UNCLASSIFIED

AD NUMBER:	AD0905229

LIMITATION CHANGES

TO:

Approved for public release; distribution is unlimited.

FROM:

Distribution authorized to US Government Agencies only; Test and Evaluation, Export Controlled; 1 Dec 1972. Other requests shall be referred to Naval Fleet Missile Systems Analysis and Evaluation Group, Corona, CA 91720.

AUTHORITY

FMSAEGA, D/N ltr dtd 19 Jul 1973

THIS PAGE IS UNCLASSIFIED

GIDEP Form 2:12-71 **GENERAL REPORT SUMMARY SHEET** 1 OF 1

1. ORIGINATOR'S REPORT TITLE	2. PROGRAM OR SYSTEM	3. DATE OF	DAY	MO	YR
THE ELECTROMAGNETIC PULSE (EMP) AND ITS EFFECTS ON SYSTEMS	CF	ISSUE		4	72
	ORIGINATOR'S REPORT NO. X72-353/201	REVISION			

4. ORIGINATOR'S PART NAME/PART IDENTIFICATION	5. REPORT TYPE, ETC.
N/A	Radiation Effects

11 Apr 72

7. THIS TEST (SUPERSEDES) (SUPPLEMENTS) REPORT NO. N/A

8. MANUFACTURER	9. MANUFACTURER PART NO.	10. MFG-TYPE, RATING, SIZE, ETC.
N/A	N/A	N/A

12 034p.

17. ACCESS NUMBER D8161

11. OUTLINE, TABLE OF CONTENTS, SUMMARY, OR EQUIVALENT DESCRIPTION

10 G. E. Morgan

DDC RECEIVED DEC 1972 E

SUMMARY

It can be seen that the EMP environment generated by a nuclear weapon burst can be large in amplitude, cover a wide frequency spectrum and have a large radius-of-effect.

The system response is seen to be a total system response not understandable on a component basis alone. Analytical techniques are available for predicting these system effects. Tests are used to validate the analysis and to verify hardness conclusions.

Quality control techniques are important. Setting up the quality control program is a difficult but rewarding task.

EMP hardening techniques are discussed with some remarks on the limitations of some of the techniques.

Finally, assessment of the force is discussed including the problem of error analysis, statistical sampling, and combination of the test and analysis data.

19 MAY 1972

18. COMPONENT PART NAME PER GENERIC CODE: GENERAL TECHNICAL DATA (Radiation Effects on Parts/Mat.)

19. REPORT NO. 347.65.00.00-C1-25

18 GIDEP

12. ENVIRONMENTAL EXPOSURE CODES	13. MANUFACTURER NOTIFIED		
X	N/A		
	DAY	MONTH	YEAR

14. KEY WORDS FOR INDEXING

Electromagnetic Pulses - Systems - Hardening

15. SIGNATURE	16. PARTICIPANT
J. W. Keary (signature) J. W. Keary	NAR/Autonetics - C1

AD905229 L

DDC FILE COPY

REPRODUCTION OR DISPLAY OF THIS MATERIAL FOR SALES OR PUBLICITY PURPOSES IS PROHIBITED

34

048 100 001

ACCESSION for
NTIS
DDC
UNANNOUNCED
JUSTIFICATION
BY
DISTRIBUTION/AVAILABILITY CODES
Dist. AVAIL. and/or SPECIAL
B

NOTICES PAGE

FOREIGN NATION RELEASE

This information is furnished upon the condition that it will not be released to another Nation without specific authority of the cognizant agency (Military or NASA) of the United States Government, and that the information be provided substantially the same degree of protection afforded it by the Department of Defense of the United States.

DISCLAIMER OF LIABILITY FROM ACT OF TRANSMITTAL

When Government drawings, specifications or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specification, or other data, is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Any information disseminated by the Administration Office of the Government-Industry Data Exchange Program (GIDEP) is intended to promote test data utilization in the National interest among groups engaged in the military weapons, aerospace and related programs.

Dissemination of said information does not imply verification or endorsement of the information. The originator, in submitting the material is acting in accordance with the requirements of his contract, and neither the originator nor the disseminator assumes any liability to parties adopting any product, process or practice based upon the usage of the information. Its presenting the success of failure of one (or several) part number(s), model(s), and lot(s) under specific environment and output requirements, does not imply that other products not herein reported on are either inferior or superior.

OMISSION OF CHARGES FOR FOLLOW-ON ACTIONS

Any compliance by the report originator with requests from recipients for more detailed information in GIDEP reports originated under Government contracts will be considered within the scope of present contractual obligations. Compliance with such requests will be at the discretion of the report originator and will be performed without cost or obligation to the requester unless otherwise negotiated in advance.

REPRODUCTION OF THIS REPORT

Reproduction or duplication of any portion of this report is expressly forbidden, except by those organizations receiving it directly from the GIDEP Administration Office or originator, for their internal use or the use of their subcontractors. Reproduction or display of all or any portion of this material for any sales, advertising or publicity purposes is prohibited.

8161

THE ELECTROMAGNETIC PULSE (EMP) AND ITS EFFECTS ON SYSTEMS

APRIL 1972

Prepared by

G. E. Morgan
Autonetics Division

Presented to

University of California, Los Angeles

Short Course on
Radiation Effects on Semiconductor Devices

Distribution limited to U.S. Gov't. agencies only; Test and Evaluation; 1 DEC 1972. Other requests for this document must be referred to Naval Fleet Missile Systems Analysis & Evaluation Group. Code 862, Hdqs office, Corona, Calif 91720

Autonetics
North American Rockwell

3370 Miraloma Avenue, Anaheim, California 92803

003

THE ELECTROMAGNETIC PULSE (EMP) AND ITS EFFECTS ON SYSTEMS

INTRODUCTION

The following is a very brief and introductory discussion of EMP and its effects on systems which is meant primarily to initiate and orient the newcomer. The treatment here is broad and general and attempts to cover a wide spectrum of subjects. It is, therefore, not intended as an in-depth discussion of the subject which would clearly require a book of considerable thickness, if not several books. Many valuable references, or experienced personnel, can be consulted for more detail by the interested reader.

I. THE EMP ENVIRONMENT

The electromagnetic pulse (EMP) is a radio-frequency emanation which results from the detonation of a nuclear weapon. It is a generic term for any pulse caused by any nuclear weapon and, as such, it encompasses many different phenomena. Seven different types are listed in Figure 1.

Probably the most important EMP environment is that resulting from a high-altitude, exoatmospheric burst. This type of environment is caused by the interaction of the nuclear weapon gamma-rays with the upper regions of the atmosphere and the earth's magnetic field. Compton-electrons, generated by the gamma-rays from the weapon interacting with air atoms, tend to spiral about the earth's magnetic-field lines. The composite effect is a large electromagnetic radiation below this source region and extending outward in all directions, with roughly uniform field-intensity to a large radius from the burst-point. This large area-coverage is the reason for the importance of the high-altitude burst phenomenon. The large radius is determined essentially by the line-of-sight tangent from the burst-point to the earth's surface (See Figure 2).

The atmospheric burst is much less important because the gamma-rays are much more quickly absorbed and because the outward movement of ions is nearly symmetrical about the burst point resulting in a smaller net current flow and smaller radiation.

Ground-burst EMP is very large due to the assymetry of the ionization traveling from the burst point. This environment can be an important one to blast-hardened facilities. The charge is displaced upward and outward from the burst-point (charge headed downward is quickly stopped in the soil). This charge motion results in radial E-fields and horizontal H-fields as the first-order effects. Inside, or below, the ion-hemisphere the fields are non-plane, near-fields, in which the wave impedance ($z = E/H$) varies with position and time. Much of the displaced negative charge returns to the burst-point through the ground causing late-time fields and currents. The effect is somewhat different at burst-points slightly above ground.

EMP also results from nuclear detonations underground, as in underground nuclear tests, and can seriously affect local instrumentation near the test site.

Internal EMP is the generation of electromagnetic fields inside an enclosed (unshielded) system. It is the result of Compton and/or photoelectric effects inside the system due to penetrating gamma-rays or X-rays. The effects can be severe where the ionizing dose rate is large and penetrates the walls of the vehicle.

System-generated EMP is similar to Internal EMP except that the effects of interest are externally induced. In this form of EMP, large currents may be caused to flow on the outside of an exoatmospheric vehicle by charge knocked off the exterior in an assymetric way. Some of the knocked off charge can escape the vehicle entirely, while other charges will be decelerated by the retarding fields and return promptly to the vehicle. The net residual charge on a satellite will be slowly neutralized by the free-charges in space.

TYPE	AMPLITUDE	AREA AFFECTED	SYSTEMS AFFECTED
1. HIGH-ALTITUDE BURST	LARGE	VERY LARGE	MISSILES, AIRCRAFT, GROUND EQUIPMENT
2. ATMOSPHERIC BURST	SMALL	SMALL	MISSILES, AIRCRAFT, GROUND EQUIPMENT
3. NEAR-GROUND BURST	VERY LARGE	SMALL	BLAST-HARDENED GROUND FACILITIES
4. GROUND BURST	VERY LARGE	SMALL	BLAST-HARDENED GROUND FACILITIES
5. UNDERGROUND BURST	LARGE	SMALL	LOCAL INSTRUMENTATION
6. INTERNAL EMP	LARGE	MODERATE	MISSILES, SATELLITES, HARDENED SITES
7. SYSTEM-GENERATED EMP	LARGE	MODERATE	MISSILES, SATELLITES

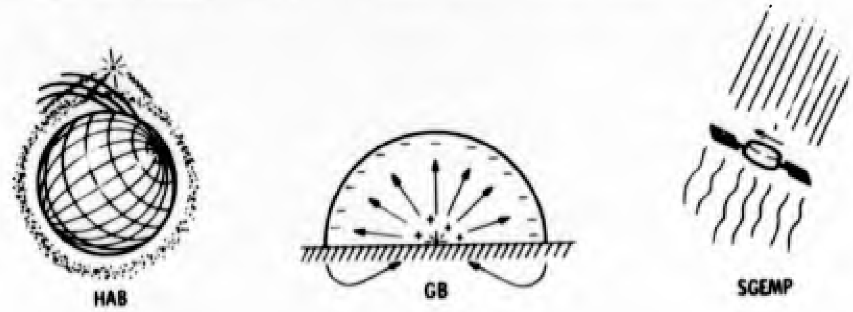


Figure 1. EMP Environments

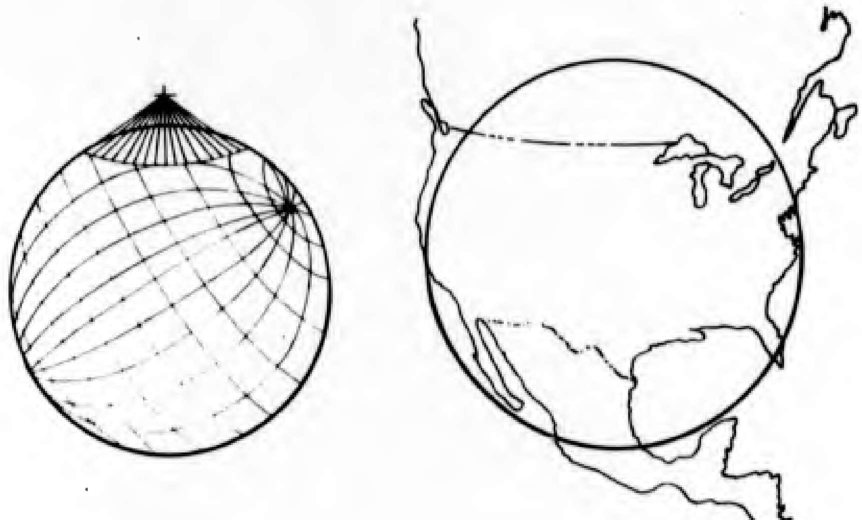


Figure 2. Area Coverage of HAB

006

The pulse shapes vary, depending on the type of EMP as is suggested by the curves in Figure 3. For high-altitude bursts (HAB) the pulse is a fast-rising, slowly decaying pulse of short duration which has considerable bandwidth. The ground-burst waveforms for close-in (A) and distant (B) effects are also shown and again cover a broad spectrum of frequencies but are somewhat richer in low-frequencies. The system generated EMP waveform can take many forms but tends to have a short pulse initially followed by a zero-crossover and a long tail.

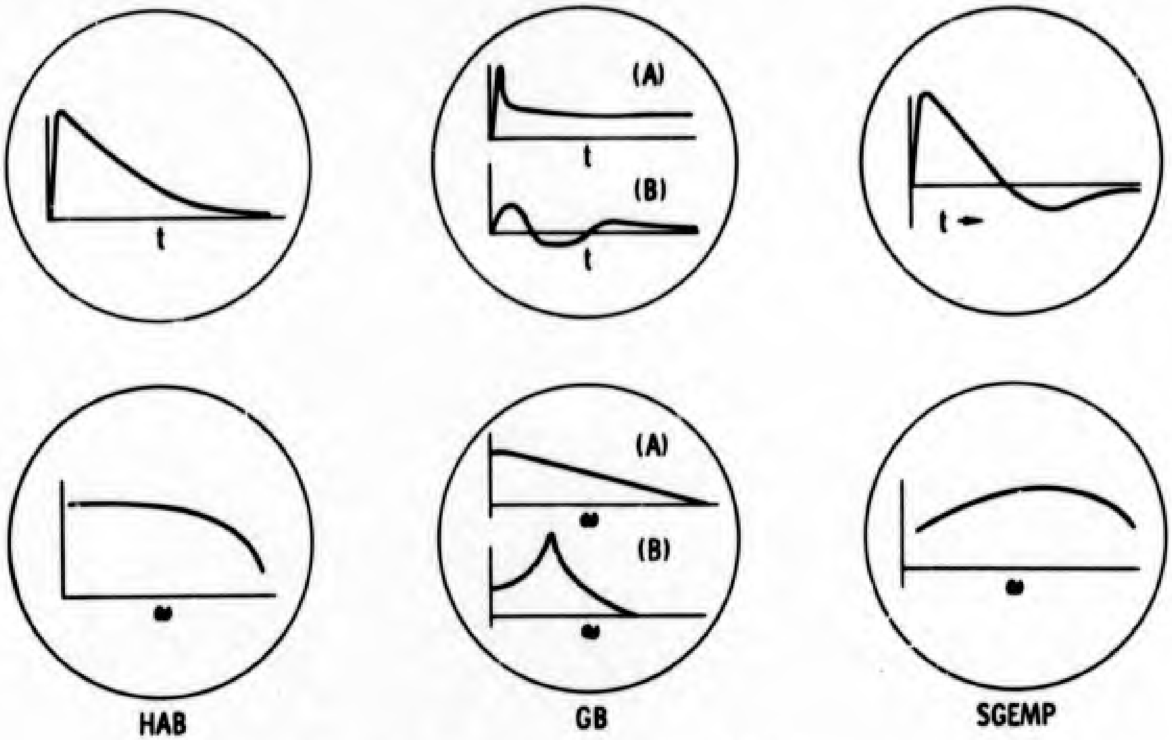


Figure 3. Characteristics of EMP

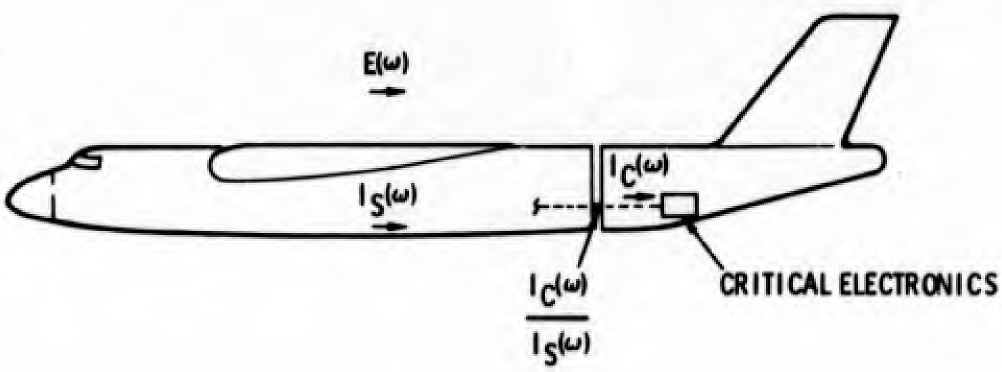
007

II. THE EFFECTS OF EMP ON SYSTEMS

Given a transient electromagnetic excitation, systems respond in a manner depicted in Figure 4. That is, the external incident fields induce a current on the skin, or surface, of the exterior of the vehicle. These skin currents are analytically predictable in terms of the response of the vehicle structure acting as an antenna. Given these currents on the exterior, which largely govern the dominant frequencies of the system response, some energy leaks into the interior of the vehicle by way of holes, slots, discontinuous joints or other openings. These openings are called apertures. Energy is coupled into interior cables by way of internal fields that are driven by aperture-coupling from the external total fields. The total field outside the vehicle is the sum of the incident free-field and the scattered fields resulting from the vehicle antenna response. This aperture coupling can, almost always, be described in terms of a linear transfer-function which relates the current induced on a cable inside to the outside skin current, or ratio of fields-inside to fields outside.

Given a current induced on a cable inside the vehicle, the current propogates down the cables in accordance with tranmission-line theory. Cable responses are usually linear at moderate to low levels (amplitudes) and can, therefore, be analytically described in terms of general transfer functions.

When the current reaches a box of electronics, voltages are developed at critical circuits. Virtually every wire in every circuit in a typical box will see some type of transient voltage. Thus, the circuits are said to be under "multiport" excitation. The circuit responses are, in general, non-linear.



1. INCIDENT ELECTROMAGNETIC FIELD INDUCES CURRENT ON SKIN OF STRUCTURE
2. CURRENT ON EXTERIOR COUPLES TO INTERNAL CABLES
3. CURRENT DISTRIBUTES ON INTERNAL CABLES
4. CURRENT PRODUCES VOLTAGES IN ELECTRONIC CIRCUITS

Figure 4. Effects of EMP on Systems

008

Each of the above four factors are analytically describeable in terms of mathematical models using antenna theory, aperture theory, transmission-line theory, and time-domain or frequency-domain circuit analysis methods. Total system responses can be modeled with simple models (approximate) or very sophisticated models (precise).

A brief analytical survey of these techniques below will serve to illustrate the effects and typical results.

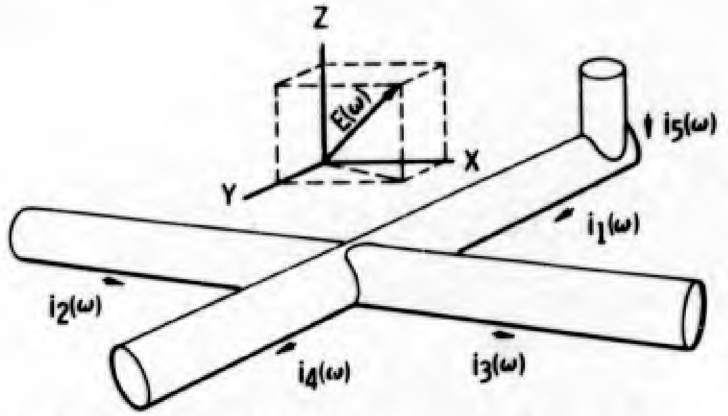
009

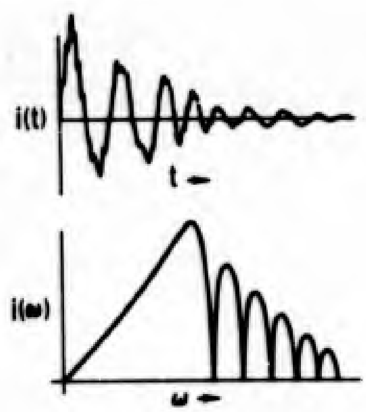
III. ANALYTICAL MODELS

A. SKIN CURRENTS

The aircraft shown in Figure 4 might be modeled as a series of orthogonal right-circular cylinders as is shown in Figure 5. The response of this configuration of cylinders can be understood in terms of cylindircal antenna theory with due consideration for the mutual coupling between the elements. The analysis can begin, for example, with computer solutions of the King-Middleton antenna equations which results in an antenna transfer-function (constant field intensity at each frequency) shown in Figure 5. Note the linearly increasing amplitude below antenna resonance, followed by cyclic harmonic resonances and anti-resonances (nulls). This plot might represent the current at the center of the fuselage section. Other (different) transfer functions would exist at other locations along the fuselage.

If the vehicle is parked on the ground and exposed to a vertically polarized EMP, currents would be induced on the vertical stabilizer and distributed onto the fuselage and wings which tend to behave as transmission lines. Near the ground, an image of the vehicle is formed in the ground which leads to a two-wire transmission line model. Standard transmission-line theory can predict this effect given the stabilizer driving currents.





• FOR LINEAR ANTENNAS

$$\int_{-h}^{h} I_Z(Z)\, K(Z, Z')\, dZ' - j\frac{4\pi K_0}{\zeta_0} Z^i(Z)\, I_Z(Z) = -j\frac{4\pi K_0}{\zeta_0} E_Z^i(Z)$$

• FOR ELEMENTS AS TRANSMISSION LINES

$$T(\omega) = \frac{1}{\cosh \gamma \ell + \frac{Z_L}{Z_0} \sinh \gamma \ell}$$

Figure 5. Skin Currents

010

If these transfer-functions are convolved with the incident field spectral distribution, the time-domain result can be developed by performing an inverse Fourier transform of the result. In general the response is a damped sine-wave consisting of many frequencies with the higher frequencies dying out generally faster than the lower frequencies (see Figure 5).

Before the scattered fields incident on a particular aperture can be known with accuracy, however, we must not only know the total cyclinder current, as was determined above, but we must also determine the variations in current density around the cylinder. Figure 6 illustrates the variations typically resulting from the shadowing effect and shape effects. Shadowing causes the currents to be higher on the side of the cylinder upon which the incident field is impinging and can be pronounced at high frequencies (20 - 100 MHz). Distortion of the cylinders into airfoils (as in the case of wings) does not appreciably change the total longitudinal current along the element but the shape does affect the current density variations around the cross-section. Typically, as should be expected, the highest current densities around a wing are found at the leading and trailing edges as can be seen in Figure 6.

B. APERTURES

Once the fields in the aperture are known, the coupling of fields through the aperture into the interior can be predicted using aperture theory. In general, but not always, the apertures of interest for EMP are relatively small compared to wavelength. Occasionally predictions must account for apertures which are comparable in size to the wavelengths of interest and hence must deal with the more difficult problem of the resonance of the aperture itself or coupling above resonance where the fields vary appreciably across the face of the aperture.

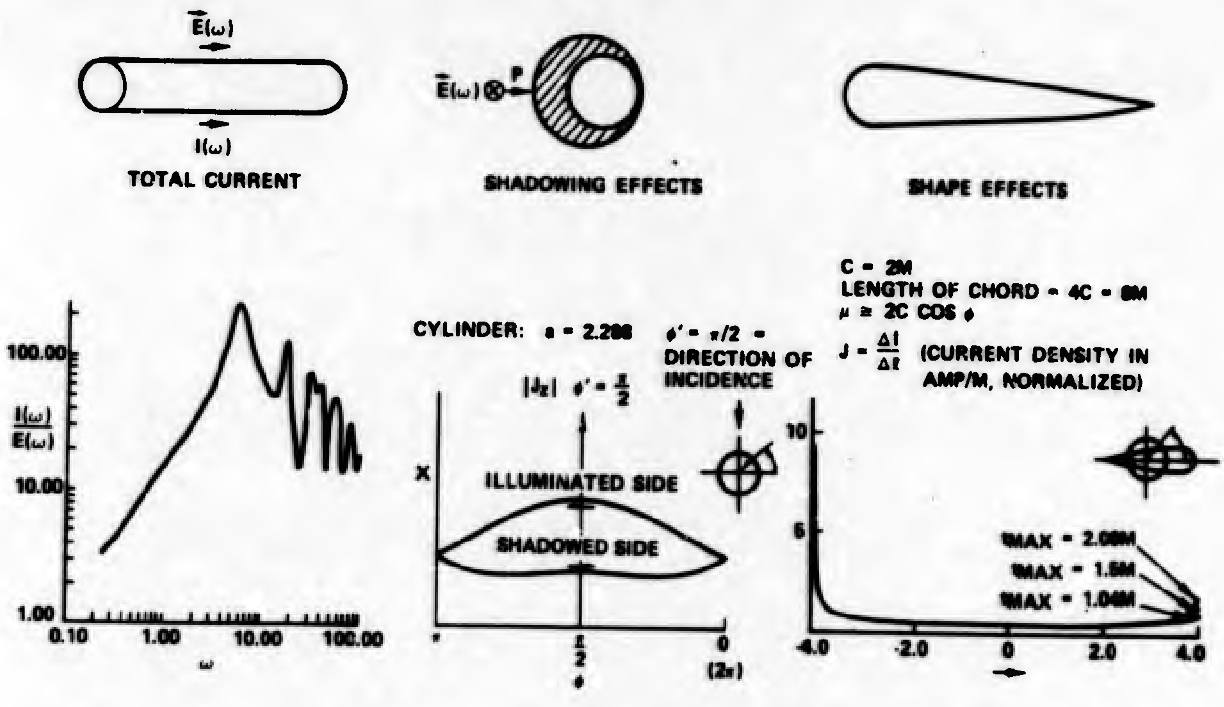


Figure 6. Computer Analysis of Antenna Responses

011

For apertures that are small with respect to wavelength it can be shown that the behavior of the aperture (as viewed from the interior) is similar to that of an antenna located in the hole. The equivalent aperture effects can be described in terms of electric and magnetic dipole moments located in the aperture. The internal fields, then, near the hole are non-plane, near-fields, which decrease initially as $1/R^3$ and subsequently as $1/R^2$ and finally as $1/R$ as the observer moves away from the hole. Obviously, therefore, cables directly behind an aperture may be particularly vulnerable to stray pickup.

In real systems the hole, or aperture, invariably leads into some type of enclosure, or bounded volume, such as a compartment or room. This enclosure can resonate and add different sensitivities to the coupling that would not be expected for an aperture leading to an infinite, unbounded region.

The area of apertures is probably the least-well developed areas of the EMP coupling analytical technology. Nevertheless there are numerous techniques that have been developed and are adequate for most analyses. Many are documented in the open literature. For difficult cases not workable by classical modeling techniques, semi-empirical synthesis and modeling techniques have been developed. By one or the other of these techniques, analytical models can be and are developed for apertures in systems to accurately predict their effects (see Figure 7, for example).

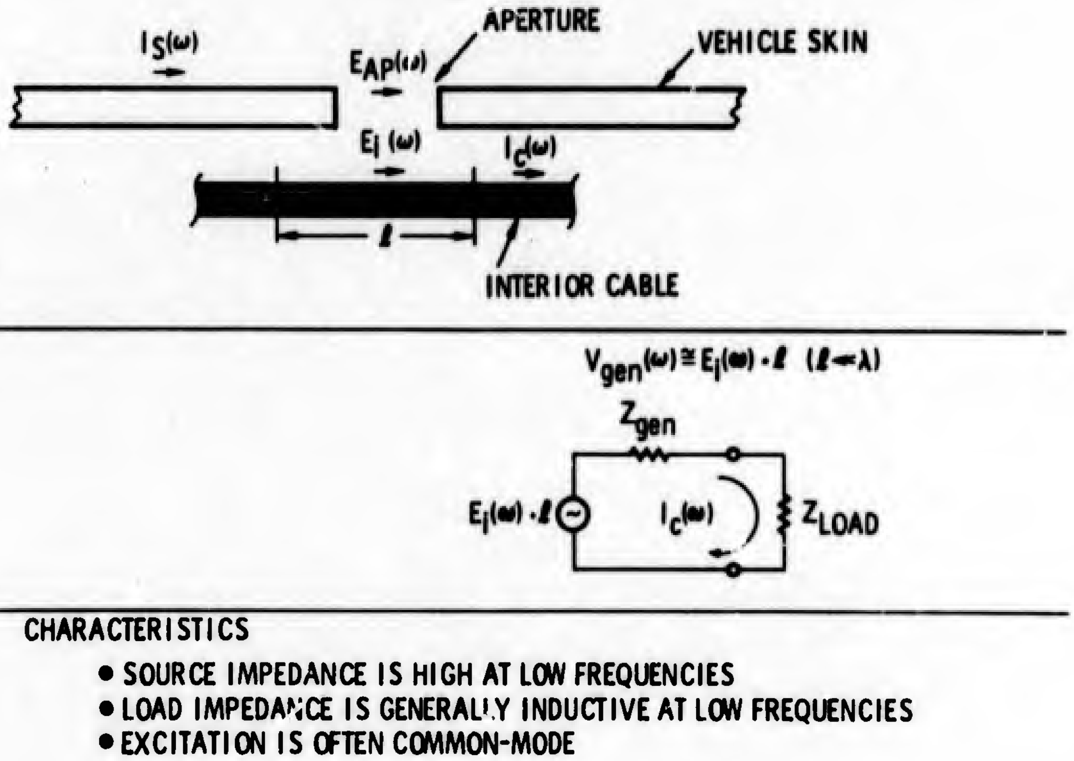


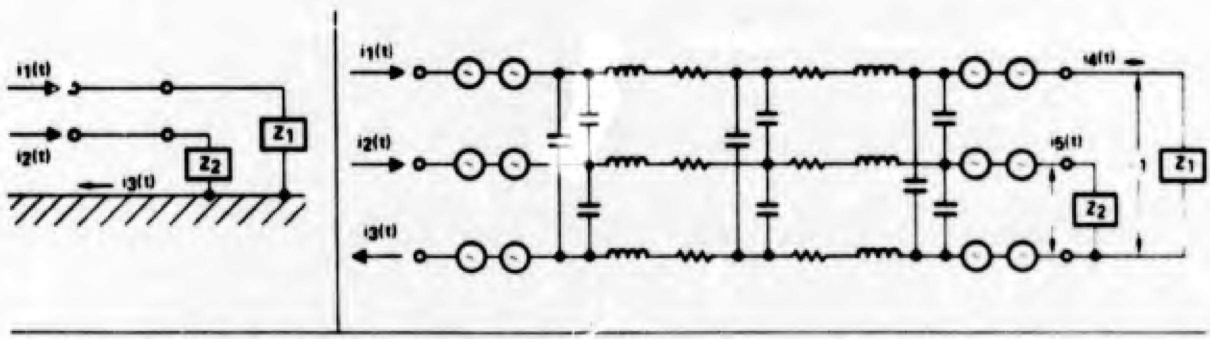
Figure 7. Current Coupling to Cables

012

C. CABLE CURRENTS

The fields which penetrate the system via apertures will induce currents in internal cables. Cables can be modeled as linear, or loop, antennas to estimate this current, once the internal fields are known. The induced voltage or current can then be modeled in terms of the Thevenin or Norton equivalents. Given these source generators, the cables tend to behave as linear transmission-lines. Cables can be modeled as distributed systems using transmission-line equations or in terms of lumped-parameter equivalents such as that shown in Figure 8. These models include skin-effect (which makes the resistance vary with frequency) and mutual coupling between conductors.

Modeling cables for high-frequencies requires that the cable length be modeled in segments, each of which is short with respect to wavelength ($\ell \simeq 0.1\lambda$). For real systems the cable models can become very large and complex and require special circuit-analysis computer codes which can handle thousands of network nodes. Such codes do exist for either frequency-domain (linear) or time-domain analysis. Time-domain analysis is, of course, necessary when the behavior is non-linear, as it can be if either arcing or non-linear load-impedances are involved. In real systems, the matrices resulting from these networks are, in general, quite sparse, making analysis easier and faster.



- AT HIGH FREQUENCIES, MUST USE SERIES OF LUMPED EQUIVALENTS ($\ell \simeq 0.1\lambda$)
- NETWORKS GET VERY LARGE EVEN FOR TYPICAL CABLES
- CAN SOLVE IN FREQUENCY - DOMAIN IF LOADS ARE LINEAR
- SOLUTIONS IN TIME-DOMAIN FOR NON-LINEAR LOADS; SYSTEMS ARE STIFF
- MUST INCLUDE RESISTANCE DUE TO SKIN EFFECT AT HIGH FREQUENCIES
- MUTUAL COUPLING BETWEEN WIRES IS IMPORTANT

.... BUT MATRIX IS SPARSE

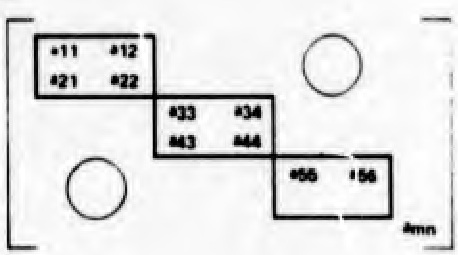


Figure 8. Cables as RF Transmission Lines

013

Typical transfer-functions for cables are shown in Figure 9 for three particular load impedances. The universal load-impedance is one that was synthesized from the observed (measured) impedances of numerous real electronic packages.

It can be seen that the transfer function for the case of the so-called universal load impedance rarely exceeds unity. However, for capacitive or small resistive loads, should they occur, as they sometimes do, the cables exhibit a current gain of as much as an order-of-magnitude at certain frequencies. This effect is similar to the shorted quarter-wave stub behavior of basic transmission line theory.

D. CIRCUIT RESPONSES

Circuits in the electronic packages are, in general, non-linear. For modeling circuits for EMP, time-domain circuit-analysis computer codes are used to predict the response of the circuit to transient excitation. In general it has been necessary to characterize the components carefully, to account for their true high-frequency parameters in order to achieve acceptable correlation between the analyses and tests.

In addition to accurate component characterization, it has also been found desirable to modify the Ebers-Moll transistor model to a two-lump equivalent to accurately predict the switching times (see Figure 10). In addition to the important effects of multiport excitation at the circuit level (discussed earlier), it is also important to note that circuits do not always respond only to the peak voltage at the input. Some circuit can integrate the waveform over a period of time and respond after numerous cycles. Such circuits are called voltage stackers and are clearly waveform dependent (see Figure 11, for example).

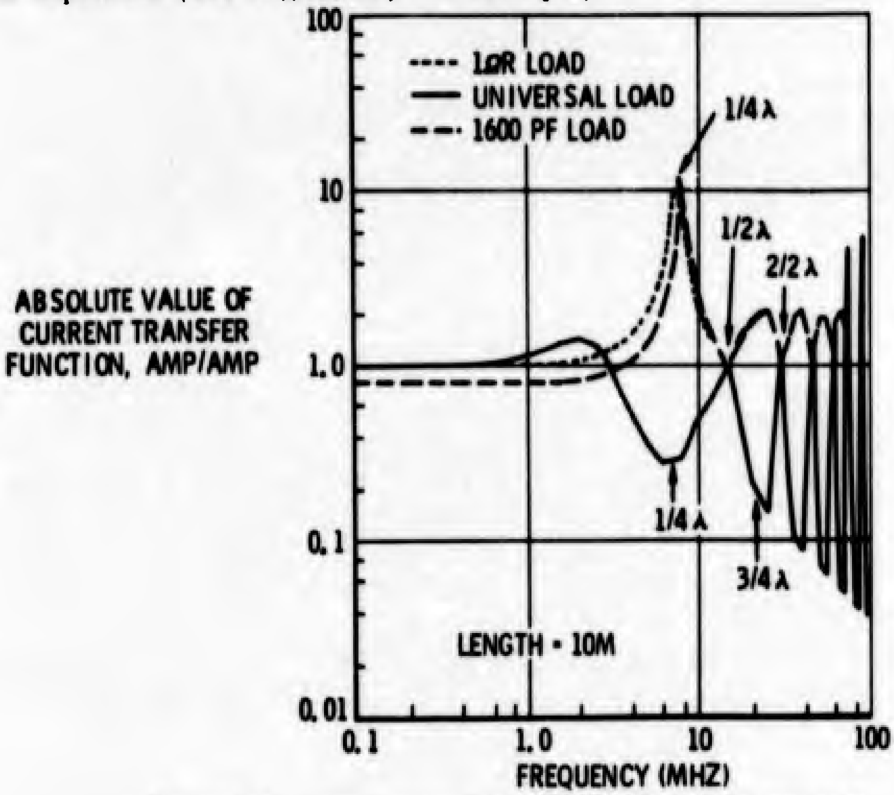
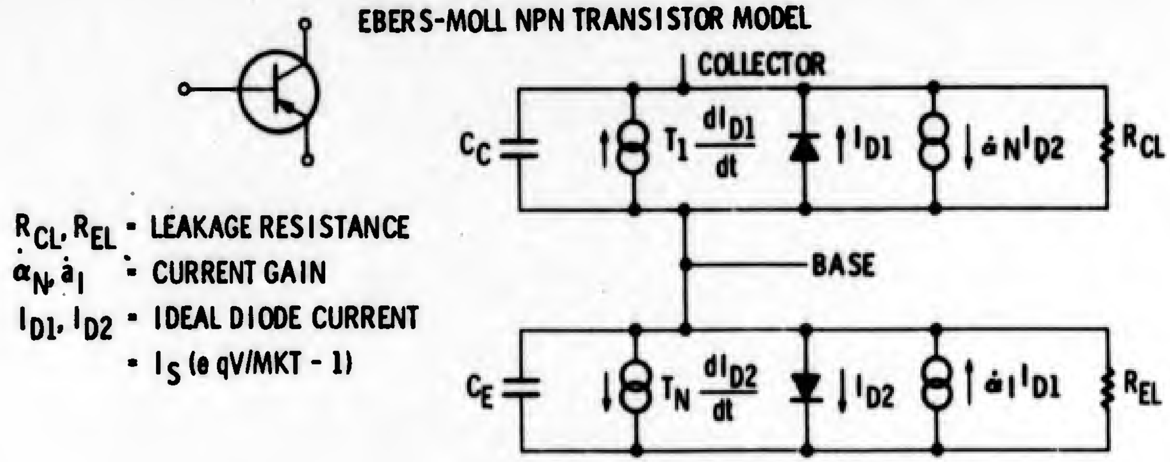


Figure 9. Computer Analysis of Cable Responses

014



- ACCURATE COMPONENT CHARACTERIZATION IS IMPERATIVE
  - CAPACITANCES BECOME IMPORTANT
  - SWITCHING TIMES ARE IMPORTANT
  - CIRCUIT STRAY-CAPACITANCE AND INDUCTANCE CAN BE IMPORTANT
- STABILITY OF NUMERICAL TECHNIQUES CAN BE A PROBLEM FOR SOME CIRCUITS

Figure 10. Radio-Frequency Response of Circuits for EMP Response Predictions

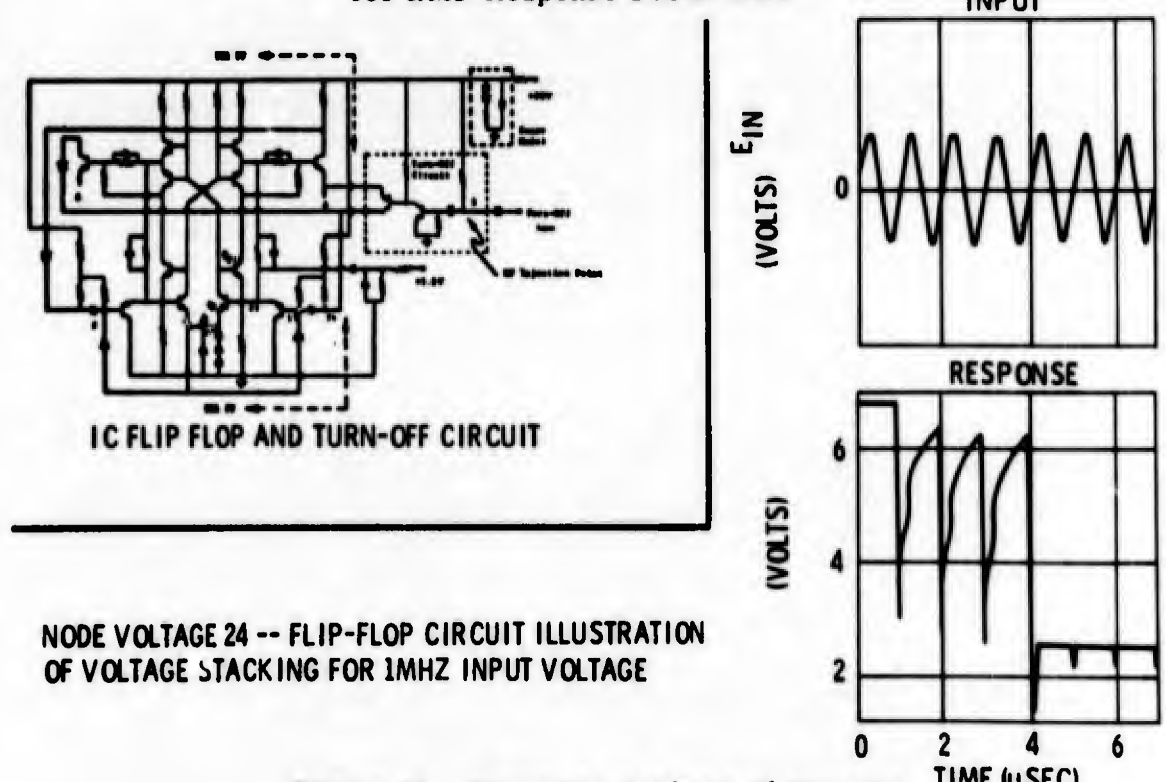


Figure 11. Computer Analysis of Circuits

Circuits may also be damaged permanently by EMP. Junction burnout, usually by avalanche, is the dominant mode-of-failure for semiconductor transistors and diodes. This failure-mode is caused by excess heating in the junction and results in melting of the material and destruction of the device. The power-per-unit area required to damage a device is

$$P/A = kt^{-1/2}$$

where K is roughly 500 for transistors and t is the duration of the equivalent square-wave pulse. Thus, devices with small junction areas are more vulnerable to burnout. This usually means devices which are fast, and/or neutron hardened. Thus, we see that EMP hardening (to permanent damage) and neutron hardening are in conflict, at the component level.

Other devices, such as integrated circuits, have other additional permanent-damage failure-modes including burnout of metal interconnects, oxide punch-through, bond failures or substrate latching (see Figure 12). It might be noted that junction burnout, interconnect burnouts and bond failures are usually induced by heating due to excess current. The oxide punch-through and substrate-junction-reversal failure-modes are voltage induced.

Other components are generally resistant to damage. However, low-voltage, thin-film resistors have been observed to fail and polarization-sensitive capacitors can short-circuit. Under severe stress, arcing may occur in many components, and be damaging, or wires or relay contacts may be damaged.

- JUNCTION BURNOUT IS DOMINANT MODE-OF-FAILURE IN TRANSISTORS AND DIODES

$$P/A = Kt^{-1/2}$$

- IC'S ALSO FAIL FOR OTHER REASONS

  METAL INTERCONNECTS
  OXIDE FAILURES
  LATCH-UP OF COLLECTOR-TO-SUBSTRATE JUNCTIONS

Figure 12. Permanent Damage to Transistors, Diodes and IC's

IV. EMP TESTS

Analysis alone cannot be depended upon to confidently assess the hardness of a system. Tests are required to validate the analysis. The interaction of tests, analysis and assessment activities is simply described in Figure 13. Note that the tests and analysis may be iterated until correlation is achieved. There are at least four classes of EMP tests (see Figure 14).

EM-Coupling tests utilize electromagnetic fields produced by EMP simulators to excite a system for the purpose of validating test predictions and to experimentally assess difficult EM-coupling variables. In performing such tests there must be adequate recognition of the many variables affecting the EM-coupling (see Figure 15 for types of variables).

Some different EM simulators which have been used in the past or are planned for the future are shown in Figures 16, 17, 18, 19, and 20. Some are bounded-wave simulators in which the fields are largely contained. Others are radiative simulators which are simply broad-band antennas.

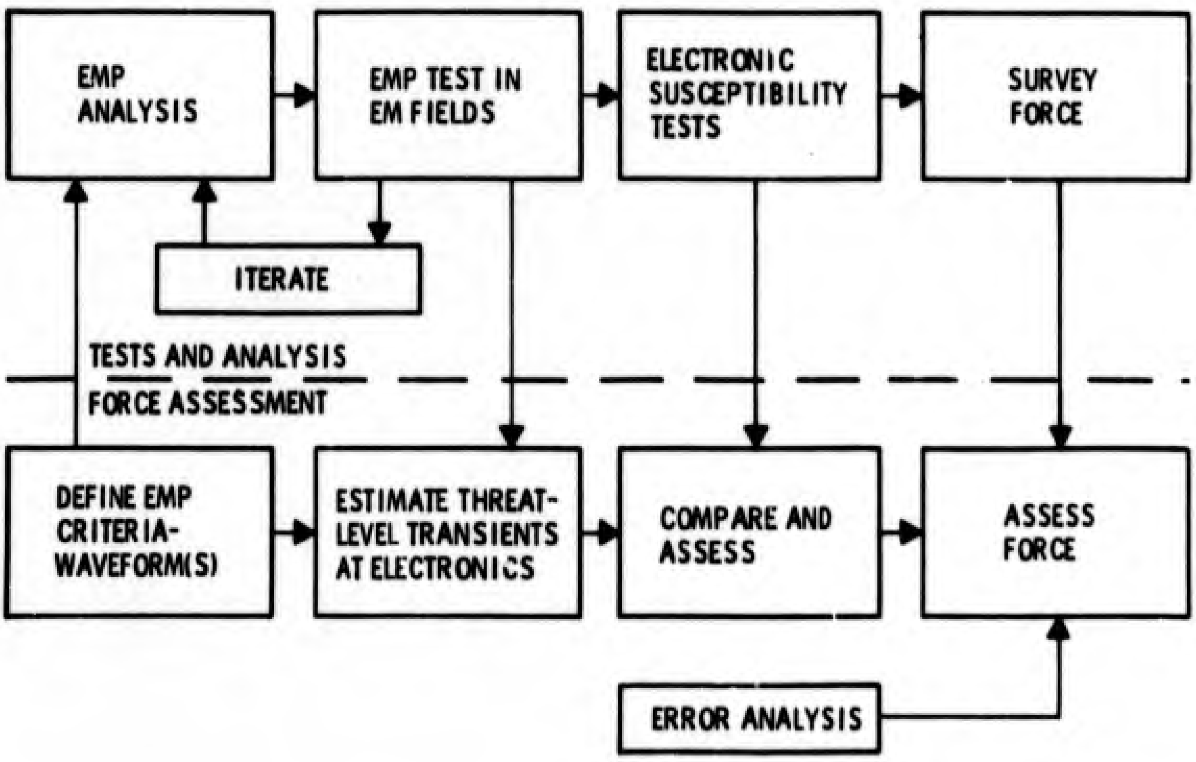


Figure 13. EMP Program Flow

017

TYPE	FUNCTION
1. EM COUPLING TESTS (TOTAL SYSTEM IN EMP SIMULATOR)	1a. VALIDATE THEORETICAL PREDICTIONS OF DOMINANT SKIN CURRENTS AND COUPLING TO INTERNAL CABLES 1b. TO EXPERIMENTALLY ASSESS COUPLING VARIABLES
2. ELECTRONIC THRESHOLD TESTS (SYSTEM, SUBSYSTEM AND CIRCUIT)	2a. TO DETERMINE ELECTRONIC SUSCEPTIBILITY LEVELS TO TRANSIENT STIMULI 2b. TO DETERMINE SYSTEM FAILURE-MODES AND FAILURE MECHANISM 2c. TO VALIDATE CIRCUIT/SYSTEM ANALYTICAL MODELS
3. QUALITY ASSURANCE	3. TO ASSURE HARDNESS DURING MANUFACTURE
4. SYSTEM-LEVEL HARDNESS VERIFICATION	4. TO DEMONSTRATE TOTAL SYSTEM HARDNESS TO CRITERIA-FIELDS FOR AT LEAST SOME CASES OF INTEREST

Figure 14. Types of EMP Tests

ENVIRONMENT

- POLARIZATION, DIRECTION-OF-ARRIVAL, WAVEFORM, ETC

SYSTEM PHYSICAL CONFIGURATION

- POSITION OF DOORS, ACTUATORS, ETC
- LOCATION OF VEHICLE WITH RESPECT TO GROUND
- PRESENCE OF SUPPORT EQUIPMENT

SYSTEM ELECTRICAL CONFIGURATION

- POSITIONS OF RELAYS AND SWITCHES
- THE STATE OF THE ELECTRONICS WHEN TRANSIENTS ARRIVE
  - OPERATING MODE
  - FUNCTION BEING PERFORMED

SYSTEM SUSCEPTIBILITIES

- MISSION-CRITICAL FUNCTIONS
- DEPENDENCE ON EXTERNAL SUPPORT FUNCTIONS

Figure 15. Types of Variables

018

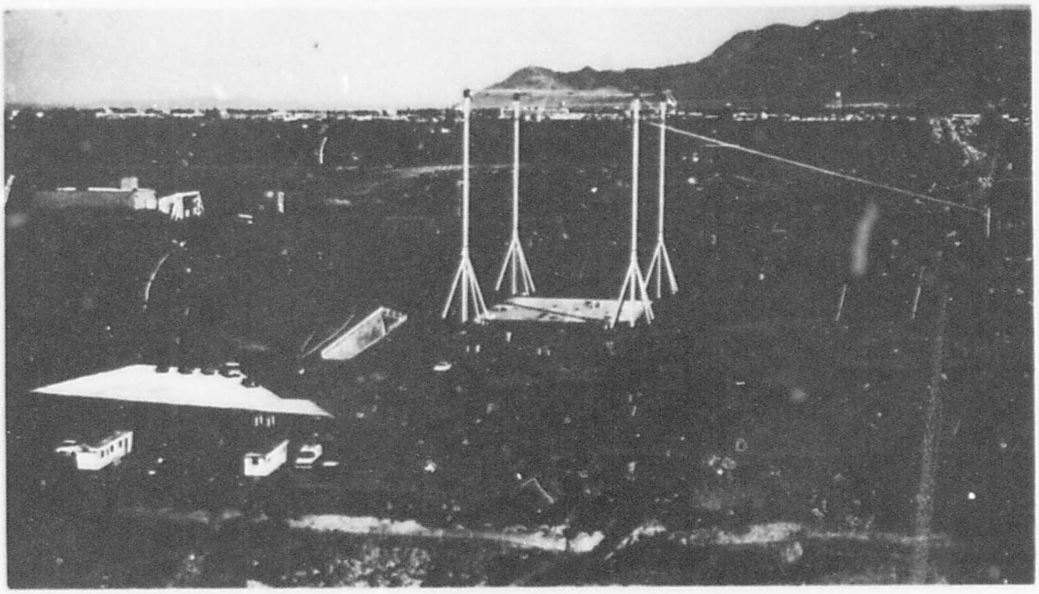


Figure 16. ARES Test Facility

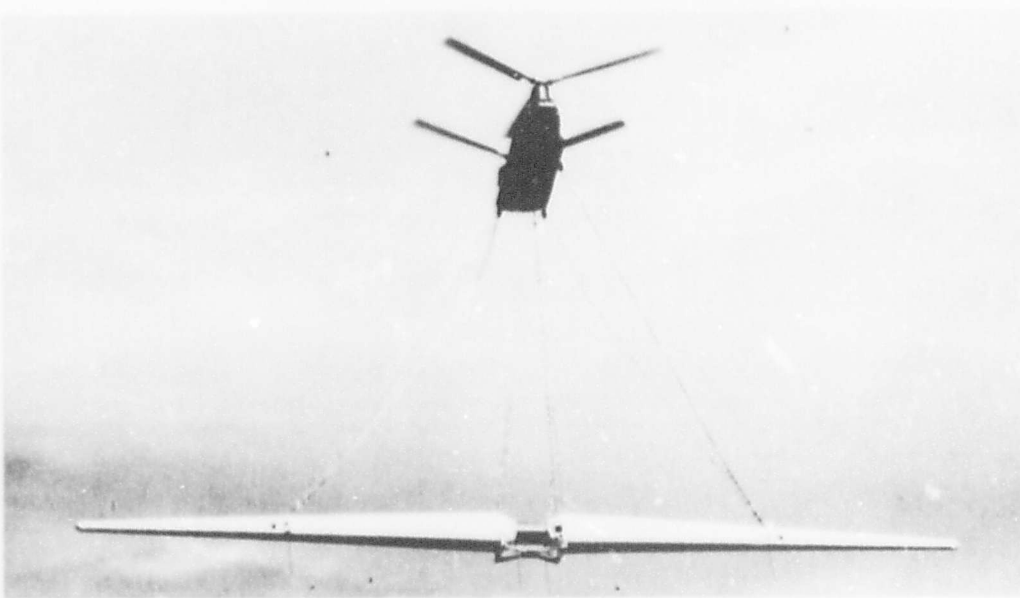


Figure 17. Horizontal RES 1 Simulator in Flight

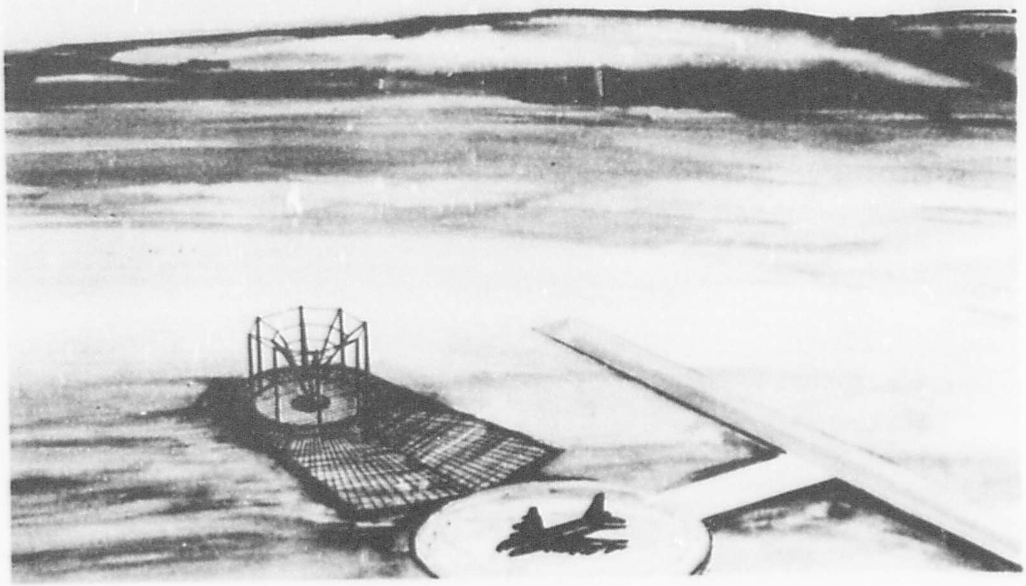


Figure 18. Vertical Dipole Simulator

Figure 19. Horizontal Dipole Simulator

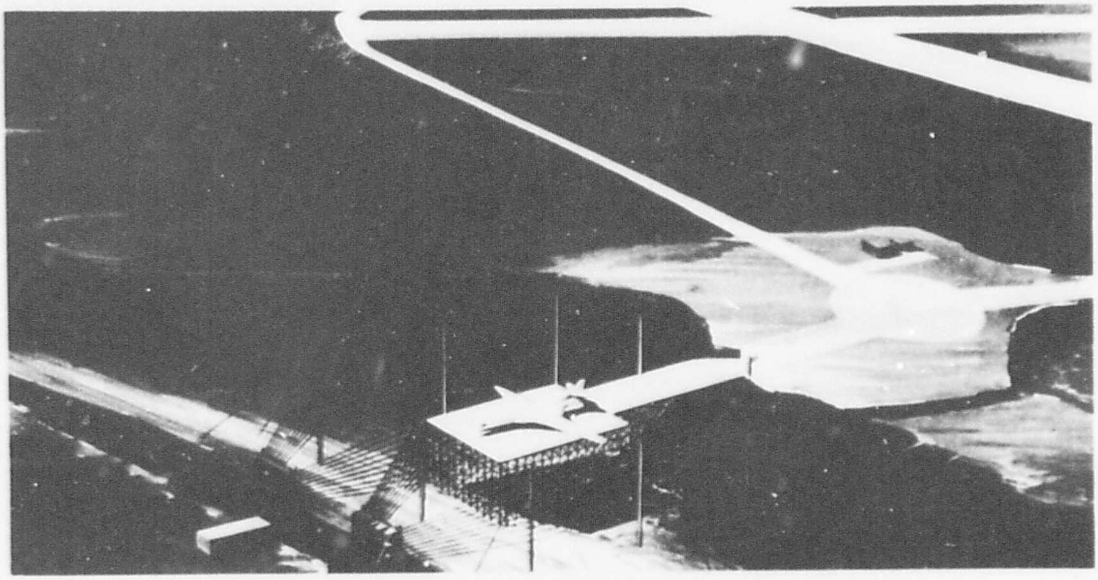


Figure 20. B-1 Testing in Trestle

Another type of testing required for EMP is the susceptibility, or threshold, testing of electronic systems, subsystems or circuits. For testing total systems, major subsystems or black-boxes, a technique known as direct-drive is used. This technique uses special pulse generators which can synthesize complex waveforms and produce high currents to magnetically or electrostatically couple transients into cables which accurately simulate the total-system EMP environment (see Figure 21). Circuit tests (see Figure 22) are performed primarily to validate the circuit analytical models (computer models) and to verify the expected circuit failure-modes.

Quality assurance tests are very important if the hardware is to meet system requirements. Shielded cables should be tested to verify that the desired shielding effectiveness has been achieved. This is not as simple as it sounds. Valid tests can only be achieved when the electrical stress on the shield can be properly controlled. A technique known as RAMS* has been applied to the problem of measuring cable shielding effectiveness (see Figure 23). This technique installs production cables into a carefully-designed trough to provide a coaxial configuration. All standing-waves are eliminated by the trough and by the load impedances built into the trough. A swept-CW excitation then quickly scans and plots the attenuation curve versus frequency. The technique is fast, efficient, repeatable and accurate.

---

* For Rapid Attenuation Measurement System.

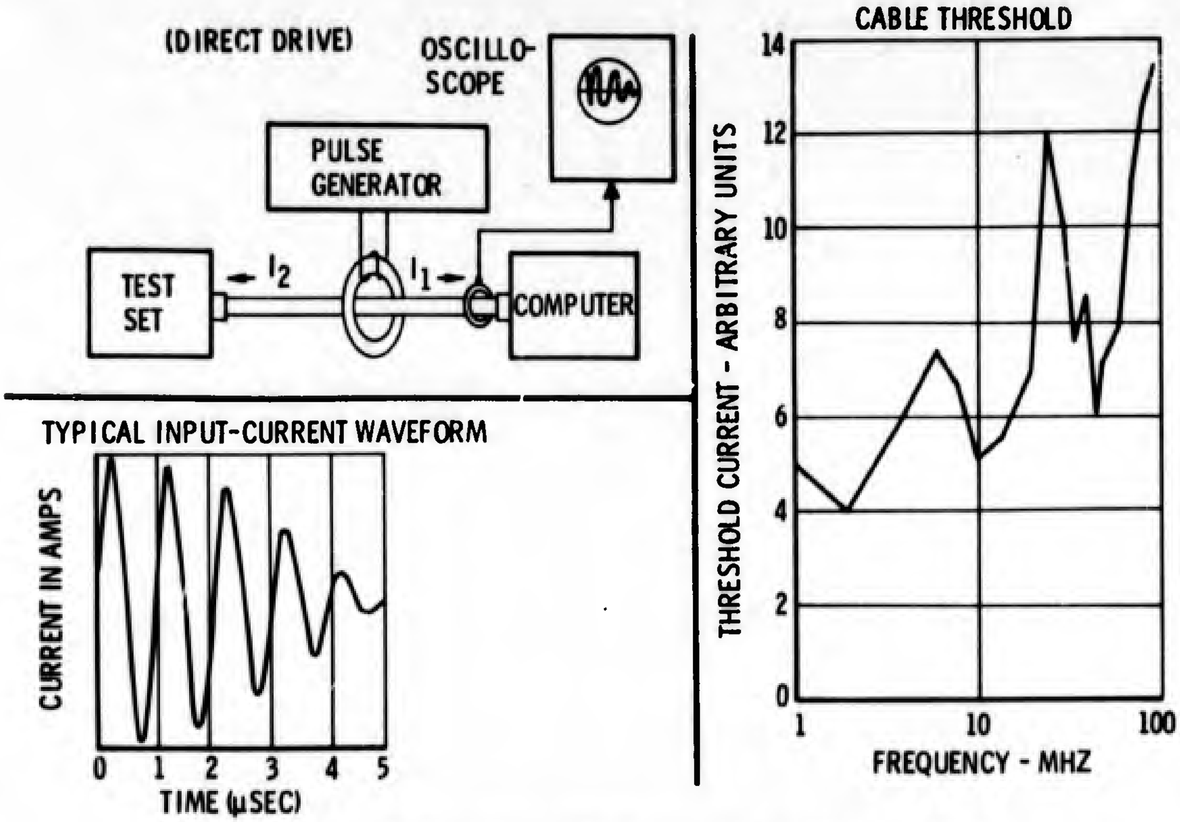
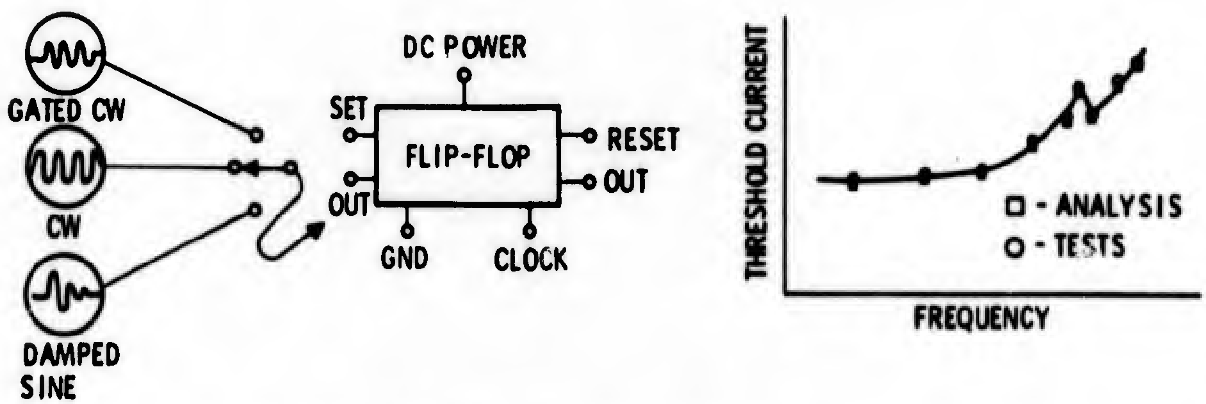


Figure 21. Electronic Susceptibility Threshold Tests



PURPOSE IS TO VALIDATE ANALYTICAL CIRCUIT MODELS

- TO IDENTIFY DIFFERENT FAILURE MODES (BY EXCITING DIFFERENT PORTS)
- TO DISCOVER AND EXPLAIN WAVEFORM DEPENDENCE ... SUCH AS STACKING
- TO DETECT UNEXPECTED CIRCUIT RESONANCES
- TO DETECT DAMAGE THRESHOLDS

Figure 22. Circuit Tests

022

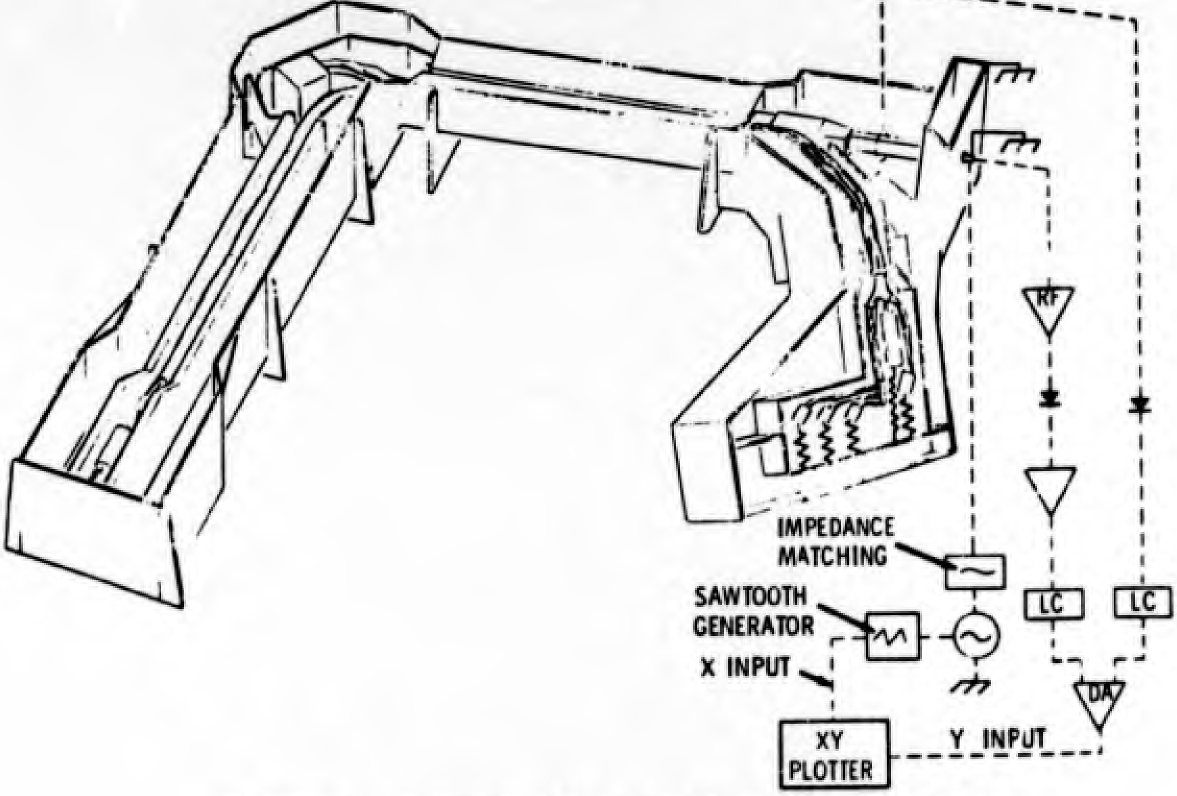


Figure 23. Example of Quality Assurance Technique

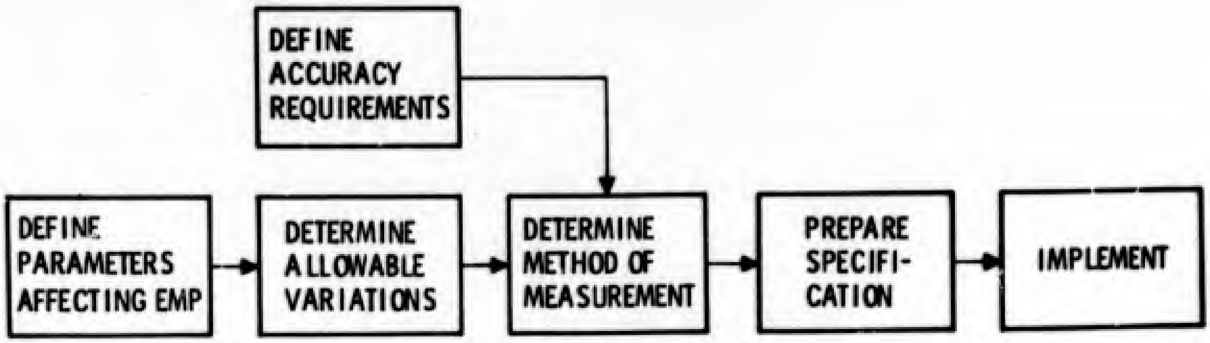
Many other elements of the system must be controlled to achieve reliable EMP-hardness. Figure 24 shows some of the steps in deciding what to control and how to control it. This is indeed a difficult and demanding task as is suggested by the list of problems shown in the figure.

Electronic susceptibility quality-control can be maintained by conducting direct-drive tests on electronic black-boxes and by component vulnerability controls during production. Many other controls may be necessary, depending on the system.

Hardness proof tests are still another class of test. In these tests EMP simulators are used (as in the EM-coupling tests) but for the proof-tests it is important that the simulator be capable of achieving the full-threat-level (or more), whereas EM coupling tests can often be performed with low-level pulses.

The test techniques have evolved over the past years and have achieved a relatively high degree of sophistication. CW-systems have been devised which can automatically measure the EM-coupling transfer-functions directly. Pulse-data data-reduction has reached a high plateau of development. Simulation techniques, both in the field and in the laboratory, have become very highly developed. It is possible today to test virtually any system.

023



PROBLEMS

- LARGE NUMBER OF PARAMETERS
- VARIABILITY AT HIGH-FREQUENCIES CAN BE LARGE
- MEASUREMENT ACCURACY AT HIGH-FREQUENCIES IS MARGINAL
- METHODS OF MEASUREMENT OFTEN DON'T EXIST
- SEMICONDUCTORS ARE NOT BEING HARDENED TO EMP
    - ALMOST NO EMP ACCEPTANCE TESTS EXIST
    - FEW COMPONENTS WERE DESIGNED TO BE EMP HARD
- MUCH DEPENDS ON CAREFUL FINAL ASSEMBLY

Figure 24. Quality Assurance

024

V. TYPES OF EMP HARDENING

There are at least five different classes of EMP hardening (see Figure 25). Shielding is very important since it is the principal means of preventing electronics burnout or permanent damage. It also makes the internal currents small enough to make arcing and other non-linear effects unlikely. Shielding can also make the task of filtering or limiting much easier by keeping current and/or voltage levels down to a reasonable magnitude.

Voltage limiting is also very useful for protection on power-lines, long-signal lines, antenna inputs and other devices which cannot be shielded.

Filtering is a valuable adjunct to shielding. The combination can be more effective than the use of either alone. Although there are many possible types of filters, the hybrid or lossy filters are generally, but not always, best since they tend to absorb the energy rather than simply reflecting it elsewhere. Some electrical connectors are now available which contain built-in filters that show great promise for EMP hardening. Arcing in choke-input filters can be a problem, as can saturation of inductor-cores by system dc currents. It must be remembered, of course, that filters can never solve a problem where the offending noise is within the necessary operating bandwidth of the system bothered.

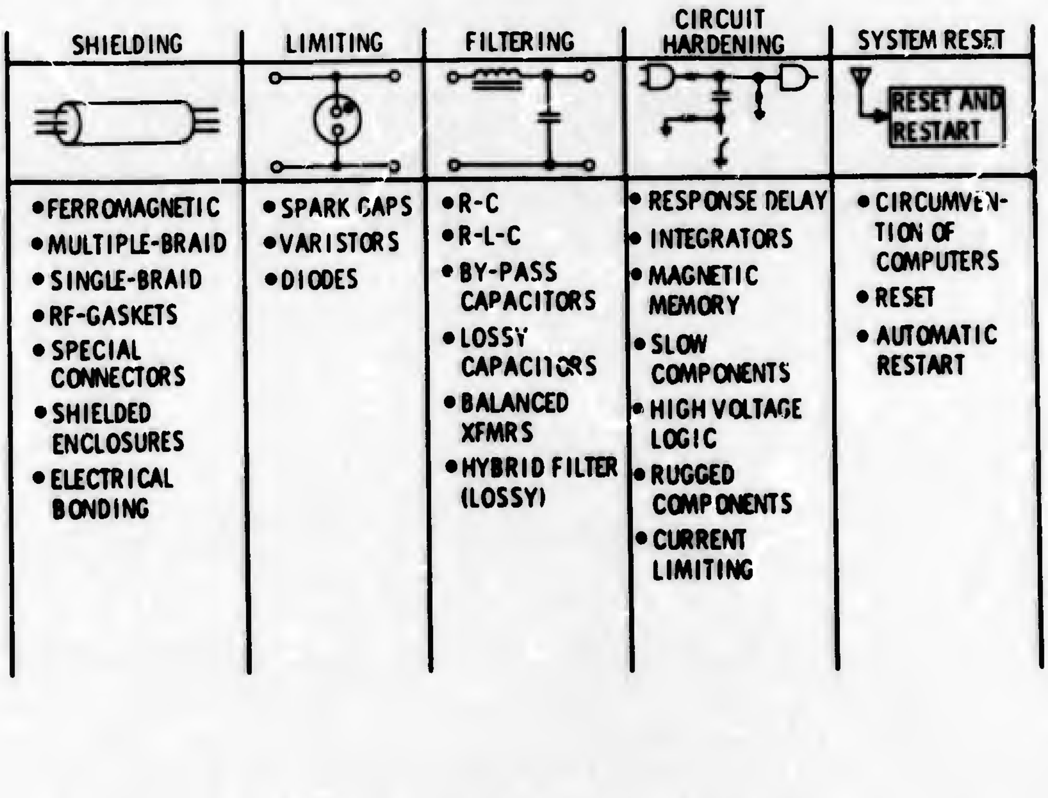


Figure 25. Types of EMP Hardening Techniques

025

Circuit hardening can be of considerable help in the design of new, EMP-hard systems. In general, techniques which reduce the high-frequency response are desired, as are rugged components. Circuits which have a delayed response which requires the input remain ON for a finite time are very good. Circuits should be protected from excess collector current by resistance in the collector circuit wherever possible.

Fast digital circuits are generally the most vulnerable to transient upset and must be given special attention. Flip-flops with a magnetic core in the collector circuit have been devised which delay the response enough to provide resistance to short-duration (microsecond) transients. Computers can be made more resistant by voting techniques or other software "forgiveness-routines".

Another hardening technique against logic-upset in digital systems is an automatic restart, reset, or circumvention technique. These systems sense the environment and, when threatened, go into a recovery mode for rapid recovery. This technique, though effective, often has the disadvantage that overall system performance may be degraded in the presence of repeated interruptions. It does not, of course, protect against permanent damage if electrical overstress is severe.

VI. ASSESSING THE EMP HARDNESS OF SYSTEMS

In the EMP Program Flow (Figure 13) presented earlier, a distinction was made between tests, analysis and assessment. Assessment is the task of combining all of the data into a meaningful system EMP-hardness conclusion with due consideration for the statistical implications of data errors, system-to-system variations and random variables.

To get some idea of the characteristics of this task some examples are presented here. The typical EMP waveform shown in Figure 26 is representative of some classes of systems. Obviously the transient waveform is complex, contains many frequencies and its effect on a particular circuit is not obvious. The computer models of circuits can be used to determine the susceptibility of the circuit to that waveform. Obviously simulation of such a waveform in the laboratory would be difficult, though not impossible.

It is often useful to obtain more general descriptions of system characteristics in the form of transfer functions which can thereafter be used to predict responses to various input stimuli. Measured transfer functions (such as Figure 27) give a good feel for the behavior of the system. These functions must be measured in terms of the amplitude and phase at each frequency (only the amplitude is shown in Figure 27).

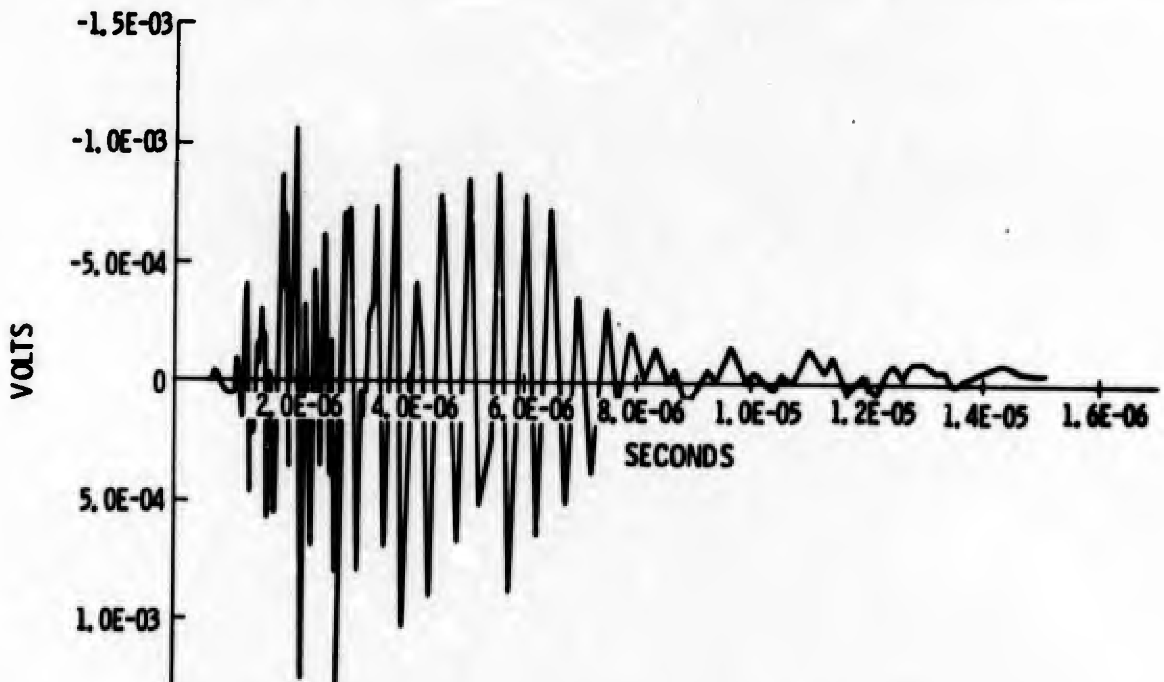


Figure 26. Typical Time-Domain Waveform

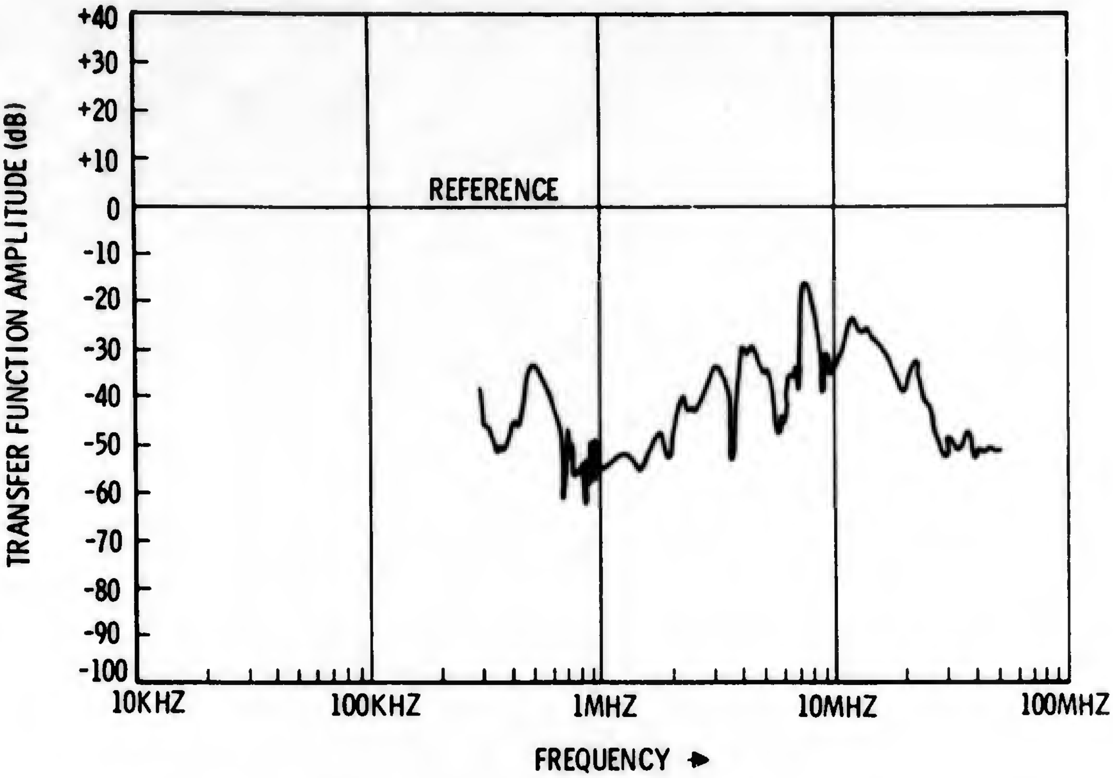


Figure 27. Typical Amplitude Transfer Function from External Field to Cable Current

Next a survey of the coupling into other samples must be considered to get some measure of the system-to-system variability. Figure 28 shows an overlay of three such sample measurements of one system. Experience has shown rather large variations can exist from one sample to another.

In analyzing and combining the data, it is important to estimate the errors associated with the data. Some sources of error are noted in Figure 29. For example, in the transforming of time-domain pulse data into the frequency-domain using the Fourier transform, sampling errors and other errors can propogate into the frequency-domain as rather large uncertainties in the transformed function (see Figure 30). Notice, however, that the errors are indeed small at the dominant frequency of 3-MHz.

In digitizing polaroid photographs for data-reduction and analysis, for another example, rather large errors can be introduced into the transform due to a very small vertical offset of the horizontal trace. Obviously even small offsets tend to destroy the validity of the low-frequency portion of the transformed data since the transform of the offset error can exceed the level of the desired function (see Figure 31).

Next, by comparing the expected levels of EMP induced transients, at each piece of electronics, against the measured or predicted thresholds-of-vulnerability of each piece, a hardness conclusion can be reached for one sample of the system. This may take the form of deriving a system probability-of-failure curve based on the combination of subsystem data (see Figure 32).

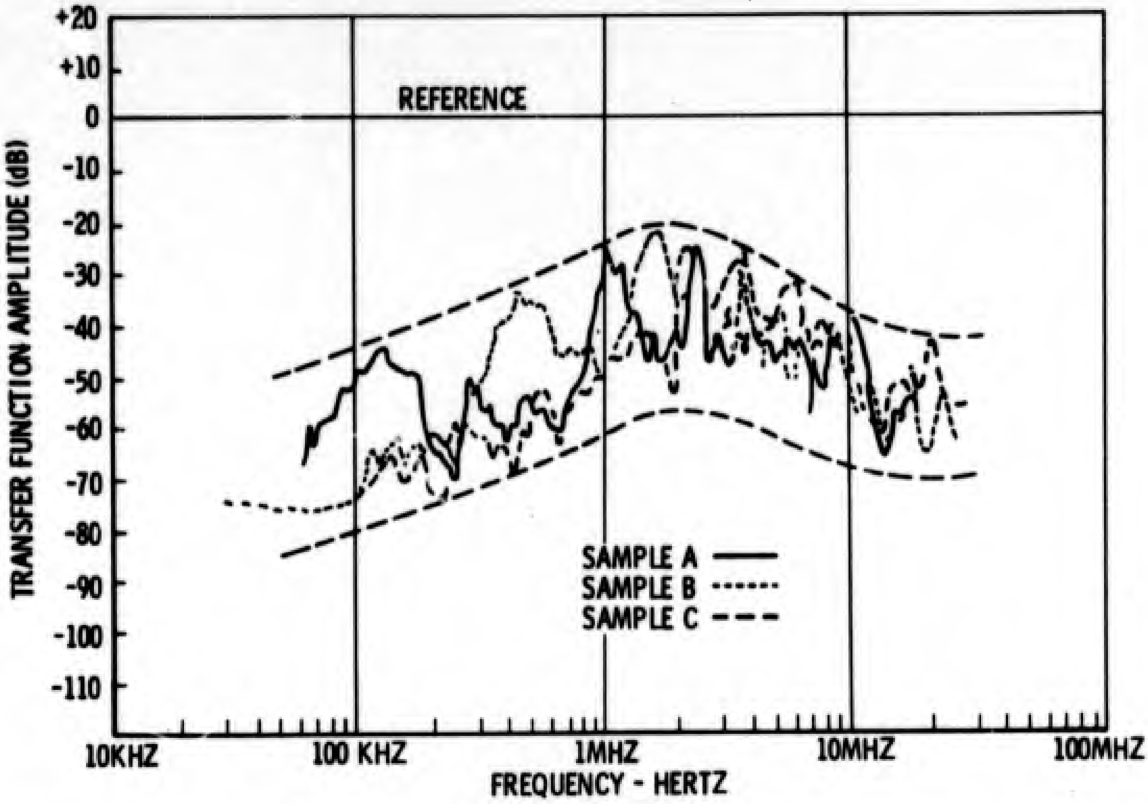


Figure 28. Example of System-to-System Coupling Variations

SOURCES OF ERRORS

- INSTRUMENTATION ERRORS
- DATA REDUCTION ERRORS
  - DIGITIZATION ERRORS
  - TRANSFORM ERRORS
  - CONVOLUTION ERRORS
  - INVERSE TRANSFORM ERRORS
  - ETC
- ASSESSMENT ERRORS
  - UNCERTAINTIES IN THREAT-LEVEL
  - UNCERTAINTIES IN SYSTEM THRESHOLDS

GOALS OF ERROR ANALYSIS

- PUT UNCERTAINTY BOUNDS ON ALL DATA
- DEVELOP BASIS FOR CONFIDENCE-LIMITS OF FINAL ASSESSMENT

Figure 29. Error Analysis

029

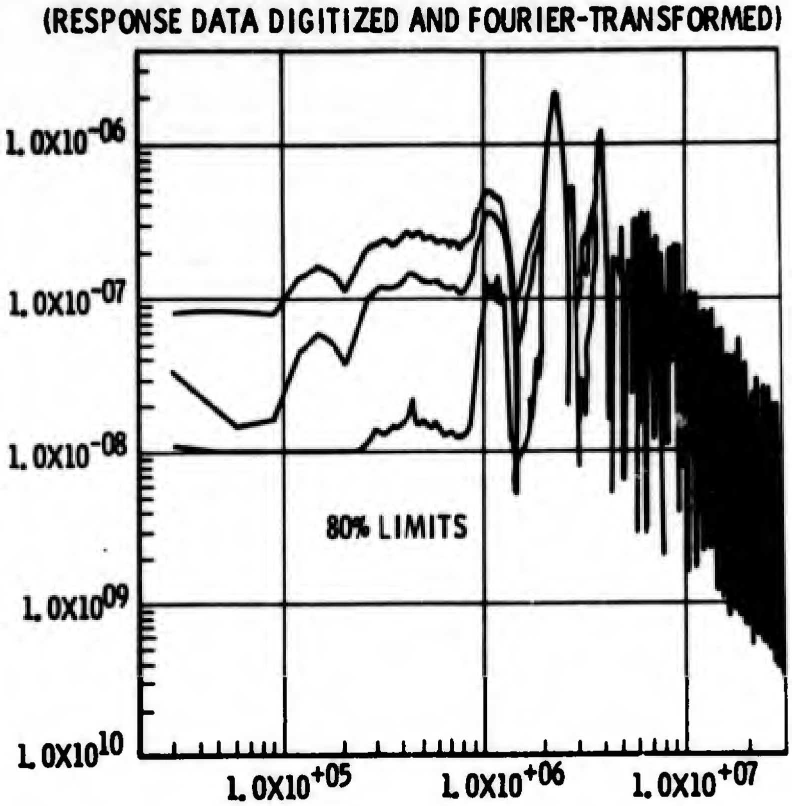


Figure 30. Typical Error-Bounds on Processed Pulse-Data (Response Data Digitized and Fourier-Transformed)

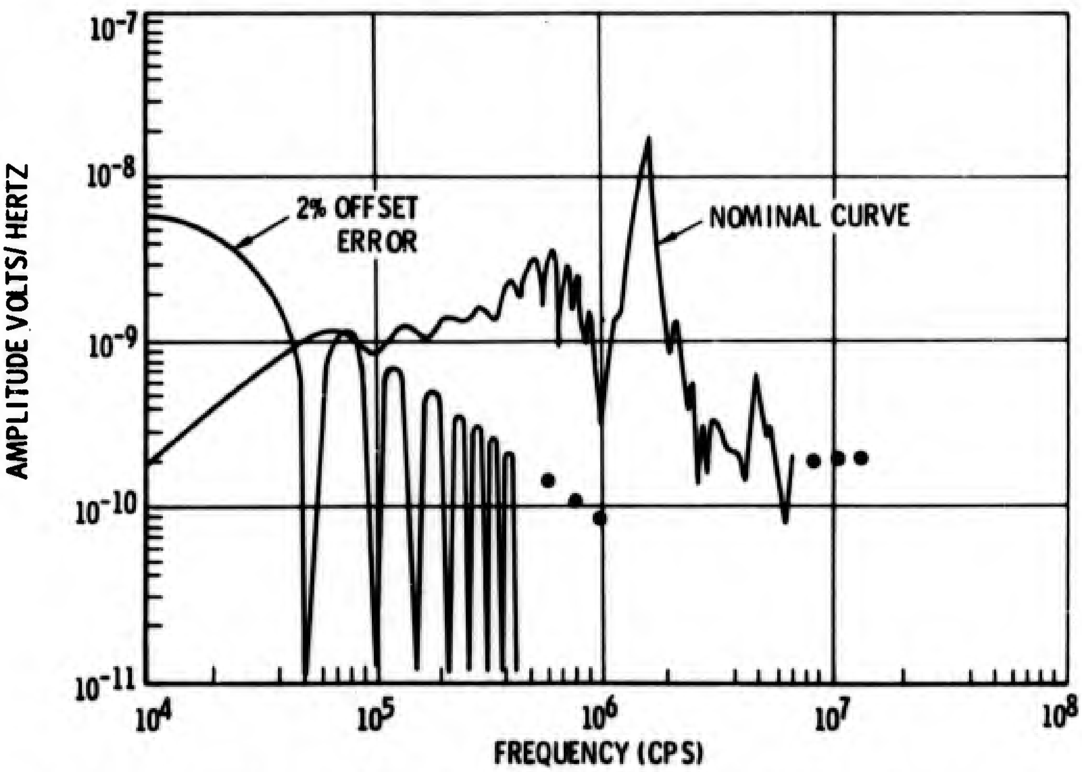


Figure 31. Example of Errors Due to Oscilloscope Trace dc-Offset

030

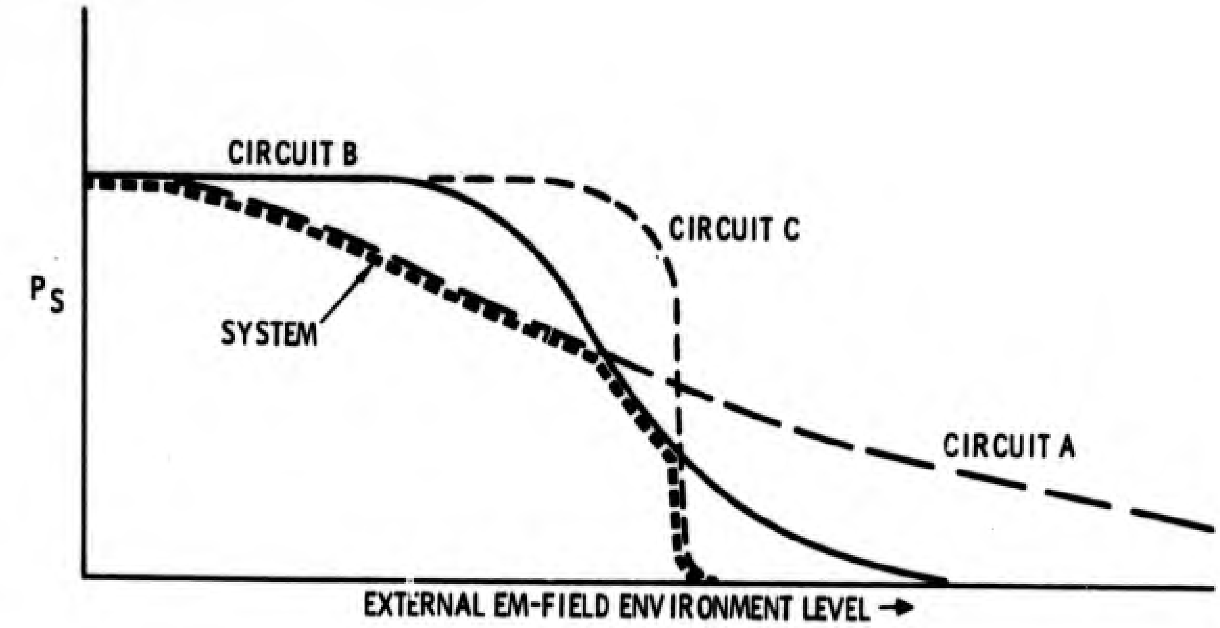


Figure 32. Assessment of One System

Finally the overall EMP hardness conclusion for the force can be derived from statistical estimates of the EMP-coupling transients (with their uncertainties) against the statistical probability-of-failure curve for the electronics (including uncertainties) as is simply portrayed in Figure 33.

031

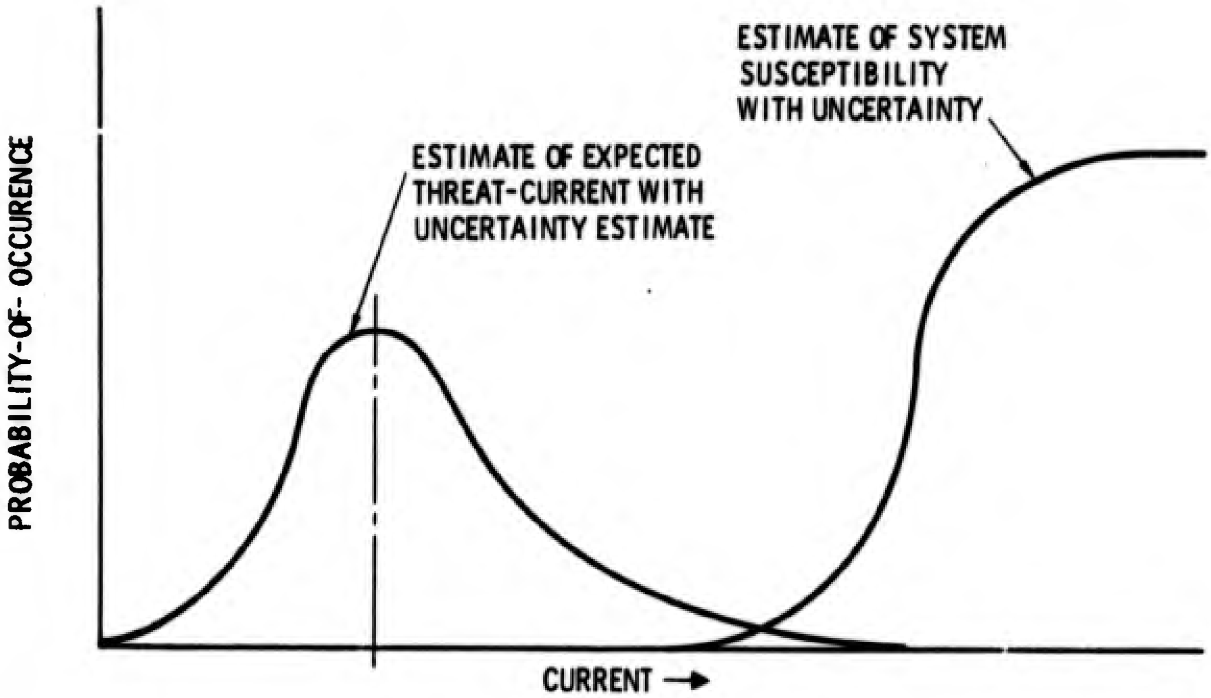


Figure 33. Force Assessment

032

VII. SUMMARY

It can be seen that the EMP environment generated by a nuclear weapon burst can be large in amplitude, cover a wide frequency spectrum and have a large radius-of-effect.

The system response is seen to be a total system response not understandable on a component basis alone. Analytical techniques are available for predicting these system effects. Tests are used to validate the analysis and to verify hardness conclusions.

Quality control techniques are important. Setting up the quality control program is a difficult but rewarding task.

EMP hardening techniques are discussed with some remarks on the limitations of some of the techniques.

Finally, assessment of the force is discussed including the problem of error analysis, statistical sampling, and combination of the test and analysis data.

VIII. SOME REFERENCES FOR MORE INFORMATION

1. Theory of Linear Antennas, R. King, Harvard Press, 1956 (Cylindrical Antenna Theory).

2. Theory of Diffraction by Small Holes, H. A. Bethe, The Physical Review, Vol 66, 1944. (Aperture Theory)

3. Transmission-Lines Texts (any)

4. Circuit Analysis codes for small circuits (TRAC, CIRCUS, SCEPTRE, ETC.)

5. Circuit Analysis codes for large networks (SECURE, CONNECT, TRAFFIC)

6. DNA EMP Handbook (soon to be released; classified), DNA Hq. Wash., D.C.

7. The Analysis of the Effects of an Electromagnetic Pulse on Missiles and Aircraft, Sandia Corporation, D. Merewether, Ed. (soon to be published), Kirtland AFB, Albuquerque, N.M.

8. AFWL EMP Note Series, Air Force Weapons Laboratory, Kirtland AFB, Albuquerque, N.M., Dr. Carl Baum, Ed. (Several series including (1) Sensors and Simulation, (2) Interaction Notes (EM coupling) (3) Theoretical Notes (environments) and many more (a continually expanding series).