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PROJECT ADMINISTRATION DATA SHEET

[x] ORIGINAL [ ] REVISION NO. ______

Project No. A-3572 GTRI/GIT DATE 6 / 27 / 83

Project Director: D. P. Millard School/Lab ECSL

Sponsor: Army/Construction Engineer and Research Lab

Type Agreement: P. O. No. DACW88-83-M-0840

Award Period: From 6/9/83 To 12/7/83 (Performance) 12/7/83 (Reports)

Sponsor Amount: This Change Total to Date

Estimated: $ ______ $ 24,947 (fixed price)

Funded: $ ______ $ 24,947

Cost Sharing Amount: $ ______ Cost Sharing No: ______

Title: High Altitude Electromagnetic Pulse (HEMP) Criteria

ADMINISTRATIVE DATA

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Defense Priority Rating: DO C-2 Military Security Classification: N/A

(or) Company/Industrial Proprietary: ______

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Date December 15, 1983

ject No. A-3572 ~~XXXXXX~~/Lab ECSL

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onsor Army/Construction Engineer and Research Lab

le High Altitude Electromagnetic Pulse (HEMP) Criteria

ective Completion Date: 12/7/83 (Performance) 12/7/83 (Reports)

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- [ ] None
- [X] Final Invoice ~~XXXXXXXXXXXXXXXX~~ (Fixed Price)
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HIGH ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION CRITERIA FOR C^3 POWER PLANTS IN A COLD WAR ENVIRONMENT

Final Report A-3572

Contract No. DACW88-83-M-0840

HIGH ALTITUDE ELECTROMAGNETIC PULSE (HEMP) PROTECTION CRITERIA FOR C^3 POWER PLANTS IN A COLD WAR ENVIRONMENT

Final Report

Project A-3572

Contract No. DACW88-83-M-0840

November 1983

by

D. P. Millard
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Prepared for

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FOREWORD

This final report was prepared by the Engineering Experiment Station of Georgia Tech under Contract No. DACW88-83-M-0840, Georgia Tech Project No. A-3572. The work described in the report was directed by Mr. D. P. Millard, Project Director, under the general supervision of Mr. H. W. Denny, Chief of the Electromagnetic Compatibility Division. The report was authored by Mr. Millard, Mr. J. A. Woody, and Mr. J. K. Daher.

1.0 INTRODUCTION

1.1 Program Objective and Scope

This report describes the research activities performed during the period 9 June 1983 to 7 December 1983 under Contract No. DACW88-83-M-0840, "High Altitude Electromagnetic Pulse (HEMP) Criteria." The basic objective of this program was to provide technical support for Appendix A, "High Altitude Electromagnetic Pulse (HEMP) Protection Criteria for C^3 Power Plants in a Cold War Environment" of the Power Reliability Enhancement Program (PREP) Design Features Manual (DFM) for Major C^3 Power Sytems. To accomplish this objective, program efforts were directed to two basic tasks:

(1) Identify, evaluate and provide relative cost analyses of all known EMP acceptance test techniques as they would apply to C^3 Power Plant testing,

(2) Determine the susceptibility of representative C^3 Power Plant components from existing in-house data, a literature search for additional data and by testing of components for which no data exists.

The scope of the research was a "first look" at the HEMP evaluation of fixed C^3 Power Plants. The design features of the C^3 Power Plant, which includes the HEMP threat, will be delineated at a future date by others.

1.2 Background

The Design Features Manual (DFM) for Major Fixed C^3 Power Systems is being prepared by the U.S. Army Corps of Engineers for the Department of the Army, Executive Agent for the Power Reliability Enhancement Program, under the auspices of the Joint Chiefs of Staff (JCS), Director of C^3I. It is the intent of the Director, JCS/C^3I to issue the Design Features Manual to all services as a DoD Manual. The thrust of the DFM is to present a system philosophy, design criteria by engineering discipline, an exemplary benchmark power plant concept, and an availability/reliability (A/R) evaluation of that concept. Overall reliability will be achieved through the application of sound engineering principles, the selection of quality components, and the redundancy of critical components.

To achieve this goal, features were identified which, when applied to the design of a major fixed C^3 power system in an environment free from man-made threats, will result in a highly reliable system. Appendices under development will treat design features which, when applied to the baseline case, will result in the enhancement of C^3 Power Plant reliability in threat environments including physical attack by terrorists and saboteurs, chemical-biological-radiological (CBR) attack, and high altitude electromagnetic pulses.

In the development of Appendix A, "High Altitude Electromagnetic Pulse (HEMP) Protection Criteria for C^3 Power Plants in a Cold War Environment," such areas as

(1) Weld/Seam Quality,
(2) EMP Protective Features,
(3) Susceptibility of Power Plant Components,
(4) Hardness Maintenance/Hardness Surveillance,
(5) Fiber Optics for Plant Application,
(6) EMP Acceptance Testing, and
(7) Design/Hardness Assessment

must be considered to ensure that the HEMP threat is properly addressed over the life cycle of the C^3 Power Plant. The major questions which are asked relating to HEMP hardness are:

(1) How susceptible are typical C^3 Power Plant components to HEMP?
(2) How does one test to determine the HEMP hardness levels at the entrance point to various C^3 Power Plant components and systems?

To answer these questions, the C^3 Power Plant must be studied to determine which systems/subsystems are critical to the A/R of the plant, which components within the systems/subsystems are most susceptibile to HEMP, and the levels at which component performance/reliability is affected. Also, known EMP acceptance test techniques must be studied and evaluated to determine their relative merit in C^3 Power Plant HEMP testing.

1.3 Report Organization

The material which follows in this report is divided into three major sections, Sections 2 through 4. Section 2 identifies, evaluates and provides cost analyses of all known EMP acceptance test techniques. Section 3 identifies critical system components and provides a technique for determining the susceptibility of each component.

2.0 EMP ACCEPTANCE TEST TECHNIQUES

EMP acceptance test techniques generally fall into two categories: 1) field illumination, and 2) direct injection. Each category has merits and is important in the life cycle of the fixed C^3 power plant testing. The field illumination test is used to determine the interaction of EMP with the facility and its systems, whereas the direct injection test is used to determine the effect of EMP on a particular system and its components. The configurations, merits, and relative costs of commonly employed field illumination and direct injection test techniques are summarized in the following sections.

2.1 Field Illumination Tests

A field illumination EMP test is one in which the test object is exposed to an electromagnetic field and specific responses of the test object are monitored. In the case of a power system for a fixed C^3 installation, the test object is the power system facility which includes the total power switching, conditioning, and on-site generating system. The electromagnetic fields used for the tests can vary from low level CW fields to threat-level, pulsed fields. Test sources and configurations may range from low power CW signal generators and small antennas to large multi-megavolt EMP simulators.

The specific responses which must be monitored during field illumination tests of C^3 power systems must be chosen to ensure compliance with the pass/fail criteria for the system. These criteria are specified to ensure that the system will continue to supply power to all critical loads when exposed to an EMP environment. Hence, the location of the response monitoring points depend on the criteria which is specified. Typical responses that may be monitored include the levels of the resultant EM fields inside the facility, the levels of the resultant currents (or voltages) on interconnect cables in the facility, and the performance of the power system during all operational phases.

2.1.1 Test Sources/Configurations

A large number of energy sources exist for performing field illumination tests of a facility. The type of source used for a particular test depends on a variety of factors including the objective of the test, the nature of response being evaluated (based on the specified pass/fail criteria), and whether the response being monitored is linear or nonlinear. If the objective is to evaluate a specific response (including nonlinear effects) to an EMP environment with a single test, then a large EMP simulator capable of generating a threat level environment must be used. For tests to evaluate linear characteristics where no arcing, breakdown, or saturation are involved, low power CW sources are usually adequate.

The two basic classes of field illumination sources are pulsed and CW. The pulsed sources of EM fields used for conducting facility acceptance tests are in the form of transportable EMP simulators. The simulators are transportable in that they can be moved to a test site, assembled, and operated. After the tests are completed, the simulators can be disassembled, relocated, and used again at another facility. The transportable simulators range in size from those that must be transported by several tractor trailers to ones that can be transported in a station wagon.

The transportable simulators include the static, radiated, hybrid, and bounded wave (transmission line) simulators.* The static simulator is not a radiating type and the test object is located within or very close to the simulator. In its simplest form, the static simulator is used to produce a single E-field or H-field component incident on the test object. It is appropriate for driving very small test objects and penetrations on larger test objects with highly conducting surfaces, particularly if only the perpendicular E-field or H-field is important. Its application is limited to lower frequencies where the wavelengths are large compared to the dimensions of the simulator and the test object.

The radiating simulator may be either a dipole or long-wire antenna. These simulators have an energy source, a biconical matching section located

*C. E. Baum, "EMP Simulators for Various Types of Nuclear EMP Environments: An Interim Categorization," IEEE Transactions on Electromagnetic Compatibility, Vol. EMC-20, No. 1, February 1978, pp. 35-53.

at the antenna center, and a wire structure that forms the antenna arms. The wire structure may be resistively loaded or have distributed impedance loading along the arm length. An important advantage of the radiating simulator is that the test region is not directly limited by the structure's dimensions. The disadvantage of such a simulator is that only a fraction of the available energy is directed to the system-under-test due to the relatively nondirectional characteristics of the dipole antenna. Futhermore, there is a geometrical 1/R attenuation of the radiated field amplitude with distance. This attenuation requires a difficult tradeoff between field level and field planarity. If the distance between the radiating simulator and the test object is small relative to their dimensions, then the resulting field is not a plane wave and unwanted interactions may occur. On the other hand, if the separation distance is increased, the resulting field amplitude at the test object may not be sufficient to perform meaningful tests.

For the dipole radiating simulator, the polarization and angle of arrival can be changed by positioning the dipole. For the long-wire antenna, the available polarization is predominately horizontal on the line normal to the dipole axis and through the feed point of the bicone. Angle of arrival from the long-wire is changed by changing the position of the system-under-test.

Hybrid simulators are constructed by combining the features of radiating and static (low-frequency) simulators. On a hybrid simulator, the high-frequency portion of the waveform is radiated from a relatively small part of the overall simulator, while the low-frequency portions of the waveform are associated with the currents and charges distributed over the entire structure. Thus, both low and high frequency performance is obtained.

The bounded wave simulator excites and guides an electromagnetic wave in a transmission line. The system or facility being tested is located within the transmission line and is exposed to the excited electromagnetic wave. The essential elements of this simulator include an energy source, transition sections, a test volume, and a termination. A transverse electromagnetic (TEM) wave is excited in the transmission line by a pulser or CW generator connected to one end of the line, and the wave propagates to the termination end. The pulser or generator is connected to the transmission line using transition sections having constant impedance. At the termination end, a resistive load absorbs the electromagnetic wave to prevent reflections on the line. To obtain field uniformity in the bounded wave simulator, the system or facility under test must be small in relation to the size of the test volume. The bounded wave simulator is capable of generating high-level fields since the available energy is contained in, or bound to, the space within the transmission line. In general, the bounded wave simulator produces only a single polarization and a single angle of arrival. For smaller systems, different polarizations and angles of arrival can be achieved by rotating the system within the test volume.

Field illumination EMP simulators may be capable of simulating either threat or sub-threat levels. A threat-level simulator can normally generate only one threat-level pulse every 6-10 minutes. These simulators tend to have a high failure rate because of the higher operating voltages. A sub-threat simulator can normally deliver several pulses per minute with a smaller failure rate. The time between pulses and the time between failures are significant factors for facility testing, since these times impact the time necessary for data collection. Many test technicians prefer to work with simulators having a fast repetition rate because it makes data collection easier. On the other hand, most analysts prefer single shot data because they are certain what the incident field was when the data were measured. In general, low-level, fast-repetition simulators are used mostly for diagnostic-type data collection where the quantity of data is important, and threat-level simulators are used for certification-type data collection where quality is more important.

Table I summarizes the characteristics and features of several pulsed field illumination EMP simulators including the TEMPS, REPS, VEMPS, SUITCASE, RES-1, TEFS, and SEIGE 1. Each of these simulators is described briefly below.

The Transportable EMP Simulator (TEMPS) was conceived and specified by Harry Diamond Laboratories (HDL) and sponsored by the Defense Nuclear Agency (DNA). The simulator was designed and constructed by Physics International. The TEMPS is a threat-level, hybrid simulator which takes the form of a biconical wave launcher and a cylindrical wire-cage dipole. The wire cage can

TABLE I

EMP SIMULATORS

SIMULATOR	CONTACT	TYPE	BURST SIMULATED	SIZE (meters)	PULSER VOLTAGE	RISE TIME	PULSE CROSSOVER	PULSE REP RATE	MAXIMUM ELECTRIC FIELD	POLARIZATION
TEMPS	HDL	Pulse Radiating	Exoatmospheric Threat Level	300 L	7 MV	8 ns	800 ns	one pulse per 10 minutes	50 KV/m (50m)	Horizontal on Centerline
REPS	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	300 L	1 MV	5 ns	800 ns	one pulse per 4-60 seconds	8 KV/m (50m)	Horizontal on Centerline
RPC	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	50-300 L	250 KV	4 ns	200-800 ns	one pulse per second	1.8 KV/m (50m)	Vertical
VEMPS	HDL	Pulse Radiating	Exoatmospheric Sub-threat Level	20 H	50 KV	10 ns	65 ns	one pulse per 2-10 seconds	0.4 KV/m (50m)	Horizontal on Centerline
SUITCASE PULSER	AFWL	Pulse Radiating	Exoatmospheric Sub-threat Level	70 L	125 KV	4 ns	400 ns	one pulse per second	0.8 KV/m (50m)	Horizontal on Centerline
RES-1	AFWL	Pulse Radiating	Exoatmoshperic Sub-threat Level	60 L (Hor) 183 L (Vert)	1.6 MV	4-5 ns	70 ns	one pulse per second	3.75 KV/m (100m)	Horizontal on Centerline
TEFS	NSWC (White Oak)	Bounded Wave	Exoatmospheric Sub-threat Level	12 L 6 W 6 H	--	40 ns	300 ns	--	5 KV/m	Horizontal on Centerline
SIEGE	AFWL SAMSO	Transmission Line	Surface	50 L 50 W 30 H	300 KV	10-20 ns	500 ns	--	80 KV/m	Vertical

be varied in length in 100-meter increments to a maximum of 300 meters. The cage is 30 feet in diameter and is supported horizontally above ground on dielectric towers at elevations up to 20 meters as measured from the antenna centerline to ground. The cylindrical cage ends are returned to earth ground through the use of tapered conductor sections and each end of the antenna is resistively terminated.

The TEMPS pulser, located at the midpoint of the wire cage dipole, is a bilateral, gas-insulated pulse generator which drives the 120-ohm biconical wave launcher. In operation, two 35-stage Marx generator-peaking capacitor electrical circuits are dc charged (100 kV maximum) in about 40 seconds. The two pulsers are connected back-to-back and synchronously timed with a jitter of only a few nanoseconds. The generators charge their respective peaking capacitors in about 65 nanoseconds, at which time the preset output switch closes, discharging the pulser in series with the wire-cage dipole. The pulser has an energy content of 6 kilojoules, an overall length of 31 feet, and weighs about 14,000 pounds.

The electromagnetic wave launched from the biconical wave launcher is horizontally polarized when located on a centerline perpendicular to the launcher. The polarization changes as a result of the interaction of the initial EM wave with the nearby earth medium, and the field distribution becomes essentially vertically polarized as the EM wave expands. Basically, each one-half of the dipole acts as a transmission line above a ground plane to yield the vertical polarization. Good wave planarity can be achieved within a test region that measures 50 X 50 meters and is centered on a line perpendicular to the pulser.

The TEMPS is a complete simulator system and includes an instrumentation van, a data recording system, a computer aided handling and analysis system, and support facilities. It is currently in storage and needs refurbishing.

The Repetitive Electromagnetic Pulse Simulator (REPS) was designed and built by Physics International under contract to HDL. The REPS is a transportable, sub-threat level simulator having a variable pulse repetition rate, with intervals being adjustable from 4 to 60 seconds. The simulator was specifically designed to perform field illumination tests on the power plants at SAFEGUARD MSR and PAR sites. The REPS is a horizontal dipole antenna and has a cylindrical wire cage that is nine feet in diameter, and the antenna is supported at a height of 50 feet by a transportable wooden structure. Each end of the wire cage is tapered and terminated in a resistive load.

The REPS pulser has an adjustable output from 750 kilovolts to 1.25 megavolts and produces an output pulse with a rise time of seven nanoseconds and a fall time of 800 nanoseconds. Within the pulser, a 16-stage, triggered Marx generator provides a total usable energy storage capability of 1.7 kilojoules. The unusually fast output rise time is obtained by using a very low inductance pulser output circuit consisting of a 200 pF self-healing gas peaking capacitor in conjunction with a self-breaking spark gap in an atmosphere of sulfur hexafloride. All command and control functions are linked between the pulser and a small trailer via pneumatic lines or fiber optics. Primary power is transmitted from the trailer to the pulser by a high pressure hydraulic line. A hydraulic motor in the pulser drives an alternator which provides all pulser electrical power. These techniques result in complete electrical isolation between the pulser and the ground except at the terminating ends.

The field generated by the REPS is horizontally polarized when observed on a centerline perpendicular to the pulser biconical section. The span of uniform coverage is 25 meters on each side of the centerline at 50 meters from the pulser. Over this test region the peak fields vary less than ten percent. The angle of incidence of the electric field at 50 meters from the pulser is 18 degrees when the pulser is at a maximum height of 15 meters.

The Repetitive Pulse Generator (RPG) was designed and fabricated in-house at HDL for testing various penetrations at SAFEGUARD RSL sites. The RPG was the first wave simulator specifically used to assess the attenuation of large structures. The simulator is designed to be highly portable and adaptable to a wide variety of support structures. Its main function is to provide a high-repetition-rate EMP source for diagnostic and quick-look data. The RPG is a horizontal dipole antenna and has a cylindrical wire cage that is 40 inches in diameter. By adding sections, the length of the dipole can be adjusted between 50 to 300 meters. A pulser containing a Marx generator is used as the energy source and the pulser has a 250-kilovolt output. The pulser can produce one pulse every second. Polarization is horizontal when observed on a centerline perpendicular to the pulser. The span of uniform coverage is dependent upon the particular test setup, and the angle of incidence of the electric field is dependent upon the pulser height relative to the system-under-test.

The Vertical Electromagnetic Pulse Simulator (VEMPS) is a prototype high-frequency, fast rise-time vertical simulator, and was designed to support tests that require predominantly vertical fields on systems such as communication equipment with whip antennas. The VEMPS simulator is a vertical wire cage that is 20 meters high with a cone angle of 56 degrees at the lower apex and an angle of 14 degrees at the upper apex. At its maximum diameter, the wire cage is four meters. The shape of the antenna was designed to give a clear-time of approximately 10 nanoseconds. A 50-foot diameter, aluminum-screen ground plane is used with the antenna cage.

A specially constructed pulser is used to drive the VEMPS, and the pulser is located in a steel reinforced concrete tank under the ground plane. The pulser contains a spark-gap type switch in a sulfur hexaflouride pressurized plexiglass container. In this design, a capacitor bank of 1380 picofarads is charged to a point where the switch self-fires and the resultant voltage is discharged into the apex of the wire cage. The pulser is driven by 110 volts ac which is converted to 50 kilovolts dc. The output pulse is a double exponential with approximately 30 percent undershoot and with a first cross-over at 65 nanoseconds. The free field generated by the VEMPS is uniform around the antenna at any given distance.

The SUITCASE PULSER (SP) is a miniature, transportable, sub-threat simulator with a high pulse repetition rate. The simulator was designed to be completely self-contained, transportable in a station wagon, and to be set up in one hour for tests in remote areas. Its main function is to provide a reliable EMP source for diagnostic tests in areas without electric power or other utilities. A 125-kilovolt pulser is contained within the simulator, and the pulser drives a 30-meter horizontal dipole antenna with a 20-meter wire extending from each end to ground. The output pulse is a double exponential with less than 20-percent undershoot, and the first crossover occurs at 400 nanoseconds. The span of uniform coverage depends on the test setup, and the angle of incidence of the electric field depends on the height of the pulser and the location of the system-under-test.

The Radiating EMP Simulator (RES) was built for the Air Force Weapons Laboratory. The simulator is a lightweight, sub-threat level, high-altitude simulator consisting of a pulse source and a dipole antenna that can be operated while suspended from a helicopter. When the dipole is carried horizontally, a length of 60 meters is used, and when carried vertically a 183-meter length may be used. Ground based versions of the RES also exist, but in this configuration, the ends of the antenna are resistively connected to earth ground. The antenna structure uses a distributed resistive coating to attenuate the antenna current to minimize reflections. A 150-ohm biconical wave launcher is used at the center of the diplole to guide the EM wave from the switch region to the nine-foot cylindrical dipole antenna.

The center of the antenna is fed by a pulser system which consists of a 1.6 Mv Marx generator, a water dielectric transfer capacitor, and an output switch. The Marx generator has 16 stages and is gas-insulated at a few psi in a five-foot diameter aluminum cylinder. The pulser weighs about 3,000 pounds. It charges the water capacitor in about one microsecond. In series with the capacitor is a 100 psi SF_6 switch that self-closes to discharge the system into the antenna. The output waveform is a double exponential pulse. The low frequency content is limited by the short physical length of the antenna. A unique feature of the RES-1 is its ability to provide all angles of arrival since it is airborne.

The Transportable Electromagnetic Field Simulator (TEFS) is a bounded-wave transmission line simulator with multiple feeds that is designed to propagate a transient in the vertical downward direction. Five hundred and seventy-six transition sections, each with a line impedance of 200 ohms, are used. Four transitions are paralleled and driven from a 50-ohm cable.

The cables (144 total) are commonly driven from a single switch and capacitor bank. The 144 sections can be configured in a variety of ways to illuminate an area of 40 X 40 meters. A field of 50 kV/m is provided with a four nanosecond rise time and a decay time constant of 350 nanoseconds. Versions of this simulator are available at the White Sands Missile Range, New Mexico, and the Naval Surface Weapons Center, White Oak Laboratory test facility at Patuxent Naval Air Station.

The Simulated EMP Ground Environment (SIEGE) simulator is a bounded-wave transmission-line type with multiple feeds or transition sections. This simulator is designed to test a buried facility or system. A buried transmission line is employed to propagate low frequencies down into the earth in the vicinity of a buried facility near the ground surface. Vertical rods are used to earth guide a lossy TEM wave propagating downward. At the bottom of the rods, the wave is reflected, but the severe attenuation avoids significant resonant effects. Low-frequency considerations require that the depth of the rods be larger than their spacing, and several times the depth of the facility-under-test. At the top of the transmission line, a current path is provided to connect the two rod arrays to a source. One version of this simulator is at the Air Force Weapons Laboratory.

CW field illumination sources can be employed in several possible configurations. For instance the antenna systems of the pulse simulators described above can be driven by an CW generator. These configurations could be used to evaluate facility shielding effectiveness and to determine facility transfer functions for use in predicting the facility response to HEMP environments.

Another CW configuration includes the use of relatively small dipole or loop antennas driven by CW generators.* A known CW field is established exterior to the facility and the field inside the facility and/or currents and voltages on specified internal interconnect cables are then monitored. This technique is used to evaluate the shielding effectiveness and transfer functions of a facility, to evaluate known penetrations and apertures, and to

*D. M. Ericson, et. al., "Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems," Sandia National Laboratories, NUREG/CR-3069, SAND82-2738/2, Vol. 1 & 2, February 1983.

locate unintentional penetrations and apertures. If the facility shielding effectiveness or facility transfer function (exterior fields to interior currents and voltages) is specified, this technique could be used as part of the acceptance tests to determine if the specifications had been met. It would normally be used in conjunction with injection tests which evaluate other specified criteria. Likewise, the specified EM requirements for penetrations and apertures could be evaluated on a pass/fail basis with this technique.

Recent research* has evaluated historical analytic techniques to determine their validity for converting CW shielding effectiveness test data to values meaningful for EMP radiation hardness evaluations of tactical shelters. The results of this investigation produced recommendations for CW test techniques for use in determining EMP hardness. These recommendations may lead to improved, low-cost methods of assuring EMP hardness.

Another use of the CW measurement technique is in determining if any inadvertant penetrations or apertures exist. While the fields and/or interconnect cable currents are monitored inside the facility, the CW field illumination source is moved around the facility. If undesirable penetrations or apertures do exist, unexpected increases in the monitored responses will be observed when the source is near the facility compromise.

A final CW field illumination configuration is the continuous-wave-radiated (CWR) testing system developed by DNA.** This system was designed as an analyst's tool to support the electromagnetic evaluation of a ground-based facility. In addition to providing transfer functions from the CW-field source to critical interconnect cables, the system is capable of "folding in" EMP pulse spectra to the transfer functions and performing an inverse Fourier

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*R. Axford, R. McCormack, and R. Mittra, "Evaluation of Applicability of standard CW EMI/RFI Shielding Effectiveness Test Techniques to Assessment of EMP Hardness of Tactical Sheldters," CERL-TR-M-307, Contract No. MIPR FY76208100019, Project ESD/OCR-3, U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois, March 1982, AD-A113-042.

**T. Buckman and R. W. Steward, "Procedures Manual for the Conduct of CW Radiated Tests," DNA 6200F, Contract No. DNA 001-79-C-0387, IRT Corporation, San Diego, California, July 1982.

transform to yield time domain pulse measurements. This system consists of a special antenna system, CW signal generators, a network analyzer, current probes, field probes, a controller, etc.

2.1.2 Merits and Limitations

Field illumination measurement techniques as they would apply to C^3 power plant acceptance testing have merits as well as limitations. The primary advantages and disadvantages of field illumination tests are summarized below for both pulse and CW sources and configurations.

Pulsed field illumination sources have several advantages. These type sources generate a field which simulates an EMP environment; hence, the name EMP simulators. Also, EMP simulators can be used to illuminate a relatively large portion of a facility. For small facilities, it is conceptually feasible to illuminate the entire facility at once. Thus, a significant part, or all, of the facility/power system including penetrations and apertures can be excited simultaneously. Furthermore, if a threat level EMP simulator is used, the system will be exposed to an environment which represents, as close as possible, an actual EMP environment. Hence, high level and nonlinear responses such as shield saturation, surge protection device operation, etc., are included in the tests.

An important disadvantage of the pulsed field illumination sources for use in acceptance testing of C^3 power facilities is the tradeoff between achievable field amplitude and unacceptable test object-to-antenna interaction. Ideally, the simulator should be sufficiently far away from the test object to minimize coupling (reactive) and multiple scattering. This interaction between the antenna and test object can "load" the antenna and change its drive currents and, hence, the resulting fields. It can also change the amplitudes of test object responses and may alter any complex resonances of these responses. To reduce these unwanted interactions, the simulator is normally moved further away from the test object. However, the amplitude of the field produced by the simulator is inversely related to the distance from the simulator. Therefore, increasing the separation distance between the simulator and the facility (test object) to reduce unwanted interaction also reduces the maximum field amplitude that can be achieved at the facility.

In addition, pulsed testing using an EMP simulator has other significant disadvantages in terms of cost and time. The set up, use, and disassembly of an EMP simulator is a very expensive and time consuming process. A discussion of typical costs and times required is provided in a later section.

The advantages of CW measurement techniques for acceptance tests of C^3 power facilities are that the set-up and use times are relatively fast, and that this technique is relatively inexpensive. The CW measurement technique is a quick way of locating shielding compromises such as shield apertures and penetrations. It is probably the best technique for evaluating shielding effectiveness and linear transfer functions. As discussed previously, recent research indicates that it may be feasible to convert CW shielding effectivness data to values meaningful for EMP hardness evaluations.

The major disadvantage of CW testing is the the pass/fail criteria must be appropriately specified to ensure that the resulting data will allow a direct determination of whether the measured response meets the criteria. For example, the results of a CW shielding effectivenss test can be used to indicate acceptance only if the required shielding effectiveness is specified in the procurement. Also, this technique cannot directly provide the response of a facility or system to an actual EMP environment nor can it be used to evaluate nonlinear responses.

2.1.3 Cost

The major expenses associated with EMP simulator field illumination tests are those for the simulator, for getting it in place and operational, and for disassembly and removal of it after the completion of the tests. Labor as well as materials and equipment costs must be included. The total costs can vary over an extremely large range depending on the test site and the simulator used.

The conduct of tests at a facility with the TEMPS would cost typically \$200,000 to \$250,000 for transportation (1,000 miles), site preparation, logistics, and disassembly. This cost does not include response monitoring equipment, tests conduct, land rental and preparation, data collection, analysis, and reporting. The set up alone for the TEMPS takes two to three weeks and requires 10 to 12 people. Land rental can cost $20,000 to $30,000 and 70 yards of concrete are needed to set up the TEMPS. It should be noted that the TEMPS is currently in storage and needs refurbishing before it can be used (The costs to get it operational has been estimated to be approximately $1,000,000.).

It is feasible that a simulator such as the Army EMP Simulator Operation (AESOP), which is a "fixed-site" TEMPS located a HDL, could be disassembled and moved to a test site; however, this is probably impractical since it is estimated to cost up to $500,000 to build a mechanism to transport it. This cost is in addition to the above costs.

If subthreat level tests are sufficient, then a smaller simulator such as the REPS could be used. It is estimated that its transportation, site preparation, logistics, and disassembly cost would probably be one-fifth of the costs for the TEMPS and AESOP.

In summary, the cost to perform a full scale EMP simulation test at a facility would probably be $2,000,000 to $3,000,000 at the present time (1983).

2.2 Direct Injection Tests

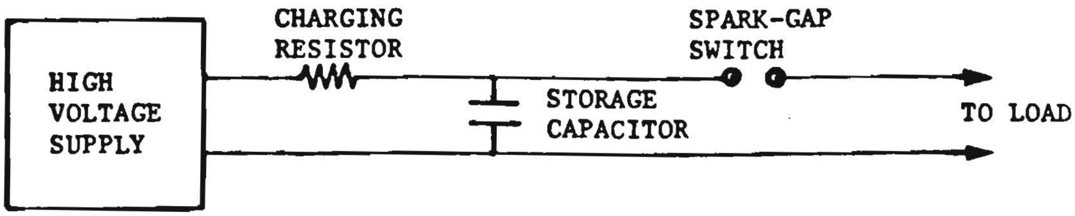
A direct injection EMP test involves the coupling (in a non-radiated mode) of a simulated EMP test waveform into an equipment/system and monitoring the effects on the equipment/system performance. Radiating threat levels over a large portion of a facility is not always practical or feasible and field illumination simulators often times are not accessible. Direct injection techniques enable one to simulate high level EMP environments at far less power and cost than with field illumination techniques. This advantage stems from the fact that direct injection techniques assume some initial coupling loss (or transfer function) from the radiated EMP environment to the current/voltage induced on a conductor. Another advantage is that the conductor or cable under test can be isolated and examined singularly. However, present day direct injection techniques do not simulate free-field coupling to the total system, which would require correctly phasing and shaping pulses in a multiport injection system. Also, depending on the amplitude and the point of injection, nonlinear effects (such as firing of surge arrestors) may not be accurately evaluated.

2.2.1 Test Sources/Configurations

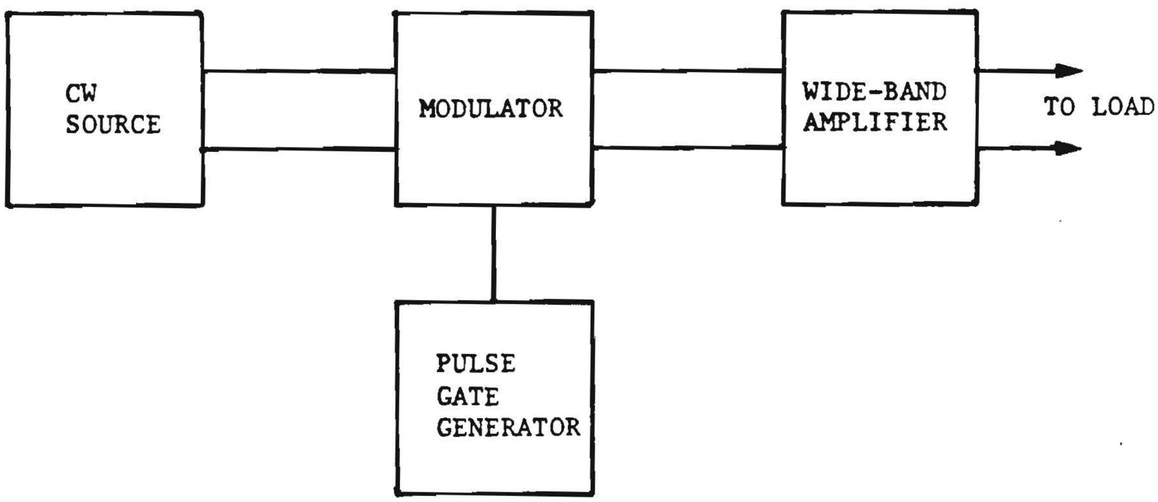
The various direct injection techniques differ as to the effect which is monitored during the test, the test waveform's shape and amplitude, the way in which the test waveform is injected (coupled), and where it is injected. The specific effects which must be monitored for EMP acceptance tests of C^3 power systems are dictated by the criteria which determine mission failure or success. Mission failure or success hinges primarily on the ability of the system to provide power to critical technical loads. Transient upsets are normally acceptable provided that the reset capability and recovery times are sufficient to satisfy the system specification requirements.

A wide variety of transient energy sources (pulsers) are used for direct injection EMP testing. The most commonly utilized pulsers range from small laboratory pulse generators used for component testing to sources capable of delivering on the order of 10 kV peak voltage and 100 A peak current. A wide variety of low power pulse sources are commercially available with voltage ranges from a few volts to a few hundred volts, and current ranges from milliamps to several amps. For applications requiring higher peak output voltages and currents, these pulsers may be used in conjunction with wide-band power amplifiers and impedance-matching networks.

The basic configuration of commercially available pulse sources is normally one of the two configurations shown in Figure 1. The basic capacitor discharge circuit, illustrated by the block diagram in Figure 1(a), consists of a high voltage power supply, a storage capacitor, a current limiting charging resistor, and a switch for connecting the storage capacitor to the load. The storage capacitor is charged by the high voltage supply through the charging resistor. When the voltage on the capacitor reaches the breakdown



(a) Capacitor Discharge Configuration



(b) Modulated CW Configuration

Figure 1. Basic Configuration for Pulse Sources.

potential of the spark-gap switch, the switch closes and discharges the capacitor into the load. The output waveform is a pulse with a very short rise time and a longer decay time. The rise time of the output pulse is determined by the inductance of the capacitor and its connecting wiring. The decay time is determined by the value of the storage capacitor and the load impedance. The basic capacitor-discharge circuit may be modified, as illustrated in the top four circuits of Table II, to produce a double exponential, rectangular, or damped sinusoidal output waveform.

The basic modulated CW pulser circuit, illustrated by the block diagram in Figure 1(b) consists of a CW source, a modulator, a gate generator, and an amplifier. The CW signal from the CW source is passed through the modulator to the amplifer during the pulse gate period. This circuit can produce a damped sinusoidal or an RF burst output waveform as illustrated in the bottom two circuits in Table II. Several key parameters which should be considered when selecting a particular type pulser are also listed in Table II. Typical characteristics of commercially available pulse sources and several pulse source suppliers are listed in Table III.

Several methods for coupling a signal onto a cable or cable shield are currently used. The method chosen for a particular test will depend on such factors as the configuration and function of the cable circuit, its impedance, the type of shielding, the power levels and waveform characteristics involved, and the accuracy requirements for the test. For tests in which the cable shield is to be driven, the shield current is of primary interest. For tests in which unshielded conductors or core conductors inside a shield are driven, the voltage between the conductor and the system ground is usually of primary interest.

The two most common methods for coupling the test waveform to a cable shield are the transmission line and the current transformer techniques. The transmission line techniques use the cable shield as one conductor of a uniform transmission line, which may be either a coaxial or a parallel wire configuration. In the coaxial configuration, the cable shield is used as the center conductor of a coaxial transmission line as illustrated in Figure 2(a). With this configuration, the outside of the cable shield and the

TABLE II

SUMMARY OF PULSE SOURCE
TYPES AND WAVEFORMS

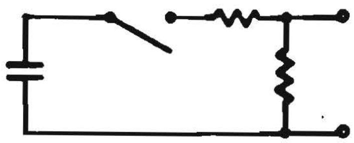
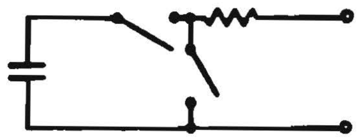
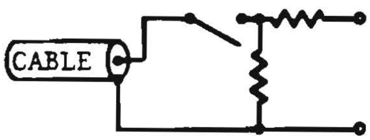
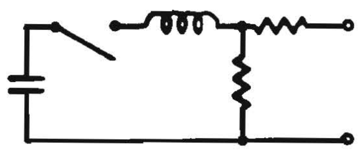
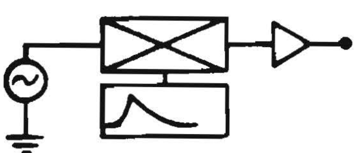
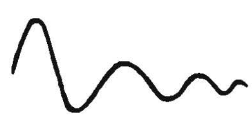
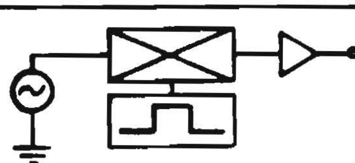
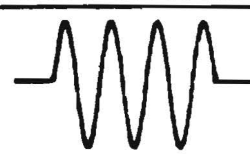
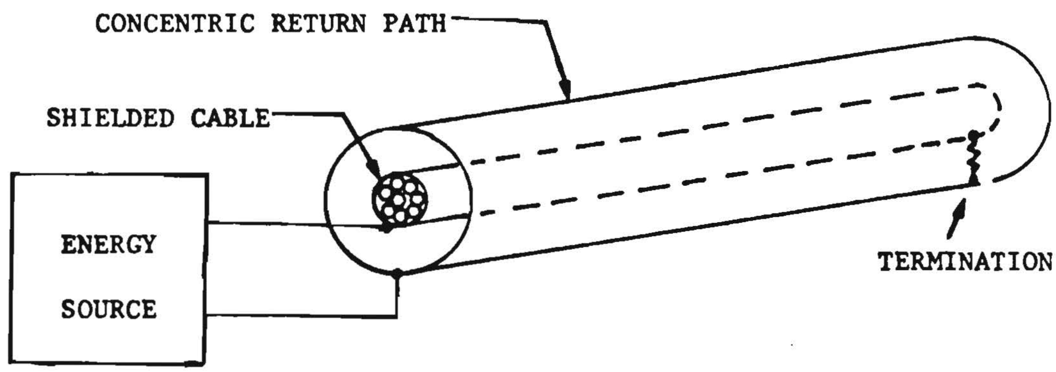
TYPE	CIRCUIT	WAVEFORM	PARAMETERS
CAPACITOR DISCHARGE		 DOUBLE EXPONENTIAL	VOLTAGE SOURCE IMPEDANCE RISETIME FALL TIME
CROWBAR		 RECTANGULAR PULSE	VOLTAGE SOURCE IMPEDANCE RISETIME PULSE WIDTH
CABLE DISCHARGE		 RECTANGULAR PULSE	VOLTAGE SOURCE IMPEDANCE RISETIME PULSE WIDTH
RESONANT		 DAMPED SINUSOID	VOLTAGE SOURCE IMPEDANCE FREQUENCY DAMPING (Q)
MODULATED CW		 DAMPED SINUSOID	VOLTAGE SOURCE IMPEDANCE FREQUENCY DAMPING (Q)
MODULATED CW		 RF BURST	VOLTAGE SOURCE IMPEDANCE FREQUENCY PULSE WIDTH

TABLE III

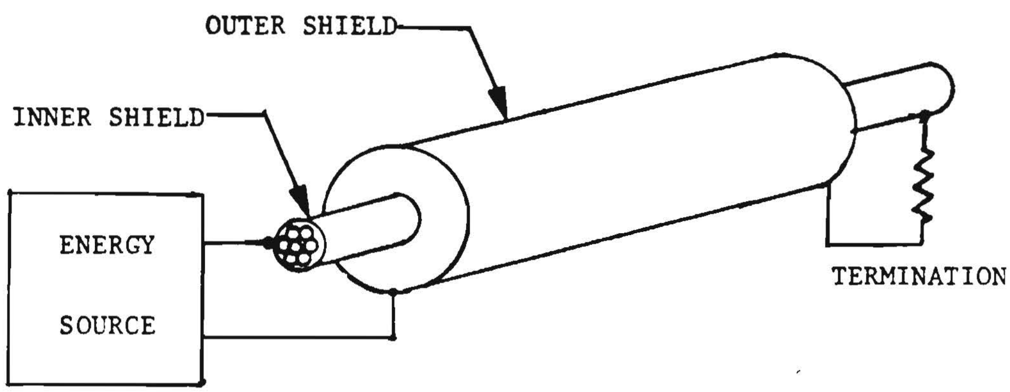
TYPICAL CHARACTERISTICS OF COMMERCIALLY AVAILABLE PULSE SOURCES

TYPE	WAVEFORMS	PEAK VOLTAGE (Volts)	PEAK CURRENT (Amps)	RISE TIME	FALLTIME	OPERATION MODES
LOW POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	10-100	2	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE
MEDIUM POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	100-1,000	5	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE
HIGH POWER	DOUBLE EXPONENTIAL RECTANGULAR PULSE DAMPED SINUSOID RF BURSTS	1,000-20,000	10-15	7-35 ns 7-35 ns	7ns-50ms 7-50ns	MANUAL PROGRAMMABLE

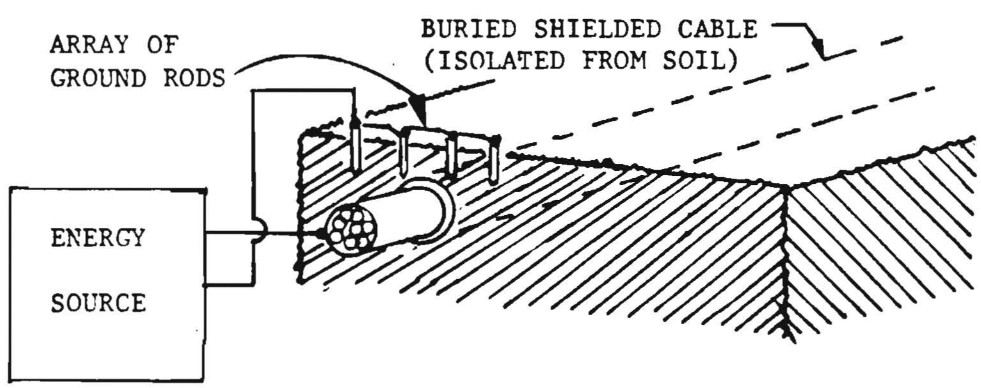
TYPICAL PULSE SOURCE SUPPLIERS	
EG&G	Albuquerque, NM
Maxwell Labs, Inc.	San Diego, CA
Physics International, Inc.	San Leandro, CA
Tobe Deutchmann Labs.	Canton, MA
Velonix	Santa Clara, CA



(a) COAXIAL TRANSMISSION LINE SHIELD DRIVER



(b) DOUBLE-SIDED TRANSMISSION LINE DRIVER



(c) BURIED CABLE TRANSMISSION LINE DRIVER

Figure 2. Coaxial Transmission Line Cable Shield Drivers.

inside of the concentric return path form a coaxial transmission line with a characteristic impedance of:

$$Z_o = \frac{60}{\sqrt{\varepsilon_r}} \ln\left(\frac{D}{d}\right) \qquad \text{(assuming air dielectric)} \qquad (1)$$

where:

ε_r = dielectric constant of the insulation between the shield and return path,

D = inside diameter of return path cylinder, and

d = outside diameter of cable shield.

If this structure is terminated in its characteristic impedance, a uniform current having a value of V/Z_o amperes will be induced in the shield over the length of the transmission line.

In most cases, it is not practical to install a concentric return path around installed shielded cables to utilize this coupling technique. However, the technique can be used on double-shielded cables where the two shields are insulated from each other. This technique, illustrated in Figure 2(b) is very efficient in terms of driver power requirements because only the current on the inner shield must be simulated, and this current is much smaller than the current that would be coupled to the outer shield. The inner shield is driven as the center conductor of a coaxial transmission line, and the outer shield serves as the concentric return path.

The coaxial transmission line driver technique may also be used on buried shielded cables where the shield is insulated from the soil. The configuration is illustrated in Figure 2(c). The cable shield, insulation, and soil form a natural coaxial geometry which can be used to induce current on the cable shield. The cable shield is driven as the center conductor of a coaxial transmission line and the soil serves as the concentric return path. It is necessary to establish a low impedance connection to the soil at the driving point so that most of the source voltage is applied to the transmission line. This can be accomplished with an array of ground rods in the vicinity of the driving point.

An alternative to the coaxial line is the parallel wire transmission line configuration. In the parallel wire configuration, the cable shield of the test cable is used as one conductor and one or more driving lines are used to form a transmission line. The characteristic impedance of a two-conductor parallel-wire line with unequal diameters, as illustrated in Figure 3(a) is:

$$Z_o = \frac{60}{\sqrt{\varepsilon_r}} \cosh^{-1} \left(\frac{4D^2 - d_1^2 - d_2^2}{2d_1 \, d_2} \right) \tag{2}$$

where:

D = spacing between wire centers, and

d_1, d_2 = diameter of test cable and driving lines, respectively.

It is possible to reduce the characteristic impedance by nearly 50 percent by using dual driving lines as illustrated in Figure 3(b). This is beneficial since, for a fixed amount of drive current, lower voltage handling capabilities are required for the pulse source capacitor bank and terminating resistor. Also, the addition of another line results in a more uniform current and electric field distribution on the surface of the shield which leads to a higher maximum shield current before breakdown of the insulation occurs.

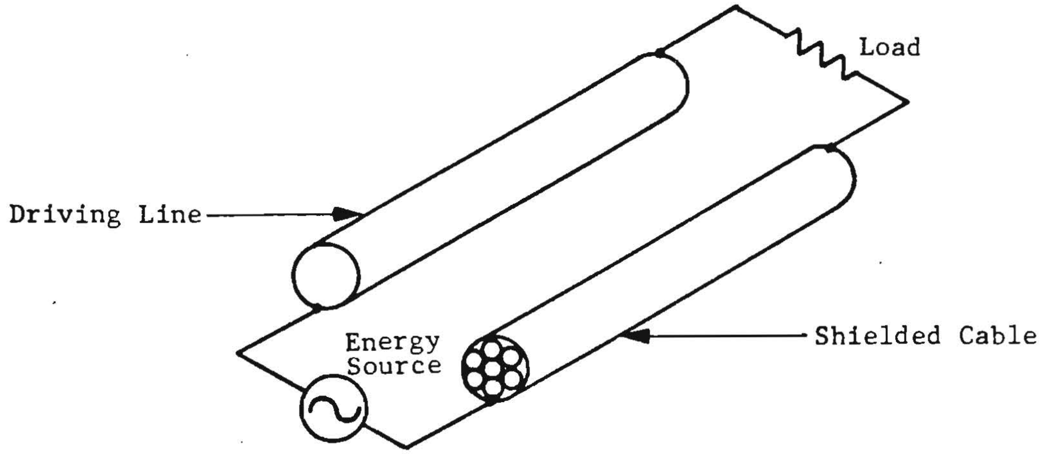
A variation of the parallel wire cable shield driver is shown in Figure 3(c). This configuration is useful for driving shielded cables with insulating jackets that are routed along a metal structure or laid in metal cable trays. Using image theory (i.e., assuming an infinite, perfect ground plane), the characteristic impedance is:

$$Z_o = \frac{60}{\sqrt{\varepsilon_r}} \cosh^{-1} \left(\frac{2h}{d} \right) \tag{3}$$

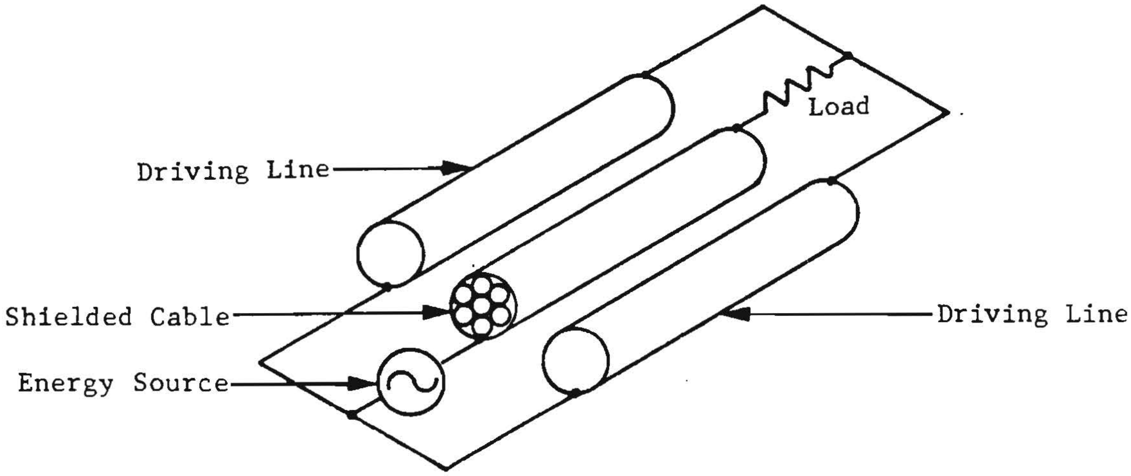
where:

h = height of shield center above the ground plane, and

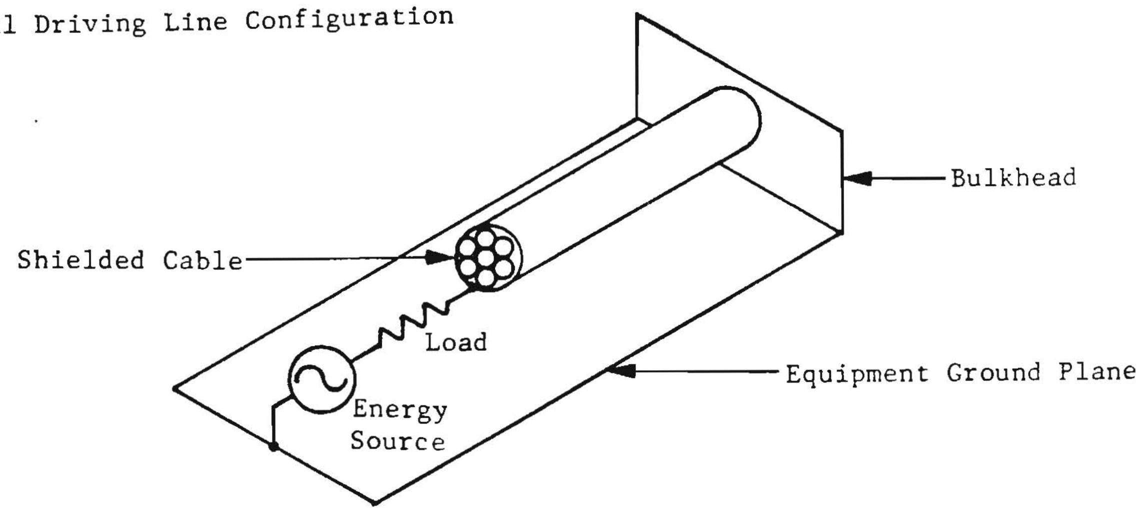
d = diameter of the shield.



(a) Single Driving Line Configuration



(b) Dual Driving Line Configuration



(c) Test Cable/Equipment Ground Plane Configuration

Figure 3. Parallel Wire Transmission Line Cable Shield Drivers.

This method of driving the shield is limited to applications where one end of the shield can be removed from the ground and connected to the energy source. It has the advantage that, if the cable length and terminations are preserved, much of the pulse shaping is accomplished by the system structure itself.

The current transformer technique illustrated in Figure 4 can be used to inject current onto cable shields if both ends of the cable shield are grounded to the system structure and it is desired to preserve the operational configuration so that the system geometry shapes the current waveform. The toroidal core can be split and clamped around the cable without disturbing the cable system, which makes this technique attractive for acceptance, surveillance, and maintenance type tests. However, this technique does not simulate EMP coupling to the shield as well as transmission line techniques (particularly the coaxial method), which provide more distributed and uniform coupling over a significant length of shield.

The three basic methods of injecting a test waveform onto a signal-carrying conductor are the resistive, capacitive, and inductive coupling techniques. Injection upon signal-carrying conductors is often considerably more difficult than injection on cable shields. This difficulty arises because of two conflicting requirements. The coupler must first provide a reasonable coupling efficiency so that the pulser power requirements are not excessive. In addition, the coupler must provide sufficient isolation between the excitation source and the injection point so that the mutual impedance between the source/interconnecting wiring and the system or subsystem under test does not significantly alter its response and therefore invalidate the test.

Resistive coupling to individual wires of a cable bundle or to individual terminals in a distribution or interface panel can be accomplished through a resistive matrix as shown in Figure 5. The values of the resistors used in the coupling matrix should be selected to present a reasonable load impedance to the excitation source and simulate the normal impedance values between the individual wires. The resistive coupling method may be used with shielded and unshielded conductors. With unshielded conductors, a cable tray, conduit, or the grounding system is used for the return path. The major disadvantage of

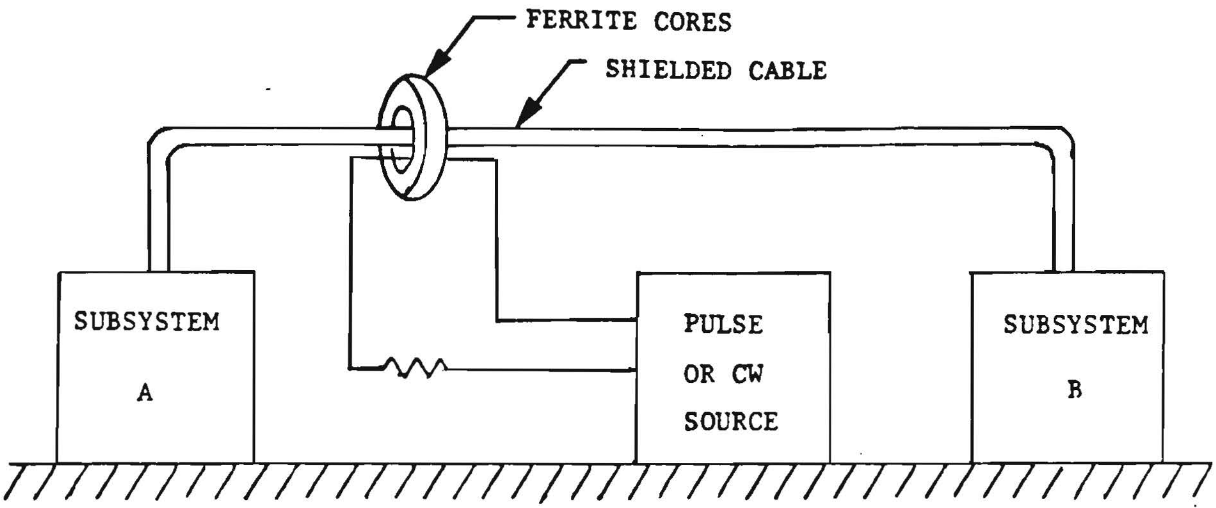


Figure 4. Current Transformer Cable Shield Driver.

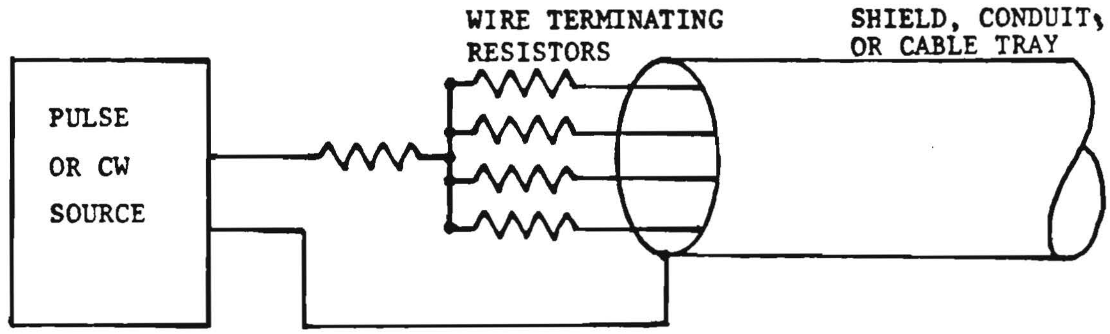
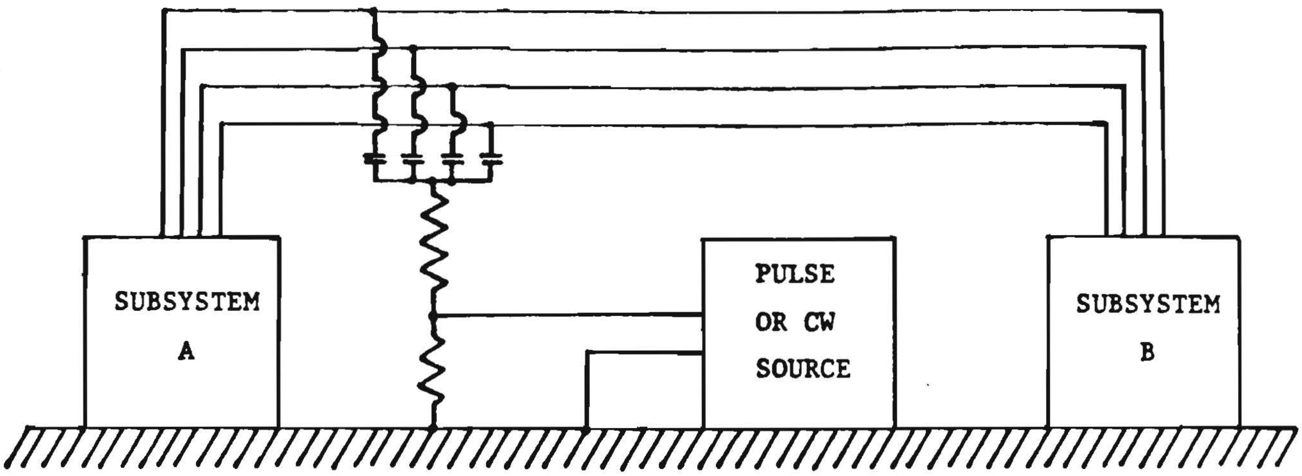


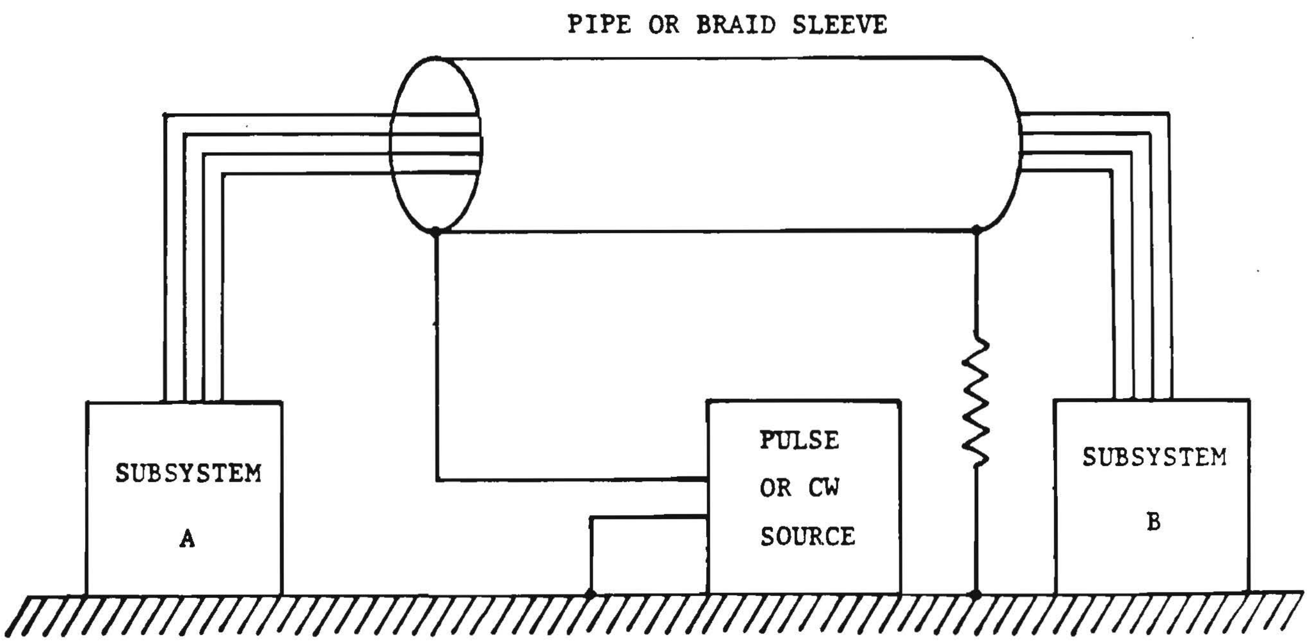
Figure 5. Resistive Coupling Matrix.

this coupling method is that one end of the cables being driven must be disconnected and the system under test may not be in its normal operating mode. In cases where both ends of the cable(s) under test must remain connected to maintain the system in normal operation, capacitive or inductive coupling techniques must be utilized. Discrete capacitive coupling is conceptually similar to resistive coupling and requires the selection of a capacitance value which is a compromise between interface isolation and coupling efficiency. An example of a discrete capacitive coupling technique is shown in Figure 6(a). This technique uses a number of capacitors to couple the test source to the individual wires in a wiring bundle. The values of the capacitors are selected to provide low series impedances to the injected signal while presenting high shunt impedances to the desired signals on the system wires. The values of the resistors shown in the diagram are selected to present a reasonable load impedance to the test signal source. This method of distributing current differs radically from the current distribution that would result from EMP excitation of the system primarily because of the current "splitting" at the injection point. This problem can be overcome by using a distributed capacitive coupling technique as illustrated in Figure 6(b). A conductive sleeve is placed over a length of the wire(s) under test. The sleeve acts as one plate of the coupling capacitor while the individual wires act as the second plate. The achievable capacitance values are limited to about 20 pF/ft. It is difficult to achieve large capacitance values unless long sleeves are used, and thus this technique tends to be inefficient at low frequencies.

Both discrete and distributed inductive couplers may be used to inject the excitation signal onto system cables. An example of a discrete inductive coupling technique is shown in Figure 7(a). This technique utilizes the transformer action between a primary formed by the test source output and a secondary formed by the wire(s) under test. This transformer action is enhanced by surrounding the primary and secondary wires with a ferrite toroidal core. A distributed inductive coupling technique is illustrated in Figure 7(b). Several ferrite cores are located at intervals over a significant length of the wiring bundle under test, forming a distributed transformer coupling between the test source and the wires under test. This type of coupling more realistically simulates the coupling of an EMP transient to

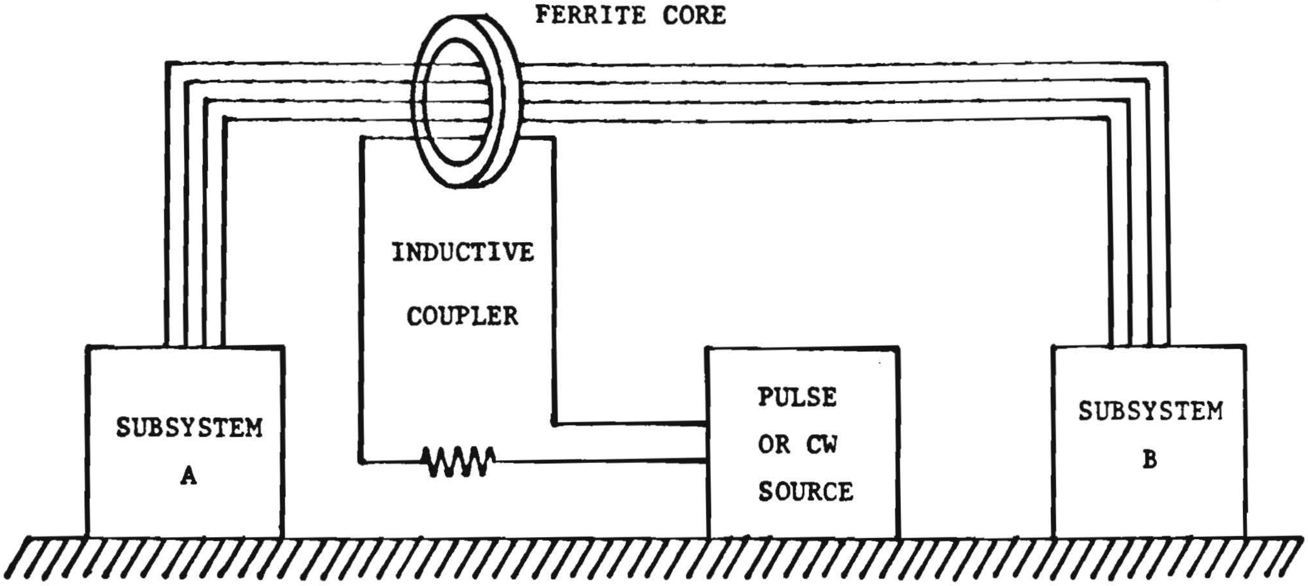


(a) DISCRETE CAPACITIVE COUPLING

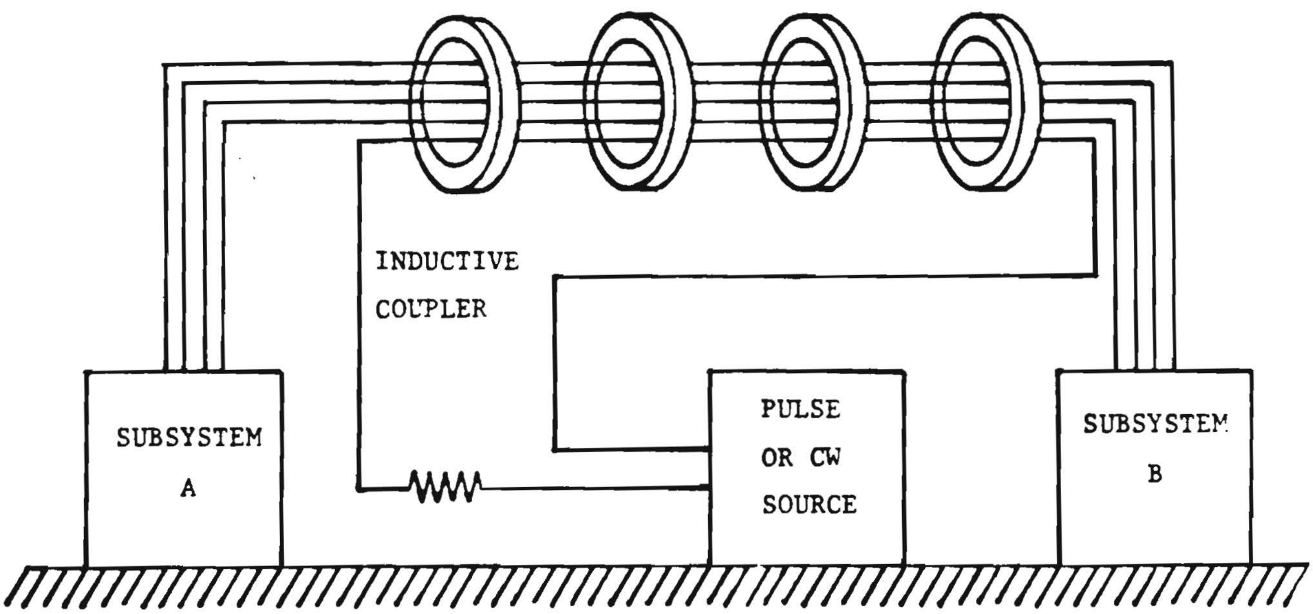


(b) DISTRIBUTED CAPACITIVE COUPLING

Figure 6. Discrete and Distributed Capacitive Couplers.



(a) DISCRETE INDUCTIVE COUPLER



(b) DISTRIBUTED INDUCTIVE COUPLER

Figure 7. Discrete and Distributed Inductive Couplers.

the system wiring. The inductive coupling techniques are particularly attractive for system level testing because the ferrite cores can be split and clamped around cables without disconnecting, removing insulation from, or rerouting the system cables.

Several different types of transportable injection simulators are available. These simulators are transportable in that they can be moved to a test site, assembled, and operated. After the tests are completed, they can be disassembled, relocated, and used again at another facility. These pulsers simulate the EMP environment by injecting currents and voltages on conductors external to the facility or system-under-test. The output of the pulser may be coupled indirectly by a cable driver or directly by hard wiring the simulator output into a cable or transmission line. The various types include cable drivers, direct injection, current injection, and indirectly coupled simulators. Brief descriptions of selected injection simulators are presented below.

<u>1020 Cable Driver</u>

Cable driver techniques consist of injecting a transient current of known waveform onto the external electrical shield of a multistrand cable and then measuring the currents induced into the internal conductors. The 1020 cable driver facility was developed by HDL to provide this capability.

The 1020 Cable Driver consists of the following subsystems:

- o PULSER: 5 nanoseconds rise time with peak amplitude continuously variable up to 200 amps.
- o TEST SECTIONS: 32-meter long cables, with or without connector assemblies.
- o INSTRUMENTATION HOUSING: 1-meter cube shielded box with connectors and adapters.

<u>Direct Injection</u>

Direct injection technology is used for threat and low-level system EMP assessment. A direct injection system creates a transient pulse on a system penetration by means of a point source or sources coupled to the penetration directly (resistance) or reactively (capacitance or inductance). This type of simulator is useful whenever other simulation techniques are inadequate or impractical from the standpoint of either peak amplitude or area of illumination.

HDL has designed and built a variety of direct inject pulsers for specific applications. Some examples of direction injection pulsers are:

- 1 NANOSECOND PULSER - 1 nanosecond rise time, floating 600 nanosecond pulse into 50 ohms, voltage range 5-4000 volts.

- 5 NANOSECOND PULSER - 5 nanosecond rise time, single-ended 60-nanosecond pulse into 50 ohms, voltage range 7-900 volts.

- 1 MICROSECOND PULSER - 1 microsecond rise time, floating 60 microsecond pulse into 50 ohms, voltage range 500 to 5000 volts.

- 1 MILLISECOND PULSER - 1 millisecond rise time, floating 50-millisecond pulse into 50 ohms, voltage range 0-4000 volts.

Current Injection

The Maxwell Laboratories have developed a current injection simulator for DNA. The simulator is transportable and is housed in two, eight foot wide trailers designed for unrestricted road use. The simulator consists of two Marx generators (each 4 Mj), one housed in each trailer. The two Marx generators are designed for parallel operation into a common load. A high-coulomb, rotating-arc, spark-gap switch is used in the pulsers. The pulser has an output voltage of approximately 320 Kv, and delivers a millisecond current pulse to a nominal 20-ohm load. The pulser can drive time varying loads from high impedance to near short circuit. The simulator is a complete system and includes the necessary control, instrumentation and monitoring systems. Both 440 Vac, three-phase, and 200 Vac, three-phase, primary power must be supplied to operate the simulator.

PLACER

The Pulsed Loop Antenna Conduit Electromagnetic Radiator (PLACER) was developed by HDL. The transportable device is capable of detecting, locating, and measuring EM shielding flaws in buried conduits. It was designed for the SAFEGUARD Protection Integrity Maintenance Program. PLACER produces a pulsed electromagnetic field which induces current pulses onto buried conductors, and has been used to evaluate the RF integrity of buried conduit systems. Using the 30-kV version of PLACER, it is possible to determine the shielding effectiveness (to 80 dB) of conduits buried to a depth of 16 feet. By increasing the pulser voltage and the instrumentation sensitivity for monitoring currents on cables inside the conduit, it is possible to extend this dynamic range to more than 100 dB. Since the PLACER induced excitations are localized, it also is possible to determine the precise location of a conduit flaw. By complementing the PLACER field test results with laboratory flaw data, a threat analysis can be performed to determine system vulnerability.

The PLACER consists of the following subsystems:

- 0-40 kilovolts High Voltage Power Supply/Control Console
- 30-kilovolts Pulser and High Voltage Interconnect Cable
- 3-meter Diameter Loop Antenna
- Three-Wheel Cart.

2.2.2 Merits and Limitations

In general, direct injection techniques do not account for the synergistic effects which could occur when a large portion of the facility is excited by a field illumination simulator. Also, nonlinear effects may not be evaluated depending upon the point at which the signal is injected (i.e., before or after nonlinear devices) and the amplitude and waveshape of the test waveform (i.e., risetime, peak level, etc.). The primary advantage of injection techniques in comparison to field illumination techniques is lower cost. Due to the lower costs and often times the inaccessibility of field illumination EMP simulators, direct injection techniques may be more practical than field illumination techniques for use as EMP acceptance tests for C^3 power plant facilities. The unique advantages and disadvantages associated with each of the direct injection techniques which have been identified are discussed below.

The two methods which were identified for coupling the EMP test waveform to cable shields -- the transmission line and the current transformer techniques -- are both nondisruptive in nature since they do not require disconnection or rerouting of system cables and the construction of a breakout box at the injection point. Non-disruptive techniques are generally less difficult, time consuming, and costly to implement and are therefore preferable to disruptive techniques for use in system level acceptance testing. The transmission line techniques have the advantage of a more even frequency response and a more uniform current distribution than the current transformer technique. Although the transmission line techniques will generally provide a better simulation of EMP coupling to a cable shield, the current transformer technique is easier to implement, which can result in significant time savings.

The resistive and the discrete capacitive coupling techniques for coupling to cable conductors are both disruptive in nature. These techniques are probably the most straightforward and commonly used direct injection methods. However, they do not lend themselves well to acceptance testing since they require breakout boxes and are generally not very representative of the coupling that would occur with the original cabling and equipment in place. The resistive coupling technique in particular may create practical problems. For instance, if the power leads of an equipment are being tested, the cable must be disconnected which means that the equipment (unless battery powered) would have to be tested in an unenergized state. On the other hand, the inductive and distributed capacitive coupling techniques are non-disruptive in nature, which lend themselves to acceptance-type testing. The distributed capacitive technique provides for realistic simulation of EMP coupling to the cable, but is rather inefficient at low frequencies and less straightforward to implement than most of the other techniques. The inductive coupling technique is the most convenient method for system level acceptance testing since the clamp-on, ferrite cores do not require breakout boxes or disconnecting/rerouting system cables.

2.2.3 Cost

Direct injection techniques are typically less expensive to implement than are field illumination techniques. The relative costs and time requirements for performing EMP acceptance tests using direct injection techniques is primarily a function of the point at which the test waveform is injected. For example, if the injection point is into equipment interconnecting cables, the actual testing time is probably the most significant expense. The primary reason for the long testing time requirements is the large number of injection points (i.e., unique interconnect cable ends). If, on the other hand, the injection point is into exterior conductors which penetrate the C^3 power system facility, then the major expense is associated with the injection simulator, which should be capable of injecting large current levels to simulate the levels which would be generated from free-field coupling.

As an example of how much testing time would be required to perform these tests, assume that ten minutes is required to determine whether or not the equipment/system is operating properly and that there are 50 unique cable ends to be tested. Also assume that damped sinusoid pulses are used. (For injection testing of interconnect cables, damped sinusoid pulsers are most often employed since this is the waveform which will likely exist from EMP coupling to these cables*.) These tests should be run at approximately three different frequencies per decade from 100 kHz to 100 MHz (i.e., nine different frequencies) and at three different amplitudes (say 10%, 50%, and 100% of the maximum specified level). The time required to perform the tests, not including set up and calibration time, would be 10 x 50 x 9 x 3 minutes = 13,500 minutes. This equates to approximately five and a half weeks of testing time assuming a five day, 40 hour work week. A realistic allowance for set up, calibration, and measurement problem solving would make the total test time on the order of ten weeks.

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*Gary L. Roffman, "Investigation of Equipment Specifications for High Altitude Electromagnetic Pulse," HDL-TR-1929, July 1980.

S. R. Rogers, et. al., "Engineering Design Guidelines for Electromagnetic Pulse Hardening of Naval Equipment," Electro-Magnetic Applications, Inc., Final Report, 15 July 1981.

The actual testing time associated with making injection tests on external penetrating conductors (i.e., once all the test equipment has been obtained, set up, and calibrated) would be considerably less than for interconnect cable testing. This is due primarily to the fewer number of conductors to be tested and also to a single pulse waveform being used instead of damped sinusoids at several different test frequencies. Since the peak levels for interconnect cable testing would be on the order of 10 amperes, injection onto external penetrating conductors should be at or near threat levels (i.e., on the order of 1000 amperes*) in order to excite the various nonlinearities in the system.

Since the pulse parameters are given in the test specifications and will be influenced by the test geometry and an unknown load impedance, the injection simulator must normally be developed for a specific application (e.g., waveshape, risetime, amplitude, etc.). The development may be done internally by the testing agency or by an external R & D laboratory. The primary expense for external injection tests is therefore associated with injection simulator development costs, which are estimated to exceed $1,000,000.

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*EMP Engineering and Design Principles, Bell Laboratories, Loop Transmission Division, Whippany, New Jersey, 1975.

3.0 SUSCEPTIBILITY OF C^3 POWER PLANT COMPONENTS

The EMP susceptibility thresholds of C^3 Power Plant components must be known to mitigate the effect of EMP on the operation of the power plant. Component susceptibility to EMP may be due to: (1) damage or (2) upset. Damage and upset susceptibility thresholds may be determined by analytical methods or laboratory tests. System susceptibility to upset can be predicted from the component upset levels but testing is required to find the actual system susceptibility level. Testing is required because analytical susceptibility expressions cannot be formulated for the entire power plant system with any degree of accuracy or certainty. The method of determining component susceptibility contains two steps:

(1) Identification of Critical System Components, and

(2) Analyzing the Susceptibility of the Critical Components.

3.1 Identification of Critical Components

The systems which make up the C^3 Power Plant are well delineated in the body of the DFM. The set of these systems which are critical to the mission of supplying power to the technical loads are listed in Table IV. This set of systems will be called the Critical Systems (CS). The loss or disruption of any of these CS would defeat the mission of the C^3 Power Plant.

The likelihood of component damage from EMP within each of the CS may be estimated from the EMP coupling levels and the typical damage threshold levels shown in Figure 8. Figure 8 clearly shows that semiconductor devices are orders of magnitude more susceptible to damage from EMP than typical power devices. Therefore to identify critical system components which may possibly be susceptible to EMP, the Table IV list should be searched for the system which contains equipment utilizing solid state components.

Historically, power plant equipment was designed using heavy duty components with large safety margins. The trend toward more sophisticated instrumentation and control (I & C) equipment within power plants

TABLE IV

MISSION CRITICAL SYSTEMS

1. LOAD SHEDDING
2. OFF SITE POWER ISOLATION
3. AUTOMATIC SYNCHRONIZING
4. GENERATOR FIELD CONTROL
5. AUTOMATIC DIESEL GENERATOR STARTING
6. GOVERNOR/LOAD SHARING (POWER INTERCHANGE CONTROL)
7. AUTOMATIC LOAD SEQUENCER
8. UNINTERUPTABLE POWER SOURCE (UPS), BATTERY CHARGE AND STATIC SWITCH
9. DC POWER SUPPLIES
10. LUBE OIL
11. FUEL OIL FORWARDING
12. FIRE PROTECTION

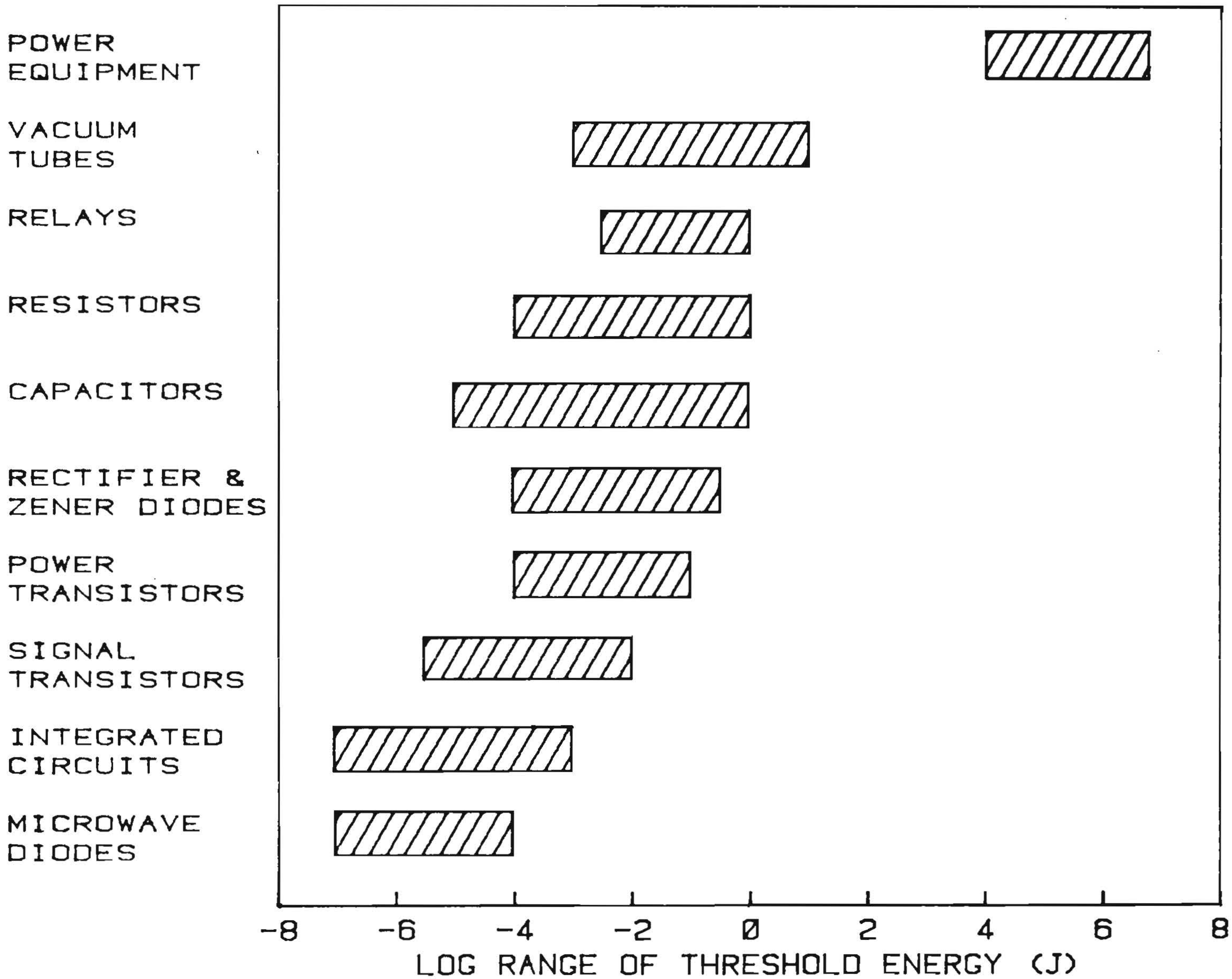

Figure 8. Typical Damage Threshold Levels.

has brought about the increasing use of solid state devices and memories. Equipment likely to employ solid state devices are listed in Table V. Since the future will probably result in more sophisticated designs for I & C equipment, the list of equipment in Table V will likely grow. Thus, an awareness by design engineers of the effects of EMP on solid state equipment will be necessary to raise the susceptibility levels of components, equipment, and systems.

3.2 Component Susceptibility Analysis

After the equipment/components which are potentially susceptible to EMP have been identified, their damage thresholds can be determined via the following procedure:

1) Obtain a complete equipment/component description from the manufacturer.
2) Search existing EMP Data Bases for component (or similar component) susceptibility levels. Stop here if all components are found in the test Data Base.
3) Select an analytical failure model for the component.
4) Collect data for all parameters of the failure model.
5) Calculate component damage threshold.
6) Identify the critical component within the equipment.
7) Calculate equipment circuit damage threshold.
8) Predict the equipment damage threshold.

The component upset limit may be determined in a similar manner, but instead of damage level, the level of excitation required for a state change is calculated. In the case of digital logic a state change can occur at the operating voltage. For protection equipment, such as an SCR, the state change will occur at the equipment protection voltage level. The state change will be considered an upset if the system cannot recover in time to maintain the mission.

The description of the equipment and components which comprise the critical systems may be obtained directly from the manufacturer or from the

TABLE V

POWER PLANT EQUIPMENT CONTAINING SOLID STATE DEVICES OR COMPONENTS

1. AUTOMATIC LOAD SEQUENCER

2. BATTERY CHARGER

   Rectifiers

3. UPS

   Rectifiers
   Transistors
   IC's

4. DC POWER SUPPLIES

   Rectifiers
   Zener Diodes

5. MOTOR CONTROL CENTERS (480 VAC)

   Rectifiers
   Zener Diodes

6. FIRE PROTECTION EQUIPMENT

   IC's
   Transistors

manufacturer's data books. Useful materials are schematics, wiring diagrams, physical layout drawings, parts lists, and test data.

The current EMP Data Bases are: SUPERSAP 2, SCORCH, Device Data Bank, and System EMP Component Parameter Parts List*. An attempt to compile all of these data bases into a large national data base is now underway. When complete, the national data base should facilitate the ease of performing susceptibility analyses.

There are several standard, widely accepted EMP device failure models. The model most commonly used for discrete semiconductors is the Wunsch** model, given by the equation:

$$P_F = Kt_p^{-1/2} \tag{4}$$

where:

P_F = power to failure (watts),
K = damage constant (determined empirically) (watt $\sec^{1/2}$),
t_p = pulse width of rectangular pulse (seconds).

For larger devices which fail due to ohmic heating of wiring the failure model is given by the equation:

$$P_f = \frac{CL\delta\pi r^2 \Delta T}{t_p} \tag{5}$$

where:

C = specific heat of material,
L = length,
ΔT = temperature difference,
r = cross-sectional radius
δ = material density,
t_p = pulse width of rectangular pulse.

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*D. L. Durgin, et. al., "The Determination of EMP Failure Thresholds," DNA 5424T, 8 September 1980.

**L. W. Ricketts, J. E. Bridges and J. Miletta, EMP Radiation and Protection Techniques, John Wiley and Sons, New York, 1976.

The collection of the parametric data to utilize the above failure models is straight forward. The damage constant, K, can be found in the SUPERSAP 2 data base, or it may be calculated from device geometry*. The damage constant has also been shown to vary linearly with the dc power dissipation parameter as shown in Figure 9.

After component damage thresholds are computed from the model and known parameters for all the components in the equipment, the critical component may be identified. Such components will have the lowest susceptibility thresholds as viewed from the terminals of the equipment. Circuit analysis may be utilized to reflect the susceptibility of selected components with low thresholds to the terminals of the equipment. This analysis may be as simple as summing the impedances leading to the critical component and applying Kirchhoff's voltage law to determine the EMP voltage at the component, or utilizing node elimination techniques to find the equivalent circuit for the component at the equipvalent terminals.

The equipment/component damage threshold may now be predicted from the most critical components on the most direct EMP coupling paths. This analysis has many sources of error such as the error introduced by the selected failure model, by the network reduction techniquues, and by the method of selecting the critical component. Where the error is felt to be large or have a great deal of uncertainty, equipment/component testing should be used to minimize the error.

*"Electronic Component Modeling and Testing Program," BDM Corporation for AFWL, AFWL-TR-78-62, March 1980.

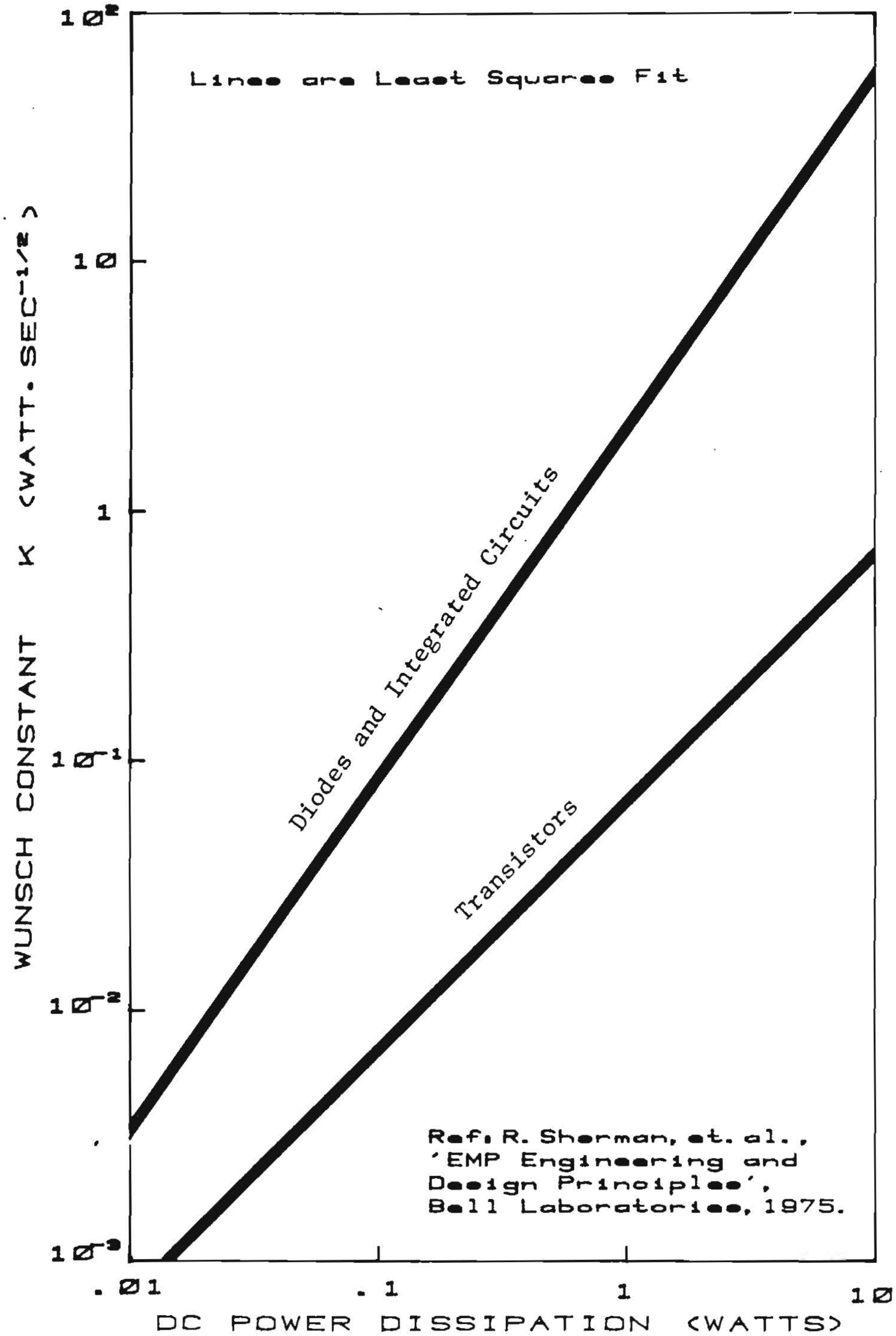

Figure 9. Comparison of DC Power Dissipation with the Wunsch Constant.