak field levels in excess of approximately 1.5 kV/m. We infer from this experience that such an exposure level is safe for current commercial aircraft and that it might be useful as a basis for a formal standard for aircraft electromagnetic compatibility with

pulsed electromagnetic fields. The sufficiency of this basis will need to be evaluated in the light of evolving aircraft and HEMP simulation technologies. Some recent work in this area is reported in [20]; a threshold level of around 8 kV/m is suggested therein.

The present aircraft-related concern deals primarily with new “fly-by-wire” commercial aircraft. Such aircraft, which rely on electronic rather than mechanical or hydraulic means for control of many flight functions, may be more susceptible to electromagnetic interference effects than present civil and military aircraft; but we note that this increased susceptibility is, at present, only conjectured. In the remainder of this section, we review some aspects of aircraft electromagnetic compatibility. We discuss means by which compatibility with respect to a “new” external interference source can be established independently of the aircraft itself. We identify research initiatives which will increase our knowledge of the ambient electromagnetic environment and the external fields of HEMP environment simulators.

5.1 AIRCRAFT ELECTROMAGNETIC COMPATIBILITY.

All aircraft routinely operate in electromagnetic environments. These environments are induced by a number of sources, and aircraft are specifically designed to operate safely in these environments. Some of the sources of these environments are listed below:

- Radio-frequency transmitters installed on the aircraft itself and high-power transmitters located on the ground;
- Radar transmitters installed on the aircraft or located on the ground;
- The aircraft power-system 400-Hz electric and magnetic fields;
- The computer and avionics microprocessor timing and control clock signals, which generate electromagnetic fields at frequencies of one MHz or higher;
- Switching transients generated within the aircraft power system by the turning on and off of aircraft lights, fans and engines or by the operation of control surfaces, ailerons, slats, and flaps; and
- Electrostatic discharges, including lightning and precipitation static.

We note that some of these interference fields originate outside the aircraft, while others originate inside. The term *electromagnetic compatibility* or EMC is used to describe the satisfactory functioning of the aircraft electronic systems in the presence of the interference environment.

We are concerned here with an external source of potential interference, the external fields of HEMP environment simulators. These fields can couple to aircraft electronic systems and they can induce some (presumably very small) electrical transients in these systems. Ideally, one would wish to quantify aircraft EMC with respect to this or any other external source of interference.

A practical approach to establishing aircraft EMC with respect to a new source of external interference is, first, to quantify the electromagnetic environment created outside the aircraft by the interference source(s) in absolute terms and, second, to compare this environment with that which is routinely tolerated (that is, the external environment with which the aircraft is known to be electromagnetically compatible). If the intensity of the new environment is substantially less than that of the routinely-tolerated environment, one can conclude that the aircraft is automatically compatible with the new environment. The most compelling advantage of this approach is that the need for aircraft testing is obviated.¹⁰ Additionally, the conclusions drawn from this approach will also apply to future, as well as present, aircraft designs because they depend only upon the characteristics of the environment and not on the specific aircraft. Of course, as the external man-made electromagnetic environment can be expected to change over time, periodic reassessment of this environment will be necessary.

The principal disadvantage of this approach is that the external ambient electromagnetic environment has not been measured and characterized as well as we would wish. In addition, the HEMP environment simulator external fields are not known as well as they might be. However, these field environments can be analyzed and measured: they

¹⁰Testing will, however, continue to be necessary for aircraft which must survive the full HEMP threat, since these levels are so much more intense than the normal ambient electromagnetic environment.

are *knowable* and, once known, can form a basis for determinations of aircraft EMC. Finally, we note that the optimal basis on which to characterize the ambient environment for the purposes of comparison to HEMP environment simulator external fields is not yet known. Determining this optimal basis is a subject for further research.

5.2 RESEARCH INITIATIVES IN ELECTRONICS EFFECTS.

We have identified potentially useful research initiatives in three areas related to external-field effects on electronic systems in general and aircraft in particular. These are summarized below:

- Quantification, through an extensive data measurement and recording program, of the ambient electromagnetic environment experienced by aircraft in the course of normal operations.
- Quantification, through analysis and a program of field-mapping experiments, of the external electromagnetic fields of HEMP environment simulators, including specific studies of existing simulators and generic studies of the three principal simulator classes.
- Identification of the relevant measures of effectiveness (MOE) for external HEMP simulator fields in inducing malfunctions in, or causing damage to, aircraft and other electronic systems.¹¹ The MOEs might, for example, comprise a set of the mathematical descriptors of the external field waveform.

5.3 A NEW EMC STANDARD FOR COMMERCIAL AIRCRAFT.

It is expected that the Federal Aviation Administration (FAA) will promulgate a new EMC standard for pulsed electromagnetic-field exposure of commercial aircraft. We note that such field exposure can arise from sources other than the proximity of HEMP

¹¹Identification of MOEs for all types of electromagnetic fields and their effects on biological and systems is a research area of critical importance. Our lack of knowledge in this area constitutes a major technology void.

environment simulators. Such an aircraft standard would prescribe field levels which aircraft must be able to survive (in contrast to personnel exposure standards, which prescribe a maximum allowable exposure level). Since any practical standard must be independent of specific aircraft type, it should be based upon a comparison between the ambient electromagnetic environment and the stress addressed by the standard, using the appropriate measures of effectiveness. This type of comparison, and inferences regarding EMC resulting therefrom, were discussed earlier in this section.

SECTION 6

CONCLUDING REMARKS

This study was prompted by manifestations of public concern over two issues related to HEMP environment simulation testing. They are:

- The potential effects on human health and on plant and animal life which may arise from exposure to the external fields of HEMP environment simulators; and
- The potential safety hazards to "fly-by-wire" commercial aircraft which may arise from such exposure.

We have reviewed in this paper what HEMP is, what its effects on defense systems are, and why and how HEMP environment simulation testing is performed. We have summarized the state of our knowledge concerning the external simulator fields and their possible effects on biosystems and electronic systems. We have identified research initiatives which would expand the relevant technology base and aid in the development of new exposure and compatibility standards. These research initiatives are intended to accomplish the following overall objectives:

- Development of options for the modification and/or relocation of HEMP environment simulator facilities so as to further reduce public and civil-aviation exposures to external fields.
- Determination of safe exposure levels for biological and electronic systems. The following areas are of particular importance:
 - Determination of the internal fields induced in biological material by short-pulse electromagnetic exposure;
 - Determination of the biological response mechanisms to, and the biological effects of, short-pulse electromagnetic exposure; and
 - Quantification of the ambient electromagnetic environment experienced by biological and electronic systems in general, and by aircraft in particular.

Recommendations based upon these research initiatives are discussed in the Appendix.

SECTION 7

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APPENDIX

RECOMMENDATIONS FOR DoD ACTION

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The Department of Defense has undertaken several research projects since 1971 to investigate the safety of HEMP environment simulator operations with respect to humans as well as the natural environment and off-site electronic systems. Experimental studies to date are limited, but they have not indicated any health risks associated with the fields generated within or near HEMP simulator facilities. In addition, though present regulations limit occupational exposures to 100 kV/m, simulated HEMP field levels are presently limited to about one kV/m at facility boundaries, in order to provide even more confidence that neither people, nor the natural environment, nor electronic systems will be harmed in any way by HEMP environment simulator operations.

It is reasonable to ask, "What more can be done?" in the light of heightened public concern over the possible adverse effects of HEMP environment simulator operations on public health and safety and on the natural environment. Several possible courses of action are available. These range from simply continuing with "business as usual" to immediately ceasing all HEMP environment simulation testing. The issues were discussed in the body of the report. In this Appendix, an approach is recommended which will permit the DoD to accommodate both the defense requirements of the United States, which involve HEMP environment simulation testing, and the health and safety concerns of the American public.

One extreme position—ignoring public concern and continuing with business as usual—can reasonably be expected to lead to the ultimate cessation of HEMP environment simulation testing. Public pressure in the form of environmental lawsuits or political action could cause simulator operations to be suspended at sites where such operations are still conducted. The end result could be the loss of a part of our deterrent

capability. This extreme position will not serve the defense needs of the United States; neither will it necessarily alleviate public concerns for environmental health and safety.

The other extreme position—that is, simply ceasing HEMP environment simulator operations—will lead to a loss of confidence in the HEMP hardness of critical defense systems. To follow this course would constitute neglect by the DoD of a portion of its responsibility for the national defense and is therefore unacceptable. There is, however, a middle course.

The elements of the course of action recommended to the Department of Defense are the following:

- Continue present HEMP environment simulator operations 1) in compliance with all existing and anticipated standards for the exposure of biological and electronic systems to electromagnetic fields and 2) in a manner which will minimize exposures of the general public and commercial aviation to the external fields of HEMP environment simulators. In particular,
 - Review and update existing operating practices and safety procedures as necessary to ensure continuing compliance with existing standards.
 - Evaluate Environmental Assessments and Environmental Impact Statements as necessary to accommodate simulator modifications and to comply with evolving standards.
- Identify present and expected future HEMP environment simulator requirements. Compare these requirements with existing capabilities and identify both redundancies and gaps.
- Develop options for the modification and/or relocation of HEMP environment simulator facilities so as to further reduce public and commercial-aviation exposures to external fields; modify and/or relocate existing HEMP simulation facilities and/or modify operational procedures as necessary to minimize the impact of testing on the general public and the environment and to accommodate evolving exposure standards.

- Initiate and support research relevant to the determination of safe exposure levels for biological and electronic systems. The following areas are of particular importance:
 - Determination of the internal fields induced in biological material by short-pulse electromagnetic exposure.
 - Determination of the biological response mechanisms to, and the biological effects of, short-pulse electromagnetic exposure.
 - Quantification of the ambient electromagnetic environment experienced by biological and electronic systems in general, and by aircraft in particular.
 - Quantification of the external electromagnetic fields of HEMP environment simulators, including specific studies of existing simulators and generic studies of the three principal simulator classes.
 - Identification of the relevant measures of effectiveness (MOE) for external HEMP simulator fields in inducing malfunctions in, or causing damage to, aircraft and other electronic systems.
- Assist appropriate government agencies in establishing future compatibility and exposure standards.

HEMP environment simulator operations are vital to the national interest and should therefore continue. These operations must, however, be conducted in accordance with all existing standards for occupational and general exposure. It is therefore critical to review, on a continuing basis, all relevant environmental laws and ensure that HEMP environment simulator operations continue to meet existing regulations and standards. It is equally important, however, to prepare for possible changes in exposure standards in order to minimize the risk associated with a hiatus in HEMP environment simulation testing of critical defense systems.

The absolute need for HEMP environment simulation facilities, and for the use of these facilities in system testing, is clear. It may be, however, that the present set of facilities is to a degree redundant; furthermore, there exist major gaps in our capability to

simulate certain HEMP environments and to conduct tests on certain types of critical systems, so that new simulators are needed. Thus it is recommended that DoD needs for these facilities be reassessed and a "critical list" of needed simulation capabilities be drawn up. For example, it can be safely assumed that testing of Navy ships will continue to be of great importance; thus the need for an ocean-going facility such as EMPRESS-II is clear. On the other hand, experience with the TRESTLE facility at Kirtland AFB, New Mexico indicates that that particular HEMP environment simulator may no longer be needed, even though the capability for testing aircraft in the in-flight configuration would be desirable. Finally, the need to simulate fast-rising HEMP environments has been recognized as critical, and facilities to meet this need must be developed.

While novel simulator designs may appear from time to time, the existing simulator types (that is, radiating, bounded-wave, and hybrid) represent capable and useful designs which are likely to be modified and improved only in an incremental sense. Thus it is recommended that research initiatives be undertaken, first, to quantify the external electromagnetic environments associated with these simulator types and with specific simulators of these types and, second, to determine means by which the external fields of HEMP environment simulators can be controlled and reduced. Placing a simulator within a large enclosure such as a Navy blimp hangar, for example, will shield the external environment from the external fields, at some cost to simulator performance. This cost should be quantified and minimized. Similarly, surrounding a simulator by a properly designed electromagnetic fence (which could absorb and/or redirect the external field) would also shield at least a part of the external environment. This means for controlling the external electromagnetic-field environment should also be investigated.

It is worthwhile to note that the external field of the new FEMPS simulator (a simulator which can produce an illuminating waveform similar to the current HEMP environment standard, although over a limited volume) has been successfully contained without adversely affecting simulation fidelity. The working volume of this simulator is not large (although objects up to the size of a two-ton truck can be tested), but FEMPS

demonstrates that the technical means are available for acceptable operation of HEMP environment simulators within shielded enclosures.

An additional means for protection of the environment lies in removing HEMP simulators to locations where risk is minimal because of the lack of nearby population. Remote sites such as Fort Huachuca in Arizona, the White Sands Missile Range in New Mexico, and the Nevada Test Site should be examined as possible locations for HEMP environment simulator operations. The principal problem to be addressed in this regard is that of logistics, both with respect to test objects and with regard to on-site personnel. It is recommended that remote sites be preferred for future HEMP environment simulator construction and operations. This recommendation is based upon practical considerations, rather than on any evidence which demonstrates a linkage between HEMP simulator external fields and biological effects.

It was noted in the report that there exist many unknowns with respect to possible adverse effects of low-level external simulator fields on biosystems and on electronics. Research in this field should be continued and new research initiatives should be undertaken along the lines described in the report, with a view toward determining safe exposure levels for biological and electronic systems. Research programs addressing these issues, especially those which involve characterizing the ambient field environment, could be undertaken immediately. Such programs would involve research partnerships between the DoD and other Federal agencies. They would support the development of aircraft EMC standards and would improve our present understanding of the details of simulator external fields and their interactions with aircraft electronics. Better understanding of the external field environments of HEMP simulators would also assist in the development of means for controlling and reducing these environments.

The responsibility for establishing standards for occupational and general exposure for aircraft and humans resides in organizations and US Government agencies other than the Department of Defense. The DoD can, however, provide valuable support to those agencies in gathering the data which would support such new standards. Experience in

the measurement of transient electromagnetic fields has been gathered over years of HEMP- and lightning-related testing. Means for measuring and recording ambient-field data have been developed. This experience and equipment could be used to establish the electromagnetic "background" on which to base an EMC standard, although there exist technological and operational issues which must be resolved for this effort to be successful. Furthermore, DoD experience in HEMP environment simulation testing could be employed in tests of fly-by-wire aircraft in or near a HEMP environment simulator at reduced and variable field levels to obtain data on threshold field levels for malfunction or damage.

It is also recommended that the DoD consider assisting in the formation, possibly through the Environmental Protection Agency, of a panel of experts under the aegis of an independent organization (e.g., ANSI or the IEEE) to review proposed changes in exposure standards and corresponding DoD options.

Each of the Services, the Defense Nuclear Agency, and some other organizations have been involved in the evaluation of potential adverse effects of simulated HEMP fields on biosystems and commercial civil electronics. The current series of individual environmental impact studies and environmental assessments are being conducted independently. The Tri-Service Electromagnetic Radiation Panel¹² exists specifically to review and coordinate DoD activities in this area. DNA must utilize this group more effectively with respect to HEMP simulator environmental issues (see [19], p. 5, para. 9).

¹²At this writing, the Panel is chaired by Dr. David Erwin of Armstrong Laboratory, (512)536-3582.

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