OAK RIDGE NATIONAL LABORATORY LIBRARY
3 4456 0002311 4

ORNL/Sub/83-43374/1/V1

ornl

OAK RIDGE NATIONAL LABORATORY

MARTIN MARIETTA

STUDY TO ASSESS THE EFFECTS OF ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEMS

PHASE I

EXECUTIVE SUMMARY

OAK RIDGE NATIONAL LABORATORY
CENTRAL RESEARCH LIBRARY
CIRCULATION SECTION
4500N ROOM 175
LIBRARY LOAN COPY
DO NOT TRANSFER TO ANOTHER PERSON
If you wish someone else to see this report, send in name with report and the library will arrange a loan.
UCN-7969 (3 9-77)

POWER SYSTEMS TECHNOLOGY PROGRAM

OPERATED BY
MARTIN MARIETTA ENERGY SYSTEMS, INC.
FOR THE UNITED STATES
DEPARTMENT OF ENERGY

Printed in the United States of America. Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22161
NTIS price codes—Printed Copy: A04 Microfiche A01

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

ORNL/Sub/83-43374/1/V1
Dist. Category UC-97a,b,c

Energy Division

STUDY TO ASSESS THE EFFECTS OF ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEMS

PHASE I

EXECUTIVE SUMMARY

J. R. Legro
N. C. Abi-Samra
J. C. Crouse
A. R. Hileman
V. J. Kruse
E. R. Taylor, Jr.
F. M. Tesche

Date Published - September 1985

Prepared for the U.S. Department of Energy, Assistant Secretary for Conservation and Renewable Energy, Office of Energy Storage and Distribution, Electric Energy Systems Program.

Report Prepared By:

Westinghouse Electric Corporation
Advanced Systems Technology
777 Penn Center Boulevard
Pittsburgh, PA 15235
Under
Subcontract 19X43374C
for

P. R. Barnes, Project Manager
Power Systems Technology Program
Energy Division
Oak Ridge National Laboratory
Oak Ridge, TN 37831
Operated by:
MARTIN MARIETTA ENERGY SYSTEMS, INC.
for the
U. S. DEPARTMENT OF ENERGY
Under
Contract No. DE-AC05-84OR21400

OAK RIDGE NATIONAL LABORATORY LIBRARY
3 4456 0002311 4

CONTENTS

Page

FOREWORD.....v

ACKNOWLEDGMENTS.....vii

LIST OF FIGURES.....ix

ABSTRACT.....xi

1. INTRODUCTION.....1

2. HIGH-ALTITUDE DETONATION NUCLEAR EMP ENVIRONMENTS.....6

3. SURFACE DETONATION NUCLEAR EMP ENVIRONMENTS.....10

4. HIGH-ALTITUDE DETONATION NUCLEAR EMP METHODOLOGY.....17

5. SURFACE DETONATION NUCLEAR EMP METHODOLOGY.....24

6. PHASE II RESEARCH 31

7. CONCLUSIONS AND RECOMMENDATIONS.....33

FOREWORD

The Division of Electric Energy Systems (EES) of the United States Department of Energy (DOE) has formulated a program for the research and development of technologies and systems for the assessment, operation, and control of electric power systems when subjected to electromagnetic pulse (EMP). The DOE/EES EMP program plan is documented in a DOE report entitled, Program Plan for Research and Development of Technologies and Systems for Electric Power Systems Under the Influence of Electromagnetic Pulses, DOE/NBB-003, May, 1983. The research documented in this Oak Ridge National Laboratory (ORNL) report was conducted under Program Plan Elements E1, "EMP Surge Characterization and Effects" and E2, "EMP Assessment Methodology Development and Testing."

The information presented in this volume is an Executive Summary of the Phase I effort to explore the interaction between electromagnetic pulse (EMP) and civilian electric utility systems. The results of this work will be used in subsequent phases of the research program to simulate such interaction, assess the possible consequences, and explore relevant mitigation techniques.

All EMP environmental data have been obtained from public domain documents and unclassified source materials. Such information is presented herein for illustrative purposes only and does not represent actual weapon characteristics or maximum threat environments.

This document is Volume 1 of a four-volume series that describes an EMP assessment methodology for civilian electric power systems. Volume 1 (this document) is an Executive Summary; Volume 2 discusses high-altitude EMP (HEMP); Volume 3 discusses magnetohydrodynamic EMP (MHD-EMP); and Volume 4 discusses nuclear surface burst source region EMP (SREMP).

ACKNOWLEDGMENTS

The research for this report series was sponsored by the Division of Electric Energy Systems, United States Department of Energy under Contract No. W-7405-ENG-26 with the Union Carbide Corporation, and Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc. The work as performed by Westinghouse Advanced Systems Technology under Subcontract No. 19X-43374C with Martin Marietta Energy Systems, Inc.

The authors wish to acknowledge and thank Mr. K. W. Klein of the United States Department of Energy, Mr. P. R. Barnes, and Mr. P. A. Gnadt of the Oak Ridge National Laboratory. Appreciation is also acknowledged to the ORNL Electric Utility and EMP Advisory Teams for their thoughtful comments and constructive guidance. Special acknowledgment is given to Dr. V. Albertson, University of Minnesota, for his assistance in the understanding of geomagnetic storms, and to Dr. C. Longmire, Mission Research Corporation, for his fundamental insights concerning electromagnetic pulse.

The physical preparation of this entire report series could not have been accomplished without the extensive efforts of Ms. C. Brown and Mr. J. E. Lokay of Westinghouse Advanced Systems Technology.

LIST OF FIGURES

Figure		Page
1	Phase I research organization	4
2	Phase I study approach	5
3	Spatial extent of selected effects from a one-Megaton surface nuclear detonation (plan view)	13
4	Transient current surge induced on an overhead line and an underground power cable located within the source region of a surface nuclear detonation	14
5	Representation of the current surge formed within the source region, on an overhead line, by a Norton equivalent source located at the source region boundary	15
6	Time-domain waveform for vertical, radiated SREMP electric field at a distance of 10,000 meters from the origin of a one-Megaton surface nuclear detonation	16
7	Elemental division of power system	21
8	Overview of HEMP assessment methodology to subsystem level	22
9	Overview of MHD-EMP assessment methodology	23
10	Overview of SREMP assessment methodology for civilian electric utility systems	28
11	Overview of source region surge assessment methodology	29
12	Overview of system stability assessment methodology	30

STUDY TO ASSESS THE EFFECTS OF ELECTROMAGNETIC PULSE ON ELECTRIC POWER SYSTEMS

J. R. Legro
N. C. Abi-Samra
J. C. Crouse
A. R. Hileman
V. J. Kruse
E. R. Taylor, Jr.
F. M. Tesche*

ABSTRACT

The high-altitude detonation of a nuclear device over the continental United States can expose electric utility power systems to intense, transient electromagnetic pulses (EMP). In addition to the initial transient fields designated as early-time, high-altitude EMP and intermediate-time, high-altitude EMP, electromagnetic signals are also produced at times from seconds to hundreds of seconds after the burst. This signal has been designated as Magnetohydrodynamic-EMP (MHD-EMP).

Nuclear detonations at or near the earth's surface can also produce transient EMP. This electromagnetic phenomena has been designated as nuclear surface burst, source region EMP (SREMP).

This volume presents an executive summary of the preliminary research effort to: (1) investigate the nature and coupling of EMP environments to electric power systems, (2) define the construction of approximate system response models, and (3) document the development of a methodology to assess equipment and system vulnerability.

The research to date does not include an attempt to quantify power system performance in EMP environments. This effort has been to define the analytical methods and techniques necessary to conduct such assessments at a later time.

---

*LuTech, Incorporated, Lafayette, CA

1. INTRODUCTION

A single, high-altitude detonation of a nuclear device over the continental United States can expose large geographic areas to transient electromagnetic fields known as electromagnetic pulse (EMP). The initial electromagnetic fields produced by this event have been defined as high-altitude electromagnetic pulse (HEMP). Later-time, low-frequency fields, produced by the same detonation, have been defined as magnetohydrodynamic electromagnetic pulse (MHD-EMP). Nuclear detonations, at or near the earth's surface, can also produce transient EMP fields. This electromagnetic phenomena has been defined as source region electromagnetic pulse (SREMP).

The Division of Electric Energy Systems (EES) of the United States Department of Energy (DOE) has developed a Program Plan [1] to investigate potential vulnerability of civilian electric power systems to Nuclear EMP events. This unclassified research effort is being conducted under the technical leadership of the Oak Ridge National Laboratory (ORNL).

Oak Ridge National Laboratory has implemented the DOE Program Plan as a sequential series of three research phases. The Phase I research concentrates on the development of applicable power system models and assessment methodologies necessary to investigate power system performance under Nuclear EMP conditions. Phase II employs the models and methodologies of Phase I to perform preliminary system assessments for selected nuclear weapon scenarios. Phase III encompasses detailed system assessments and the exploration of possible hardening approaches, where necessary, to mitigate adverse power system performance due to Nuclear EMP.

A four-volume report documents the ORNL Phase I research conducted by Westinghouse Advanced Systems Technology and its associated sub-contractors. The Westinghouse Phase I research team organization is

shown in Figure 1. The organization was constructed to complement the Westinghouse power system capability with the EMP expertise of LuTech, Inc. Electric utility perspective was provided by the Arizona Public Service Company and the Southern California Edison Company.

The Phase I study approach is shown in Figure 2. For each type of nuclear detonation, the initial research focused on the development of unclassified EMP environmental descriptions applicable to the assessment of electric utility systems. EMP interaction modes with power systems were investigated to develop the necessary system models. An assessment methodology was then developed to assess possible EMP/system interaction and the range of system response(s). An experimental program was specified to support refinement of both models and methodology. The final task was the detailed development of the Phase II technical scope.

The Westinghouse Phase I research program was conducted under guidelines provided by the Oak Ridge National Laboratory. These guidelines, discussed in detail in the applicable report volume(s), are summarized as follows:

- The Phase I research was conducted as an unclassified program. All data pertaining to nuclear weapon effects was obtained from unclassified sources. Such information should <u>not</u> be interpreted to represent actual nuclear weapon characteristics or maximum EMP threat environments.

- The EMP transient fields of interest are those produced by the high-altitude and/or surface nuclear detonation(s). The phenomena known as "Nuclear Lightning," associated with nuclear surface detonations, was intentionally <u>excluded</u> from the Westinghouse scope of work.

- Power system interaction models were developed for EMP frequencies ranging from mid-frequencies on the order of 10 MHz to frequencies less than 60 Hz.

- The methodology was constructed so that major subsystems, such as generation plants, could be separately assessed and the results used in an assessment of the total system.

This Executive Summary presents an overview of the Phase I research documented in successive volumes of this report. A discussion is presented of the approach to integrated, multi-burst nuclear EMP events. This document includes a summary of the research conclusions and recommendations reached during Phase I of the program.

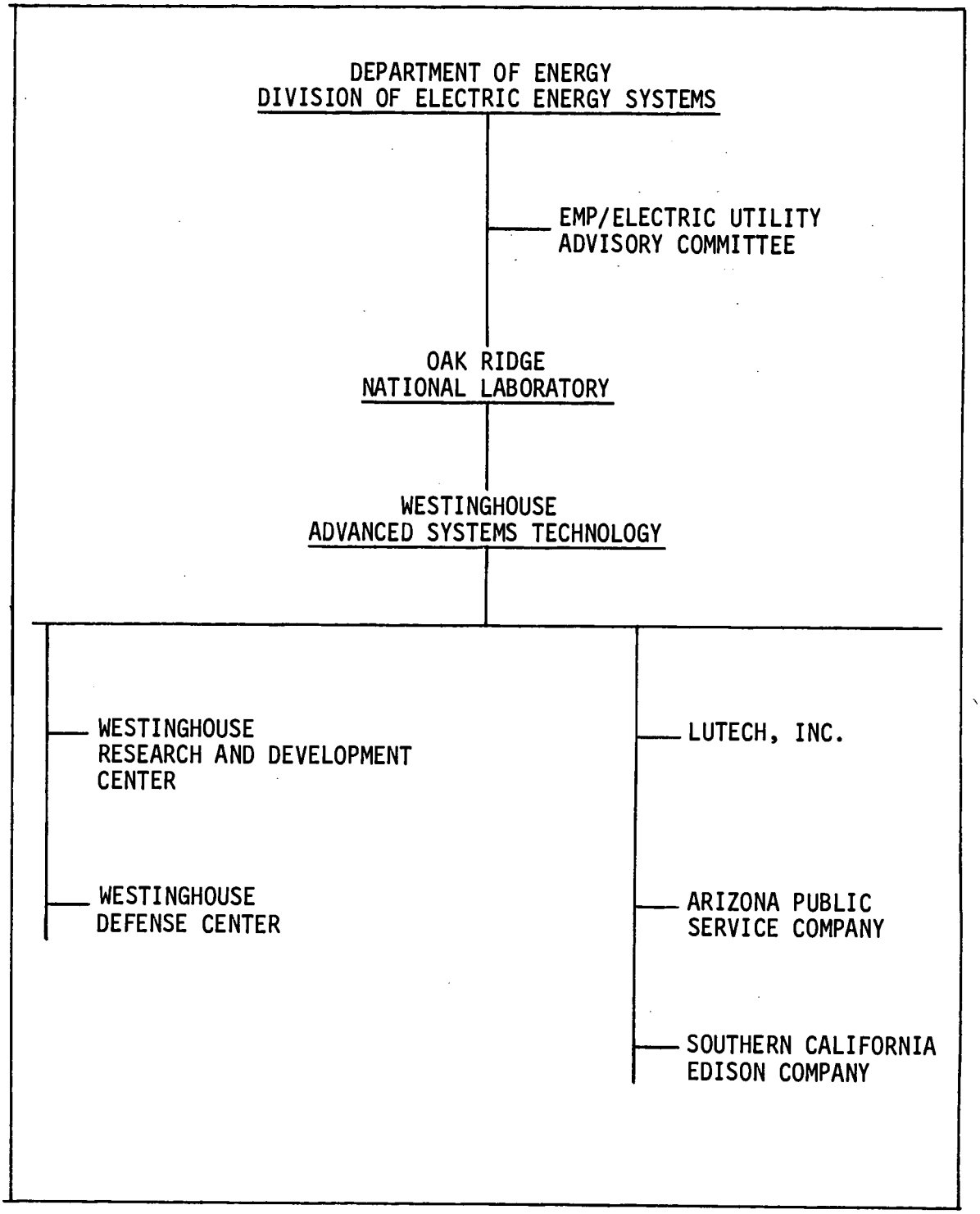


Fig. 1. Phase I Research Organization

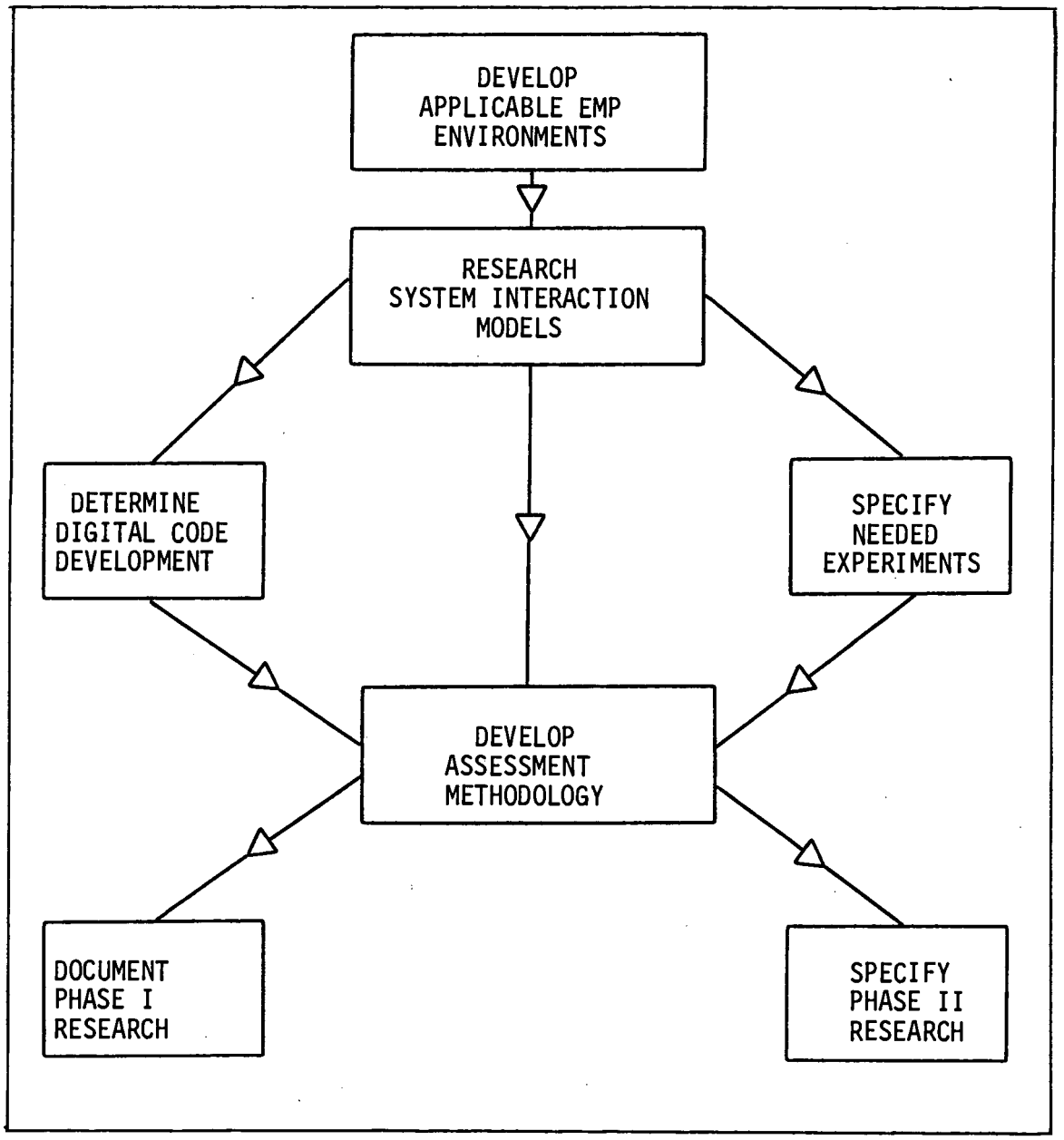


Fig. 2. Phase I Study Approach

2. HIGH-ALTITUDE DETONATION NUCLEAR EMP ENVIRONMENTS

When a nuclear weapon is detonated at altitudes greater than 40 kilometers, weapon effects interact with the earth's upper atmosphere and geomagnetic field to produce transient electromagnetic fields (EMP). For these heights of detonation, EMP is the significant weapon effect experienced by the electric power system. In time-order of appearance, components of the total EMP signal have been designated: 1) early-time HEMP, 2) intermediate-time HEMP, and magnetohydrodynamic EMP (MHD-EMP).

Any methodology developed to investigate the interaction of high-altitude nuclear EMP and electric power systems must incorporate appropriate, electromagnetic descriptions as the threat specification(s). Such specifications necessarily include an appreciation of the physics associated with EMP production and the physical and functional properties of the system under investigation.

For early-time and intermediate-time HEMP, defined as incident electric fields at the earth's surface, complete specification requires knowledge of the following:

- Area of illumination
- Field peak magnitude
- Field time-domain waveshape
- Field angle of incidence
- Field polarization

The electric field magnitude, waveshape, angle of incidence, and polarization are not constant throughout the area of illumination. Instead, they vary as functions of the orientation of any local observation point with respect to the origin of detonation.

Previous investigations of spatially small systems [2,3] have adopted a "worst-case" HEMP threat specification. The incident electric field waveform is expressed as a bounded double exponential of the form:

$$E(t) = E_0(e^{-\alpha t}-e^{-\beta t}) \qquad (1)$$

Where:

$$E_o = 5.25 \times 10^4 \text{ V/m}$$

$$\alpha = 4.0 \times 10^6 \text{ sec}^{-1}$$

$$\beta = 4.76 \times 10^8 \text{ sec}^{-1}$$

The waveform of Equation (1) is assumed to be at an angle of incidence, and polarization which provides maximum excitation to the system under examination. Such a "worst-case" specification, although physically unrealizable, does serve to place an upper bound on HEMP interaction with a spatially small system.

The civilian power system of generation, transmission and distribution is not a spatially small system within the total area of HEMP illumination. For system level analysis, the use of a spatially invariant HEMP threat specification can seriously overestimate HEMP interaction and system response. For example, numeric calculations of open-circuit voltage(s) at the end of electrically long lines using the "worst-case" threat can overestimate the voltage peak magnitude by an order of magnitude.

The Phase I research strongly suggests that, for system level electric power system assessments, at least the early-time HEMP threat specification should retain the spatial variation of the signal in order to more accurately investigate the range of possible system response(s). An approximate technique to estimate the E_o, in terms of Equation (1), as well as the local angle of incidence and polarization, is discussed in detail in Volume 2 of this report series.

A more recent approach to HEMP threat specification is to separate the total HEMP signal into an early-time HEMP signal and an intermediate-time HEMP signal. The early-time HEMP incident electric field specification retains the time-domain waveform of Equation (1). In the case of intermediate-time HEMP, little unclassified data is available

to develop as complete a definition. Intermediate-time HEMP incident electric field(s) have been described as follows:

- Average peak magnitude of 100 V/m
- Frequency spectra from 10^1 to 10^5 Hz
- Signal duration from 1 μsec to 1 second

In the absence of additional information, an unclassified definition for the intermediate-time HEMP incident electric field has been chosen as:

$$E(t) = E_1 \, e^{-\gamma t} \qquad (2)$$

Where:

$$E_1 = 100 \text{ V/m}$$

$$\gamma = 10^3 \text{ sec}^{-1}$$

The complete specification assumes that the spatial area of illumination, angle(s) of incidence and polarization(s) are the same as specified for early-time HEMP.

At elapsed times of seconds to hundreds of seconds after the weapon detonation, the power system is excited by very low frequency, magnetohydrodynamic EMP. Power system interaction to MHD-EMP is an important issue due to the existence of long transmission lines which are grounded at each end. MHD-EMP electric field specification requires knowledge of:

- Area of illumination
- Field peak magnitude
- Field waveshape
- Field orientation

The above parameters also vary spatially within the total area of illumination. As discussed in Volume 3 of this report series, an MHD-EMP electric field specification is developed as follows:

$$E(t) = E_2(x,y)\ \bar{e}(x,y)\ f(t) \qquad (3)$$

The term $E_2(t)$ is the spatial dependence of the electric field peak magnitude. The term $\bar{e}(x,y)$ reflects the spatial dependence of electric field direction. The term f(t) represents a normalized, spatially invariant, time domain waveform.

The MHD-EMP electric field calculated by Equation (3) is the total field. This is in contrast to Equations (1) and (2) where the E(t) term is only the incident HEMP electric field. The peak magnitude of the MHD-EMP electric field may be on the order of 10 V/km depending on earth conductivity.

A complete definition of the EMP produced by a single high-altitude detonation requires both HEMP and MHD-EMP specifications. The unclassified literature does not contain unified environmental descriptions for multiple, high-altitude nuclear detonations. The authors suggest that the following approximations may be acceptable for such scenarios:

- For simultaneous detonations (time-separation greater than a few microseconds but less than one second), where the areas of direct illumination do not overlap, the total specification is the independent specification for each detonation.
- For simultaneous detonations where the HEMP areas of direct illumination do intersect, the applicable total specification of the incident electric field is the time-superposition of the individual incident fields.
- For detonations time-spaced greater than one second, the HEMP signal of the second detonation is considered to be a fast transient signal occurring within the MHD-EMP environment of the first detonation.
- For detonations time-spaced greater than 300 seconds, each detonation is treated as an independent, separate event.

3. SURFACE DETONATION NUCLEAR EMP ENVIRONMENTS

When a nuclear weapon is detonated at or near the surface of the earth, intense transient electromagnetic fields are produced in a spatially local area surrounding the burst origin. This area is known as the source (deposition) region. At distances beyond the source region spatial boundary, a transient radiated electromagnetic field is also created. The phenomena are designated as Source Region EMP (SREMP).

As presented in Volume 4 of the report series, elements of the electric power system physically near the burst origin will experience the full range of weapon effects in addition to SREMP excitation. Non-EMP effects include: 1) craterization and ejected material, 2) fireball, and 3) peak-overpressure shock waves in air. Figure 3 depicts the spatial extent of these selected weapon effects with respect to the spatial extent of the EMP source region for a nominal one-Megaton surface nuclear detonation.

Civilian electric power systems, as presently constituted, have not been intentionally designed to withstand the weapon effects of surface nuclear detonations. The Phase I research strongly suggests that, for distances out to the 3.5 psi peak-overpressure contour (Fig.3), the power system will be damaged to a level where it can no longer perform its intended function(s). For weapon yields greater than 100-kilotons, available data suggests that the 3.5-psi peak-overpressure spatial boundary will exceed the EMP source region spatial boundary. Based on the concept of "balanced survivability" of a system to nuclear weapon effects, it is not constructive to assess SREMP effects on the power system located deep within the nuclear source region. System response to SREMP threat environments may be significant beyond the distance of the initial, non-EMP direct damage.

The Phase I research, presented in Volume 4 of this report series, suggest that a reasonable location to begin the definition of the SREMP environment, for civilian power system assessment, is at the source

region spatial boundary. The SREMP environmental definition focuses on the following phenomena:

- Transient electrical surges induced on power lines and cables physically traversing the source region boundary. These electrical surges are conducted away from the source region on lines and cables to the remaining power system before the line or cable is physically destroyed by other weapon effects.

- The SREMP transient electromagnetic fields existing for some distance beyond the source region.

Unclassified investigation of electrical surges, formed within the source region and conducted away to the system via power lines and cables, may be facilitated by the adoption of "canonical" surge waveforms defined at the source region boundary. Such a specification may take the form of the time-domain waveform for the short-circuit current. An example of such surge waveforms for an overhead line and an underground cable are shown in Figure 4. The source region conducted surge may then be modeled by a Norton equivalent source and appropriate source impedance located at the source region boundary. An illustration of this approach is shown in Figure 5. The Norton source approach for affected power lines and cables allows for system assessment in the absence of detailed calculations of EMP field interaction within the source region.

The physical asymmetry of the nuclear surface detonation source region, due to the air-ground interface, produces net transient SREMP fields outside the source region. These fields propagate in radial directions away from the source region. Again, a rational location to define this aspect of the SREMP threat is at the source region spatial boundary. The time-domain waveform for this radiated SREMP electric field is shown in Figure 6. The electric field polarization is taken to be vertical. Electric field strength attenuation with increasing distance from the source region is conservatively approximated as a function of distance^{-1}.

The above discussion is concerned with the appropriate SREMP threat specification for a single nuclear surface detonation. For investigations which include multiple surface detonations, the authors suggest that the following approximations may be acceptable:

- For simultaneous surface detonations where the respective source regions do not physically intersect, the total SREMP threat specification may be taken as independent source regions and superimposed radiated fields.
- For simultaneous surface detonations, spaced such that the source regions do physically intersect, the two individual detonations can be replaced with a single weapon detonation of combined equivalent yield.
- Time-spaced surface detonations at the same or physically separate locations can be treated as independent events.

For scenarios that include joint high-altitude plus surface detonations, the authors suggest that the following approximation may be acceptable:

- For simultaneous high-altitude plus surface detonations, the joint EMP threat specification consists of any SREMP conducted surges combined with the high-altitude radiated HEMP and MHD-EMP specification.
- In the case of time-separated joint detonations, each detonation is treated as an independent event.

It is important to stress that the above EMP threat specifications have been developed to support unclassified assessment of civilian electric power systems. All assumptions and approximations should not be construed as applicable to any other type of system.

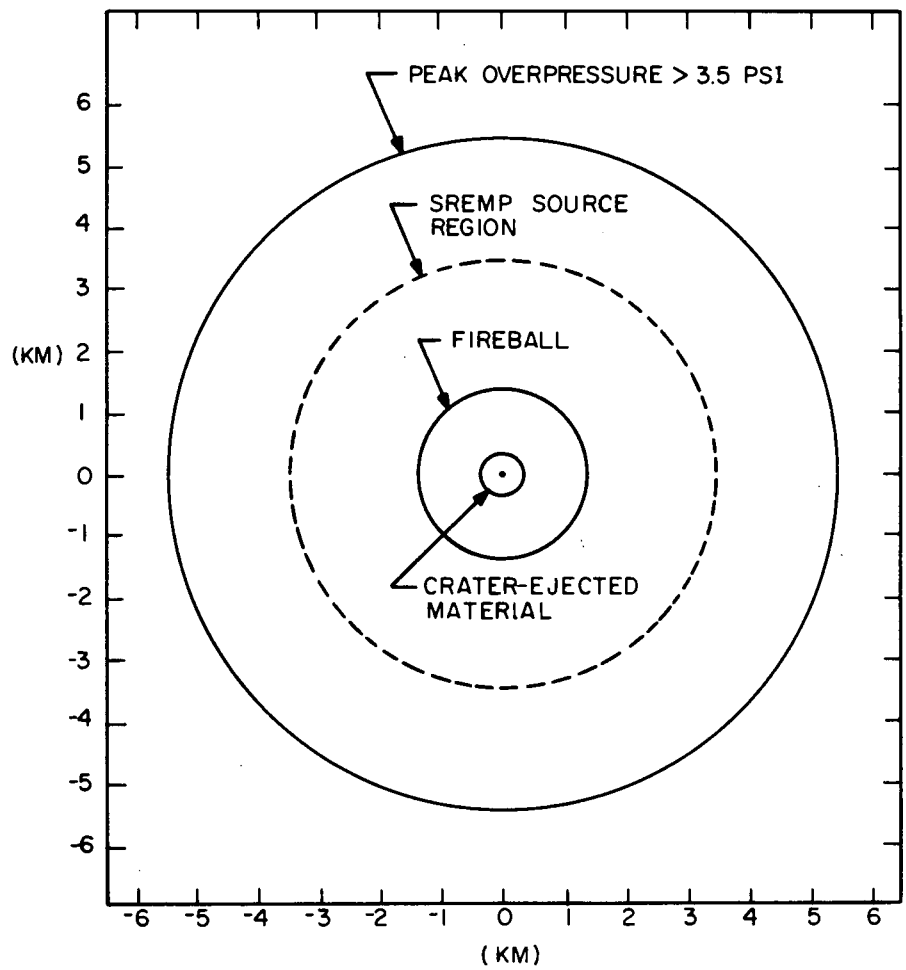


Fig. 3. Spatial extent of selected effects from a one-Megaton surface nuclear detonation (Plan View).

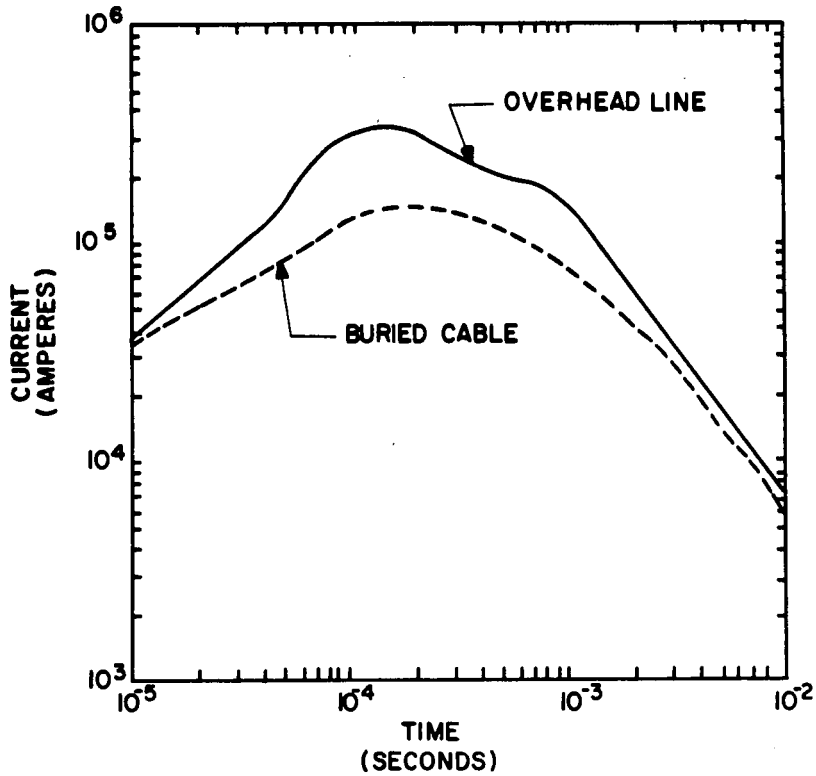
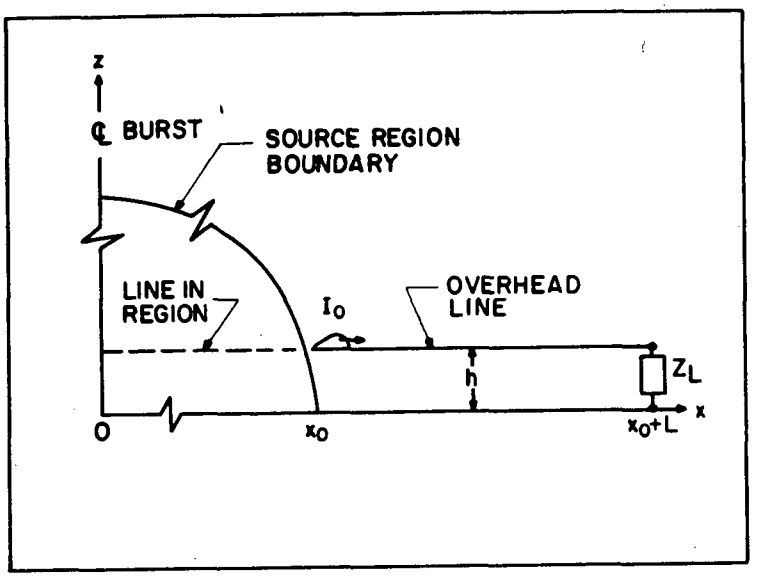
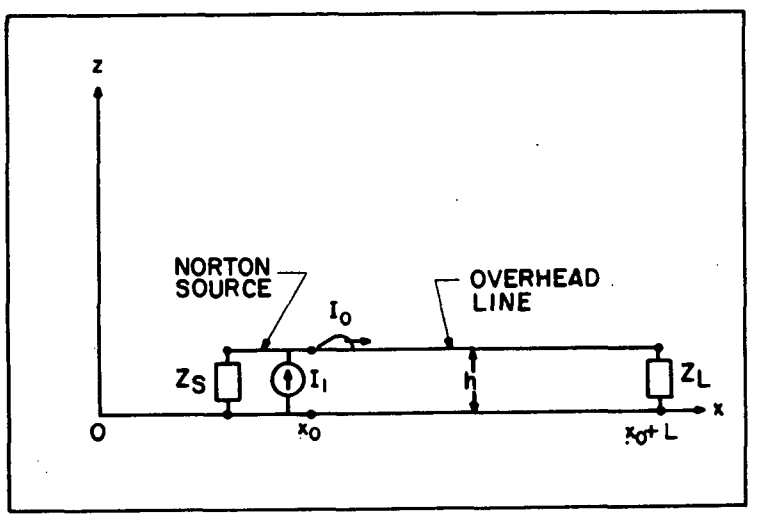


Fig. 4. Transient current surge induced on an overhead line and an underground power cable located within the source region of a surface nuclear detonation [4].



a) Physical Configuration



b) Equivalent Circuit Model

Fig. 5. Representation of the current surge formed within the source region, on an overhead line, by a Norton equivalent source located at the source region boundary.

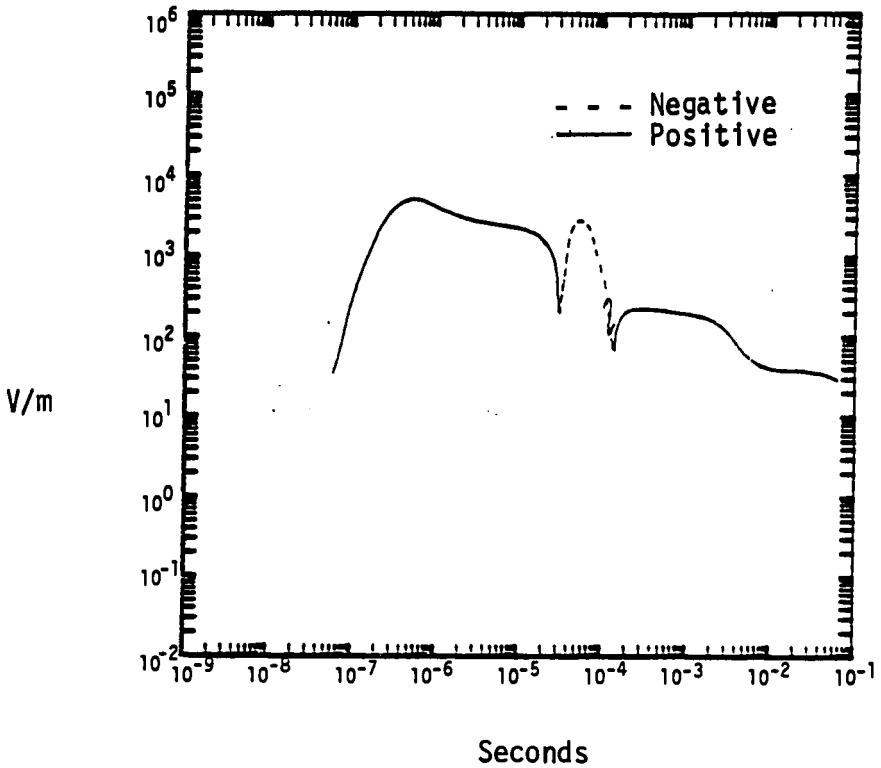


Fig. 6. Time-domain waveform for vertical, radiated SREMP electric field at a distance of 10,000 meters from the origin of a one-Megaton surface nuclear detonation [5].

4. HIGH-ALTITUDE DETONATION NUCLEAR EMP METHODOLOGY

Methodology is a system of principles, practices, and procedures applied to a set of knowledge to achieve a specified objective. The power system (or utility) network) is that group of equipment which, taken together, generates, transmits, and delivers electrical energy to customer load areas. Included are the communication and operational control necessary for this process.

This section presents a summary of the methodology developed to assess the effects of high-altitude nuclear EMP on civilian electric power systems. The total methodology incorporates assessment techniques for: 1) early-time HEMP, 2) intermediate-time HEMP, and 3) MHD-EMP threat environments. Since there are significant differences in the parameters of HEMP transient environments when compared to MHD-EMP transient environments, the relevant methodologies have been developed as separate modules. The linkage between the modules is the ability to characterize the power system "state" at an elapsed time subsequent to HEMP interaction but prior to MHD-EMP interaction. Thus, the output "state" of the HEMP assessment becomes the power system "state" set of initial conditions for MHD-EMP assessment.

The HEMP module of the total assessment methodology begins with a specification of the HEMP threat environment and the power system to be evaluated. The utility network is delineated into power delivery and communication systems. Examples of subsystems in the two systems include: 1) power generation stations, 2) generation, transmission, subtransmission and distribution substations, 3) lines between substations, 4) distribution networks, and 5) operations centers. The equipment within each subsystem can be further grouped according to the function they perform. Examples of such <u>functional groups</u> include: 1) the power delivery group, 2) the control group, 3) the protection group, 4) the instrumentation group, and 5) the communication group. It should be noted that all functional groups may or may not exist within

each subsystem. Each functional group is considered to consist of sets of circuits and devices. A circuit is a conductor or system of conductors in which an electrical current is intended to flow [6]. A device is an assembly of components to serve a specific purpose [6]. The device or circuit is the smallest entity considered by the methodology. An illustration of this system division is shown in Figure 7.

A key assumption embedded within the methodology is that for the initial period of time when HEMP interacts with the system, each functional group can be assessed separately and independently of all other functional groups. This parallel development is shown in Figure 8.

The probable response(s) of individual circuits or devices are incorporated in applicable "fault trees" to ascertain functional group and/or subsystem-level response. The complete system response is developed via conventional power system study techniques including load flow and stability studies.

A primary objective of the system-level analysis is to define the power system "state" at an elapsed time of seconds after the detonation. This state definition may be dynamic in the sense that the system may still be responding to the HEMP excitation at this time. This "state" definition serves as the system initial conditions for the MHD-EMP assessment module.

The MHD-EMP assessment methodology has been adapted from power system analysis techniques developed to explore the interaction of geomagnetic storms and electric power systems. The Phase I research, as discussed in Volume 3 of this report series, supports the validity of this approach.

An overview of the MHD-EMP assessment methodology is shown in Figure 9. The methodology focuses on the transient electromagnetic environment/power system interaction modes known to exist during geomagnetic storms. The initial system response of interest is the quasi direct-current(s) flowing in the system due to MHD-EMP excitation. The quasi-dc flow is considered to be simultaneous with normal 60 Hz current

flow. The joint, quasi-dc, and ac excitation of electromagnetic equipment, such as affected power and instrument transformers, may be the mechanism for equipment damage, upset, and/or system stability concerns.

The high-altitude nuclear EMP assessment methodology requires a significant level of digital code development as part of the Phase II scope of work. It is not intended that the total methodology should or can be accomplished as a single, unified simulation code. The methodology incorporates specific code modules as analysis tools to be used by knowledgeable power systems engineers. The digital codes used in the methodology can be divided into three categories:

- EMP Environment Codes
- EMP Interaction Codes
- System Response Codes

The EMP environment codes serve to translate a given high-altitude nuclear detonation, at a given location, to the spatially local EMP environments experienced by the power system. Environmental code development is required for both HEMP and MHD-EMP. The EMP interaction codes translate the local electromagnetic environment into the corresponding set(s) of transient stresses. HEMP coding requires a significant development effort. MHD-EMP codes can be adapted from existing codes developed to study geomagnetic storm/power system interaction. The required power system response(s) can be drawn from existing "fault tree" risk assessment codes and from conventional power system analysis codes.

The anticipated Phase II experimental program, discussed in Volumes 2 and 3 of this report series, focuses on equipment and device-level tests to determine and/or validate: 1) device transfer functions, 2) inherent strength of selected devices to withstand EMP induced surges, and 3) selected equipment performance under EMP conditions.

Where possible, the high-altitude EMP assessment methodology has been intentionally developed to build upon existing power system assessment techniques convolved with experience gained from military EMP

assessments. It is anticipated that the methodology may be refined and/or modified as the result of the Phase II research.

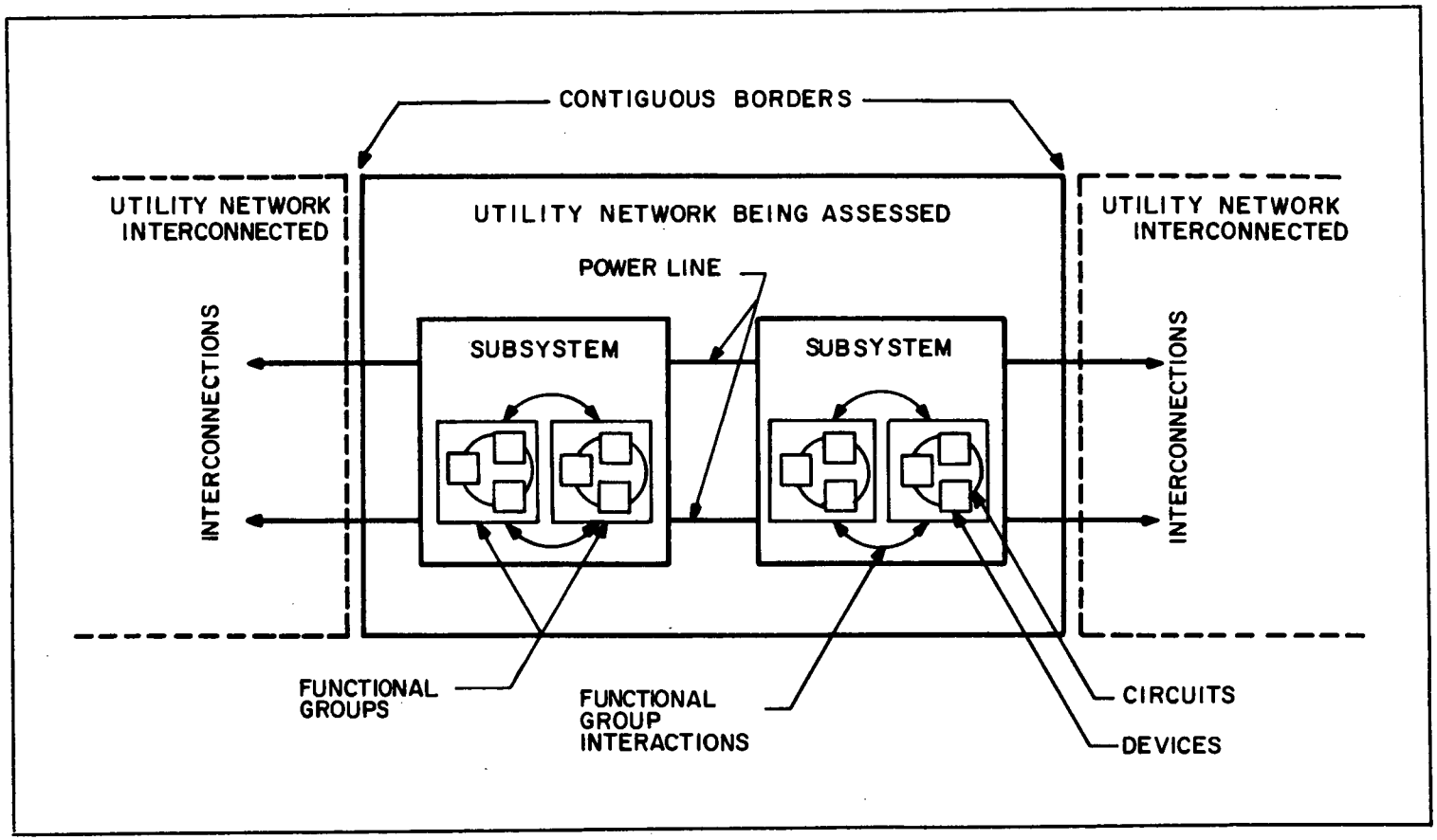


Fig. 7. Elemental division of power system.

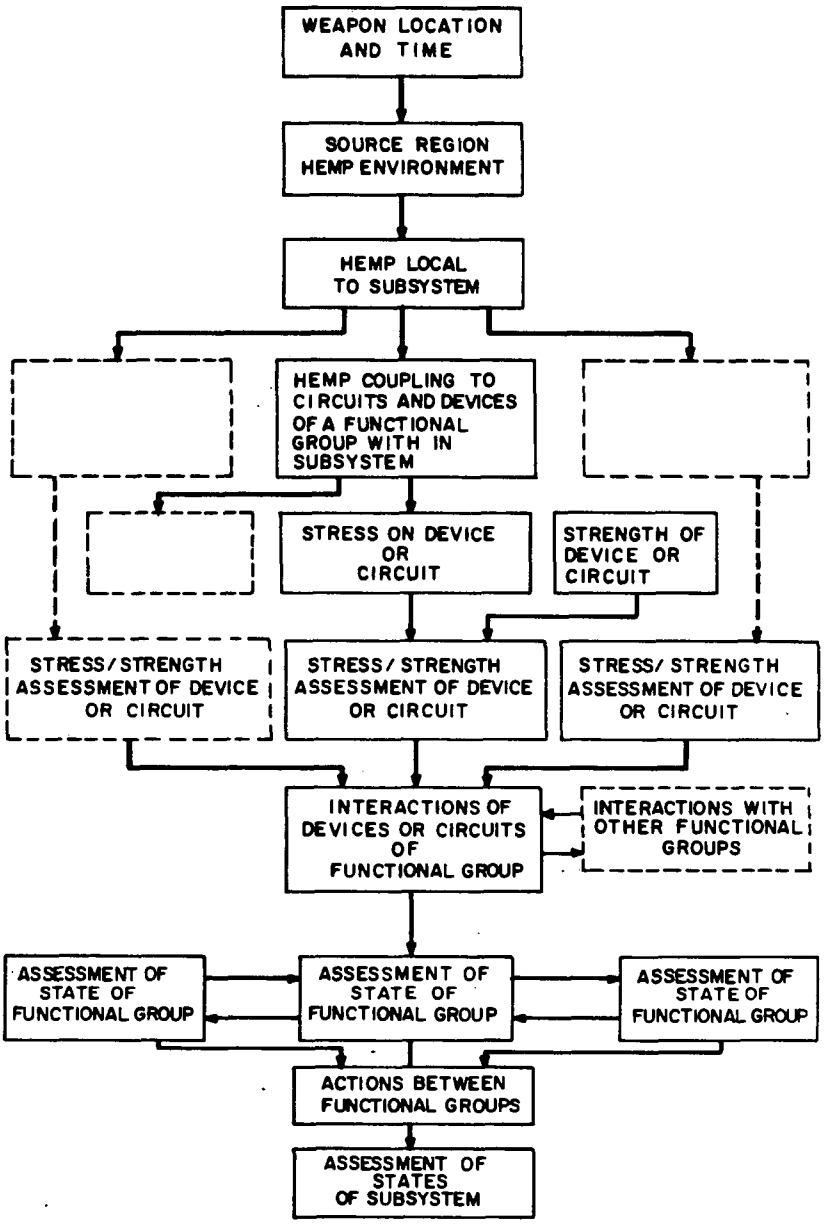


Fig. 8. Overview of HEMP assessment methodology to subsystem level.

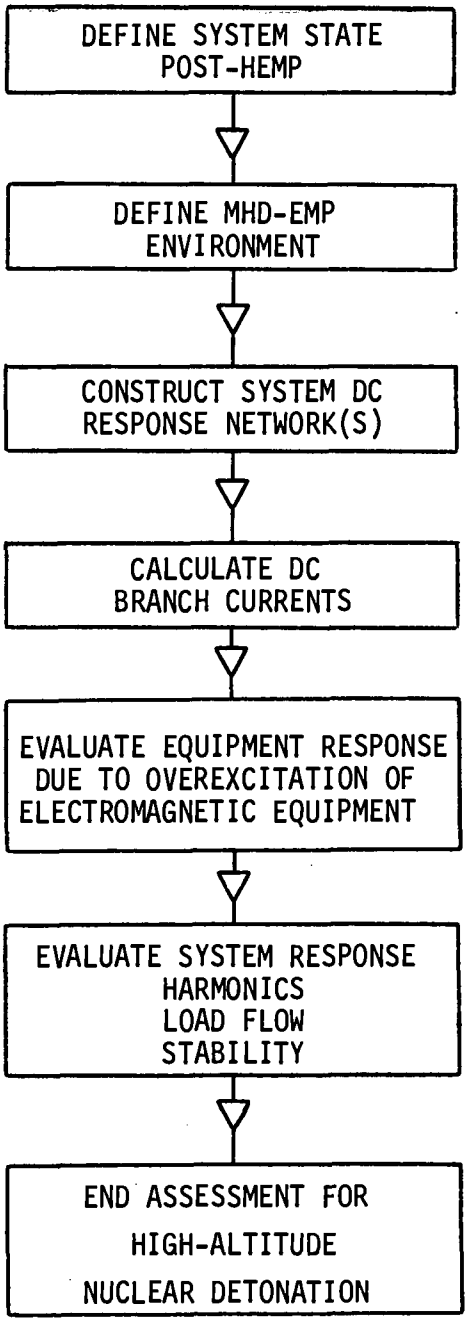


Fig. 9. Overview of MHD-EMP Assessment Methodology

5. SURFACE DETONATION NUCLEAR EMP METHODOLOGY

This section presents a summary of a structured process to assess the effects of surface nuclear SREMP on civilian power systems. The nature of the surface detonation is such that, if EMP did not exist, the civilian power system may still be severely affected by the remaining weapon effects. The methodology summarized herein is focused to investigate the additional risk due to electromagnetic pulse associated with the detonation. A complete assessment of all effects of the surface nuclear detonation on the civilian power system is beyond the scope of this EMP research program.

The methodology acknowledges three distinct, transient environments produced by the nuclear surface detonation. In terms of spatial coverage, the smallest of these environments is the source region. The threats for evaluation are transient electrical surges formed on lines exiting this region. These surges propagate away from the boundary into the grid prior to physical damage to the line. The system responses of interest include: 1) direct and/or consequential damage to equipment and facilities beyond the extent of non-EMP physical damage, and 2) system instability due to system protective reaction to such surges.

The second environment, also spatially local in area, is the area of initial, non-EMP direct damage. The methodology incorporates this threat by acknowledging: 1) the time-progressive physical destruction of the power system in this area, 2) the relevant loss of generation and/or load, and 3) system protective reaction to isolate this damaged portion of the grid from the rest of the system.

The third transient environment, of greatest spatial coverage, is system illumination by the SREMP radiated (free) fields beyond the source region. The questions and concerns associated with this phenomena are similar to those associated with HEMP investigation.

Preliminary analysis of the above environments strongly suggests that the order of consideration proceed as follows:

- Investigation of the SREMP radiated (free) field interaction with the system outside the source region.
- Evaluation of the consequences of surge propagation on lines intersecting the source region boundary.
- Incorporation of non-EMP physical damage in time-sequence of events.

An overview of this assessment progression is shown as Figure 10. Recursive load flow/stability simulations are necessary to investigate the magnitude and extent of system disturbance.

The initial conditions for power system assessment include the following data:

- Surface nuclear detonation environmental threat parameters.
- Power system initial conditions; the state of the system at the time of detonation.
- The geographic origin of the detonation.

Unlike high-altitude detonations, where EMP can illuminate vast areas, EMP environments for surface detonations are relatively local in extent. It is important to note that a spatial shift of a few kilometers in the origin of the surface weapon detonation may result in significantly different power system assessment results for otherwise identical scenarios.

The SREMP radiated field assessment methodology is qualitatively similar to that summarized for high-altitude HEMP. Electrical surges on lines, due to SREMP radiated field excitation, have similar time-domain waveforms to those induced by lightning. Unlike early-time HEMP excitation, the surge peak magnitude, expressed in terms of an open-circuit voltage at a location of interest, <u>may not be maximum</u> for increasing

increasing lengths of line. This difference is due, in part, to the attenuation as a function of increasing distance from the origin of the SREMP incident electric field magnitude.

As discussed in Volume 4 of this report series, the canonical surge waveform, ascribed to the source region surge, has a rise time of hundreds of microseconds and a decay time of several milliseconds. This waveshape is quite similar to that defined for power system switching impulse [7]. Thus, existing power system switching surge analysis can be adapted to develop possible system responses. An overview of this methodology is shown in Figure 11.

Given that the time-domain waveshape of the SREMP surge is similar to that defined for switching impulse, the prospective crest and energy contained in the SREMP surge far exceed anything experienced by the system in normal operation. The methodology addresses: 1) the profile of SREMP surge transient overvoltage along the line, 2) operation, and potential damage of surge arresters, 3) possible damage to power transmission and distribution equipment, and 4) penetration of the SREMP surge into the network.

At the conclusion of the source region surge analysis, the elapsed real-time into the scenario is several milliseconds. The methodology now incorporates selected non-EMP physical damage to the system. Such damage cannot be taken to occur all at the same elapsed time. Above ground lines and facilities, located at the 3.5 psi contour, may not experience direct damage for elapsed times of seconds after the detonation. An overview of this portion of the complete methodology is shown in Figure 12.

The non-EMP damage may be divided into a minimum of two areas: 1) an inner area defined by the fireball radius, and 2) an outer area defined by the 3.5 psi peak-overpressure contour. If the system remains stable after the fireball damage is added, the peak-overpressure damage is included and the stability analysis continued. A concluding assessment is done for system state.

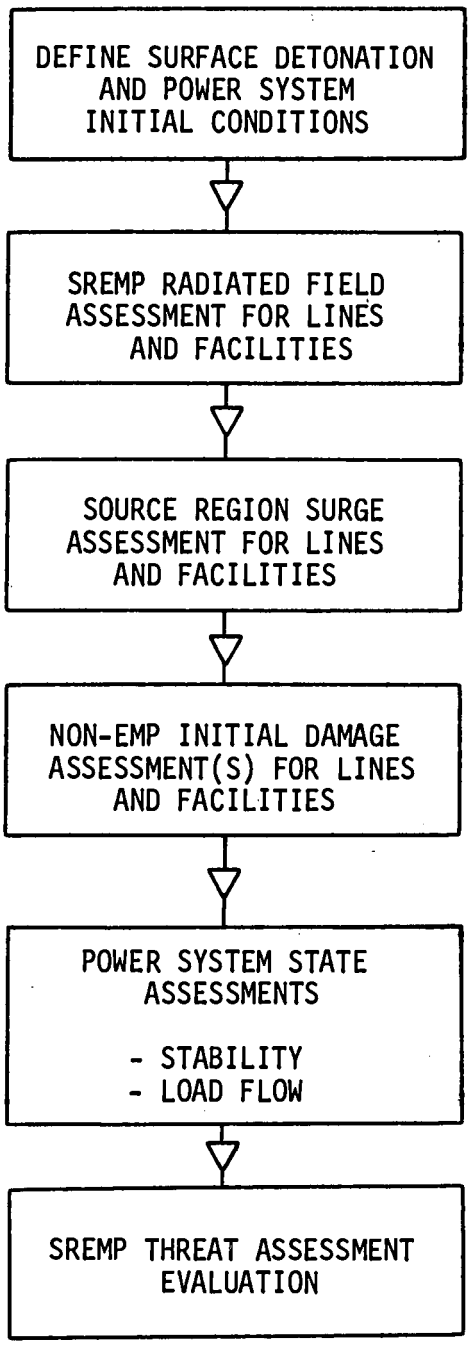


Fig. 10. Overview of SREMP assessment methodology for civilian electric utility systems.

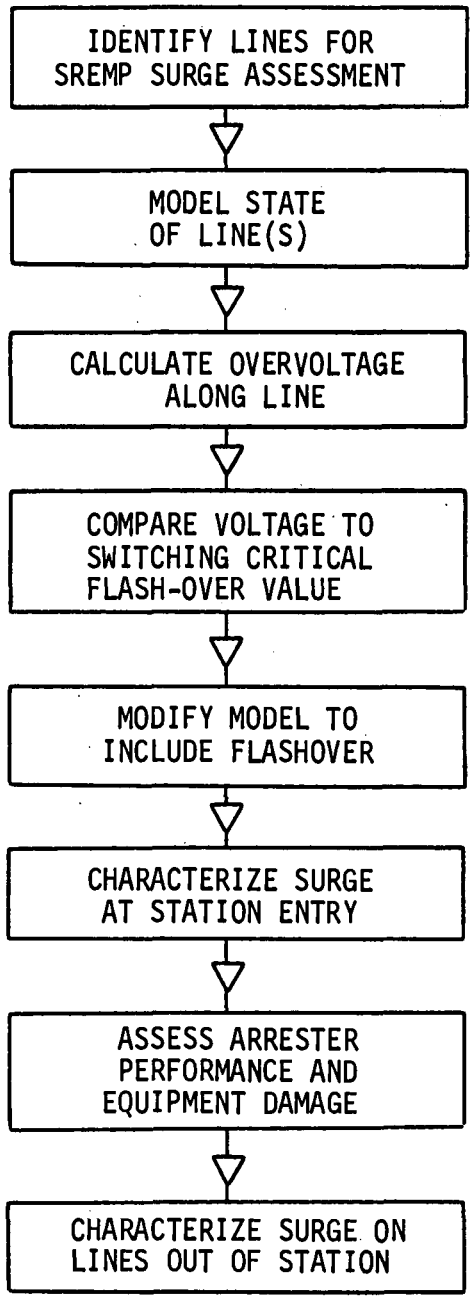


Fig. 11. Overview of source region surge assessment methodology.

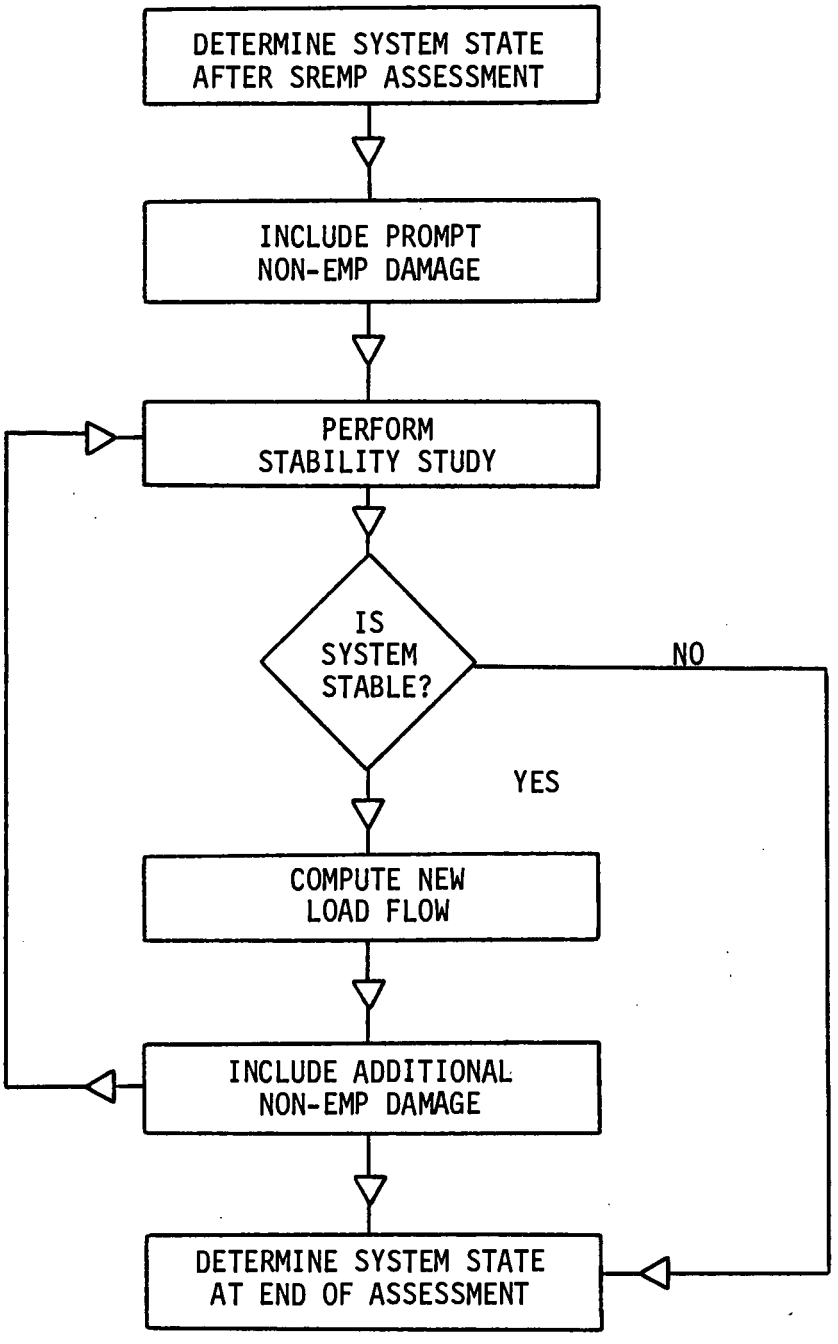


Fig. 12. Overview of system stability assessment methodology.

6. PHASE II RESEARCH

A Phase I task was the development of Phase II research recommendations. The principal objectives of the Phase II work are: validation of the models and methodology developed in Phase I, and a preliminary assessment of power system performance under EMP conditions for selected weapon scenarios.

The areas selected for further research consist of the following:

1. Develop Scenario definitions for Power System/EMP Simulation and Assessment. In this task, a set of "reasonable," worst-case weapon scenarios will be specified to support methodology validation and preliminary assessment. It is planned that the scenarios will include both high-altitude and surface nuclear detonations.

2. Develop Electric Utility Power System Data Base. Select specific electric utilities for assessment. The necessary data bases will be developed for these systems.

3. Develop Digital Computer Codes for EMP Power System Assessment. In this task, new digital computer codes necessary to perform the assessment will be written. It is intended that existing bodies of code will be used where applicable.

4. Perform Preliminary Parametric Studies on EMP Interaction with Power Systems. The task objective is to develop a set of EMP test surges to be used in the experimental program. The task will include an investigation of the feasibility of specifying a standard EMP test surge(s) for equipment certification.

5. Experimentally Determine Component Response. In this task, a set of experiments will be performed to determine the response of selected power system equipment to EMP fields and surges. The results of the experiments will be incorporated into the assessment methodology.

6. Perform Interaction Studies on EMP Interaction with the Power System Grid. The results of Tasks 1 to 5, and the methodology developed under the Phase I research, will be

used to perform a simulation study of EMP coupling with selected power systems.

7. Assess the Effects of EMP Induced Transients on Transmission and Distribution Systems. In this task, a preliminary assessment will be performed on selected T&D systems.

8. Assess the Effects of EMP on Power System Control and Communication. In this task, a preliminary assessment will be performed to investigate the performance of selected power system operational control and communication functions under EMP conditions.

9. Assess the Effects of EMP on Generation. In this task, a preliminary assessment will be performed to assess the performance of selected electric power generation stations under EMP conditions. This task will also include a review of the United States Nuclear Regulatory Commission Report NUREG/CR-3069 [2] conclusions regarding nuclear power plant safe-shutdown under EMP conditions.

10. Preliminary Power System Assessment. Based on the preceding Tasks and the Phase I research, a preliminary assessment will be accomplished as to the overall performance of selected electric utility systems under EMP conditions of interest.

11. Define Phase III Research Activities. Near the end of the Phase II work, a technical definition of Phase III research activities will be developed.

12. Reporting. All work performed under the Phase II research effort will be documented in a series of individual Task Reports and a Final Report.

The Phase II tasks will be accomplished in 24 consecutive calendar months.

7. CONCLUSIONS AND RECOMMENDATIONS

This section presents a summary of the Phase I research conclusions and recommendations documented in Volume 2, Volume 3, and Volume 4 of this report series.

In the areas of high-altitude nuclear HEMP environmental definitions, methodology development and systems analysis, the following conclusions are presented:

- For electric utility system assessment, the environmental description of early-time HEMP should retain the spatial variation of the incident HEMP electric field in lieu of a spatially invariant "worst case" definition.

- The existing, unclassified data for intermediate-time HEMP incident electric field(s) are not sufficient to develop a system-level environmental description to the same detail as early-time HEMP. The description discussed in Section 2 of this volume represents an initial effort by the authors to include intermediate-time HEMP within the methodology.

- For power system assessment, HEMP excitation of electrically long lines can be accomplished by transmission line techniques.

- The nature and time-duration of initial power system excitation by early-time HEMP is such that major subsystems can be initially assessed as a parallel set of tasks. The concept of "critical line length," combined with power system time constants, supports this conclusion.

- A major uncertainty, in the assessment of power system components and equipments, is the absence of existing "strength" data bases required for direct comparison to HEMP stress.

- The use of fault-tree assessment techniques provides a structured methodology to explore the interaction of power system functional groups, devices and circuits. Specific fault-tree development requires the interactive participation of knowledgeable power system engineers.

- Significant digital code development will be required, in the Phase II research, to incorporate the HEMP coupling techniques and environmental parameters presented in Volume 2 of this report series. Existing power system analysis codes for: 1) short-circuit studies, 2) load flow studies, and 3) stability studies can be directly incorporated in the methodology.

In the areas of high-altitude nuclear MHD-EMP environmental definition, methodology development and systems analysis, the following conclusions are presented:

- For power system analysis, the MHD-EMP environment can be defined as a spatial and time dependent, surface tangential, transient electric field.
- Previously developed MHD-EMP environmental formats are not in a format that can be directly used in power system analysis. An approach for a suitable environmental definition is presented in Volume 3 of this report series.
- The nature of MHD-EMP power system excitation exhibits sufficient similarity to geomagnetic storm electromagnetic environments that a parallel assessment methodology can be defined.
- The initial power system response of interest are the time-varying induced direct currents flowing simultaneously with 60 Hz currents.

For surface nuclear SREMP environmental definitions, methodology development and systems analysis, the following conclusions are presented:

- The SREMP transient, electromagnetic environments, created by a surface nuclear detonation, are in addition to the initial, non-EMP weapon effects. Based on the concept of "balanced survivability," the total environmental definition must include selected non-EMP weapon effects.

- For civilian power system assessment, a rational spatial location to define the surface nuclear SREMP environment is at the source region boundary. The transient source region surge, conducted out of the source region via power lines and cables physically intersecting the source region boundary and the time-domain waveform of the SREMP radiated electric field at the source region boundary are the EMP threat environments of interest.

- For power lines and cables, jointly exposed to electrical surges formed within the source region and excited by the radiated field beyond the region, the source region surge may dominant system response.

The Phase I investigation of nuclear EMP interaction with civilian electric power systems has revealed several areas of additional research necessary to better limit assessment uncertainty. Such recommendations are beyond the anticipated scope of work for Phase II research.

The recommendations for additional research are:

- Detailed development of an unclassified HEMP environmental definition, incorporating both early-time and intermediate-time HEMP signals, applicable to civilian power system assessment.

- Additional investigations are necessary to determine the effects of corona on early-time HEMP interaction with overhead lines. These investigations should include experimental validation of analytical models.

- Specification and implementation of a test program to illuminate power system facilities with free-field HEMP simulators.

8. BIBLIOGRAPHY

1. Program Plan for Research and Development of Technologies and Systems for Electric Power Systems Under the Influence of Nuclear Electromagnetic Pulse, DOE/NBB-0033, United States Department of Energy, May 1983.

2. Interaction of Electromagnetic Pulse with Commercial Nuclear Power Plant Systems, NUREG/CR-3069, United States Nuclear Regulatory Commission, February 1983.

3. National Electric Power Grid Assessment Program - Phase I Final Report, D180-26951-3, Defense Nuclear Agency, June 1982.

4. Longmire, C. L. and J. L. Gilbert, "Theory of EMP Coupling in the Source Region," Defense Nuclear Agency Report No. 6269F, February 1980.

5. Longmire, C. L., "History and Physics of EMP," presentation at the Fourth NEM Symposium, Baltimore, MD, July 2, 1984.

6. IEEE Standard Dictionary of Electrical and Electronic Terms, IEEE Std. 100-1977, Second Edition, Institute of Electrical and Electronics Engineers, Inc., NY, NY.

7. IEEE Standard Techniques for High Voltage Testing, IEEE Std. 4-1978, Institute of Electrical and Electronics Engineers, Inc., NY, NY.

ORNL/Sub/83-43374/1/V1
Dist. Category UC-97a,b,c

INTERNAL DISTRIBUTION

1-24. P. R. Barnes
25. R. B. Braid
26. R. S. Carlsmith
27. F. C. Chen
28. L. G. Christophorou
29. R. I. Crutcher
30. S. J. Dale
31. W. Fulkerson
32. P. A. Gnadt
33. T. L. Hudson
34. J. M. MacDonald
35. F. W. Manning
36. B. W. McConnell
37. J. W. Michel
38-58. M. C. Miller
59. M. O. Pace
60. R. A. Stevens
61. J. P. Stovall
62-63. Central Research Library
64. Document Reference Section
65-66. Energy Information Library
67. Laboratory Records - RC
68-69. Laboratory Records Department
70. ORNL Patent Section

EXTERNAL DISTRIBUTION

71-80. N. C. Abi-Samra, Westinghouse Electric Corporation, Advanced Systems Technology, 777 Penn Center Boulevard, Pittsburgh, PA 15232

81. W. E. Adams, Director for Radiation, Defense Nuclear Agency, Washington, DC 20305

82. V. D. Albertson, Department of Electrical Engineering, 123 Church Street, S.W., University of Minnesota, Minneapolis, MN 55455

83. H. W. Askins, Jr., The Citadel, Charleston, SC 29409

84. C. E. Baum, NTYEE, Kirkland AFB, NM 87117

85. D. W. Bensen, Federal Emergency Management Agency, Research Division, 500 C Street, S.W., Washington, DC 20472

86. T. Bolt, ED-SD, U.S. Army Engineering, USAEDH, P.O. Box 1600, Huntsville, AL 35087

87. J. N. Bombardt, R&D Associates, 105 E. Vermijo Street, Suite 450, Colorado Springs, CO 80903

88. G. E. Brackett, Code H25, Navy Surface Weapons Center, 1091 New Hampshire Avenue, Silver Springs, MD 20903-5000

89. E. H. Brehm, Department GK/CN32, Brown, Boveri, and Cie, Aktiengesell Schaft, Postfach 351, D-6800 Mannheim 1, West Germany

90. F. C. Buchholz, Pacific Gas & Electric Co., 77 Beale Street, Room 2933, San Francisco, CA 94106

91. J. F. Buck, Wisconsin Electric Power Company, 231 W. Michigan, Milwaukee, WI 53201

92. L. M. Burrage, McGraw-Edison, P.O. Box 100, 11131 Adams Road, Franksville, WI 53126

93. H. S. Cabayan, Lawrence Livermore Laboratory, P.O. Box 5504, Livermore, CA 94550

94. F. L. Cain, Georgia Institute of Technology, Engineering Experiment Station, Atlanta, GA 30332

95. R. N. Carlile, Department of Electrical and Computer Engineering, University of Arizona, Tucson, Arizona 85721

96. I. J. Carney, Nuclear Survivability Organization, Boeing Aerospace Company, P.O. Box 3999, Seattle, WA 98124

97. V. L. Chartier, Bonneville Power Administration, P.O. Box 491-ER, Vancouver, WA 98666

98. K. K. Chen, Sandia National Laboratory, Drawer 1333, P.O. Box 5800, Kirkland AFB, NM 87185

99. H. E. Church, Aluminum Company of American, 1501 Alcoa Building, Pittsburgh, PA 15219

100. B. Cikotas, DNA/RAEE, 6801 Telegraph Road, Alexandria, VA 22310

101. C. F. Clark, Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208

102. R. E. Clayton, Power Technologies, P.O. Box 1058, 1482 Erie Boulevard, Schenectady, NY 12301-1058

103. A. Clerici, Sanelmi, Via Pergolesi 25, 20124 Milano, Italy

104. H. W. Colborn, North American Electric Reliability Council, Research Park, Terhume Road, Princeton, NJ 08540-3573

105. D. E. Cooper, Southern California Edison Company, P.O. Box 800, 2244 Walnut Grove Avenue, Rosemead, CA 91770

106. R. Cortina, ENEL-Centro Ricerca, Automatica, VIA Volta 1, Cologno Monzese (M1), Italy

107. G. Dahlen, Royal Institute of Technology, S-100-44, Stockholm, Sweden

108. J. Darrah, Headquarters NORAD/G5, Peterson AFB, CO 80914

109. Defense Technical Information Center, Cameron Station, Alexandria, VA 22314

110. J. J. Dougherty, Electric Power Research Institute, P.O. Box 10412, Palo Alto, CA 94303

111. W. M. Druen, 8200 South Memorial Parkway, Suite D, Huntsville, AL 35802

112. J. C. Engimann, Commonwealth Edison, 1319 S. First Avenue, Maywood, IL 60153

113. D. M. Ericson, Jr., Sandia National Laboratory, Division 6414, Kirkland AFB, NM 87185

114. W. E. Ferro, Electric Research and Management, Inc., P.O. Box 235, Thomaston, ME 04861

115. W. G. Finney, Project Manager, Stanley Consultants, Inc., Stanley Building, Muscatine, IA 52761

116. M. Fitzgerald, MITRE Corp., P.O. Box 208, Bedford, MA 01730

117. F. Fisher, General Electric Corporation, Electric Utility Systems Engineering Department, Building 5, Room 306, Schenectady, NY 12345

118. P. B. Fleming, Science and Engineering Associates, Inc., Mariners Square, Suite 127, 1900 North Northlake Way, P.O. Box 31819, Seattle, WA 98103

119. R. Fullwood, Science Applications, Inc., 5 Palo Alto Square, Suite 200, Palo Alto, CA 94304

120. M. R. Gent, North American Electric Reliability Council, Research Park, Terhume Road, Princeton, NJ 08540-3573

121. S. M. Gillis, Economic and Public Policy, Department of Economics, Duke University, Durham, NC 27706

122. W. Graham, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291

123. J. J. Grainger, 5004 Hermitage Drive, Raleigh, NC 27612

124. I. S. Grant, Power Technologies, Inc., 1482 Erie Blvd., Schenectady, NY 12305

125. A. R. Gritzke, U.S. Department of Navy, Theater Nuclear Warfare Project Office, Washington, DC 20360

126. J. Gut, Research Intitute for Protective Construction, Auf der Mauer 2, CH-8001 Zurich, Switzerland,

127. V. Guten, R-52, National Security Agency, Fort G. Mead, MD 20755

128. R. J. Harrington, George Washington University, Department of Electrical Engineering and Computing Science, Washington, DC 20052

129. M. F. Hebb, Florida Power Corp., P.O. Box 14042, Mail Code AB, St. Petersburg, FL 33733

130. M. H. Hesse, JEC 5008, Rennselear Polytechnic Institute, Troy, NY 12181

131. D. Higgins, JAYCOR, Santa Barbara Facility, P.O. Box 30281, 360 South Hope Avenue, Santa Barbara, CA 93105

132. D. W. Hilson, Tennessee Valley Authority, 1100 Chestnut Street, Tower 2, Chattanooga, TN 37402

133. F. C. Holdes, Pacific Gas & Electric Company, 3235-18th Street, San Francisco, CA 94110

134. W. S. Howington, Noranda Aluminum, Inc., P.O. Box 70, New Madrid, MO 63869

135. R. Hutchins, BDM Corporation, 1801 Randolph, S.W., Albuquerque, NM 87106

136. J. Hunt, Emergency Preparedness Administrator, San Diego Gas and Electric Company, P.O. Box 1831, San Diego, CA 92112

137. V. Inkis, Ontario Hydro, U7E1, 700 University Avenue, Toronto, Canada M5G1X6

138. Wasyl Janischewskyj, Electrical Engineering Dept., University of Toronto, Toronto, Canada M5S1A4

139. H. P. Johnson, Georgia Power Company, 270 Peachtree Street, 11th Floor, Atlanta, GA 30303

140. V. K. Jones, Science and Engineering Associates, Inc., Mariners Square, Suite 127, 1900 North Northlake Way, P.O. Box 31819, Seattle, WA 98103

141. F. R. Kalhammer, Director, Energy Management and Utilization Division, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303

142. W. Karzas, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291

143. K. W. Klein, Chief of Power Delivery Branch, Department of Energy, CE-143, Division of Electric Energy Systems, Forrestal Building, Room 5E-052, 1000 Independence Avenue, S.W., Washington, DC 20585

144. N. Kolcio, American Electric Power, 1 Riverside Plaza, Columbus, OH 43216

145. J. Labadie, IRT, 6800 Poplar Place, McLean, VA 22131

146. H. T. Lam, South Carolina Public Service Authority, 1 Riverwood Dr., Monks Corner, SC 29461

147. T. R. LaPorte, Professor, Political Science, Institute of Government Studies, University of California, 109 Moses Hall, Berkeley, CA 94720

148. R. C. Latham, Duke Power Company, P.O. Box 33189, Charlotte, NC 28242

149. A. Latter, R&D Associates, P.O. Box 9695, Marina Del Rey, CA 90291

150. J. S. Lawler, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37916

151. K. S. H. Lee, Dikewood Division of Kaman Science Corp., 2800 28th Street, Suite 3780, Santa Monica, CA 90405

152-161. J. R. Legro, Westinghouse Electric Corporation, Advanced Systems Technology, 777 Penn Center Boulevard, Pittsburgh, PA 15235

162. M. Lessen, Consulting Engineer, 12 Country Club Drive, Rochester, NY 14618

163. Library, JAYCOR, 205 S Whiting Street, Alexandria, VA 22304

164. J. Locasso, Rockwell International, 3370 Meraloma Avenue, P.O. Box 4192, Mail Code 031-BB17, Anaheim, CA 92803

165. C. L. Longmire, Mission Research Corporation, P.O. Drawer 719, Santa Barbara, CA 93102

166. W. C. Maklin, IRT Corporation, 6800 Poplar Place, McLean, VA 22101

167. R. M. Maliszewski, American Electric Power Service Corp., 1 Riverside Plaza, P.O. Box 16631, Columbus, OH 43216-6631

168. J. N. Mallory, Southern California Edison Co., P.O. Box 800, Rosemead, CA 91770

169. J. D. Martin, Harris Corporation, PRD Electronics Division, 6801 Jericho Turnpike, Syossett, NY 11791

170. P. S. Maruvada, Hydro-Quebec Institute of Research, 1800 Montee Ste-Julie, Varennes, Quebec, CANADA J0L2P0

171. R. G. McCormack, CERL, Corps of Engineers, P.O. Box 4005, Champaign, IL 61820

172. G. F. Meenaghan, Vice President for Academic Affairs and Dean of the College, The Citadel, Charleston, SC 29409

173. C. Menemenlis, University of Patras, Patras, Greece

174. A. S. Mickley, Philadelphia Electric Corp., 2301 Market Street, Philadelphia, PA 19101

175. I. N. Mindel, IIT Research Institute, 10 West 35th Street, Chicago, IL 60616

176. D. L. Mohre, Cajun Electric Power Corp., P. O. Box 15440, Baton Rouge, LA 70895

177. B. B. Mrowca, Baltimore Gas & Electric Co., P.O. Box 1475, Baltimore, MD 21203

178. K. Muller, IABG, Einsteinstrasse 20, 8012 Ottobrunn, West Germany

179. Este-M Murtha, Booz Allen and Hamilton, General Services Administration, 18th & F Streets, N.W., Washington, DC 10405

180. H. P. Neff, Department of Electrical Engineering, University of Tennessee, Knoxville, TN 37916

181. B. O. Nettles (Code 203), Naval Electronic Systems Engineering Center, Charleston, 4600 Marriott Drive, North Charleston, SC 29418

182. D. R. Nevius, North American Electric Reliability Council, Research Park, Terhume Road, Princeton, NJ 08540-3573

183. G. B. Niles, Baltimore Gas & Electric Company, Principal Eng. Room 1020, P.O. Box 1475, Baltimore, MD 21203

184. B. Noel, Los Alamos National Laboratory, Mail Station 5000, P.O. Box 1663, Los Alamos, NM 87545

185. B. Nowlin, Arizona Public Service Company, P.O. Box 21666, Phoenix, AR 85036

186. R. Oats, Atomic Weapons Research Establishment, Building D57, Aldermaston, Reading, RG74PR, England

187. G. Orrell, Dep. Associate Director for National Preparedness, Federal Emergency Management Agency, 500 C Street, S.W., Washington, DC 20555

188. L. Paris, University of Pisa, Via Diotisalvi 2, 56100 PISA

189. R. Parker, RDA, P.O. Box 9335, Albuquerque, NM 87119

190. R. Parkinson, Science Applications, Inc., 5150 El Camino Real, Suite B-31, Los Altos, CA 94022

191. A. Pigini, CESI-Via Rubahimo 59-Milano, Italy

192. J. B. Posey, Ohio Brass Co., 380 N. Main Street, Mansfield, OH 44903

193. M. Rabinowitz, Electric Power Research Institute, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303

194. W. A. Radaski, Metatech Corp., 358 South Fairview Avenue, Suite E, Goleta, CA 93117

195. J. J. Ray, Bonneville Power Administration, P.O. Box 3621, Portland, OR 97208

196. T. J. Reed, Westinghouse Electric Corporation, Advanced Systems Technology, 777 Penn Center Boulevard, Pittsburgh. PA 15235

197. R. L. Retallach, American Electric Power, 1 Riverside Plaza, Columbus, OH 43216

198. J. Richardson, National Academy of Science, 2101 Constitution Avenue, Washington, DC 20418

199. F. Rosa, Nuclear Regulatory Commission, Division of Systems Integration, MS P1030, Washington, DC 20555

200. D. H. Sandell, Harza Engineering Co., 150 South Wacker Drive, Chicago, IL 60606

201. J. A. Sawyer, MITRE Corp., MS-H070, P.O. Box 208, Bedford, MA 01703

202. R. A. Schaefer, Metatech Corp., 20 Sunnyside Avenue, Suite D, Mill Valley, CA 94941

203. M. Schechter, A.D.A., P.O. Box 2250(81), Haifa, 31021, Israel

204. H. Singaraju, Air Force Weapons Laboratory, Kirkland AFB, NM 87117

205. A. C. Smith, Jr., Beam Research Program, Lawrence Livermore National Laboratory, P.O. Box 808, Livermore, CA 94550

206. J. C. Smith, 1 Adams Avenue, P.O. Box 44, Canonsburg, PA 15317

207. R. Smith, DNA, RAEE, 6801 Telegraph Road, Alexandria, VA 22310

208. W. Sollfrey, RAND Corp., 1700 Main Street, Santa Monica, CA 90406

209. H. Songster, Electric Power Research Institute, Electrical Systems Division, 3412 Hillview Avenue, P.O. Box 10412, Palo Alto, CA 94303

210. G. K. Soper, Defense Nuclear Agency, Washington, DC 20305

211. S. Spohn, DB4C2, Defense Intelligence Agency, Washington, DC 20301

212. J. R. Stewart, Power Technologies, Inc., P.O. Box 1058, 1482 Erie Boulevard, Schenectady, NY 12301-1058

213. R. L. Sullivan, Department of Electrical Engineering, College of Engineering, University of Florida, Gainesville, FL 32611

214. I. O. Sunderman, Lincoln Electric System, P.O. Box 80869, Lincoln, NE 68501

215. R. W. Sutton, Science Applications, Inc., 1710 Goodridge Drive, P.O. Box 1303, McLean, VA 22102

216-225. F. M. Tesche, LuTech, Inc., 3742 Mt. Diablo Boulevard, Lafayette, CA 94549

226. L. Thione, CESI-Via Rubattino 54 20734, Milano, Italy

227. R. J. Thomas, 302 Phillips Hall, Cornell University, Ithaca, NY 14853

228. R. Torres, BDM Corporation, 1801 Randolph, S.W., Albuquerque, NM 87106

229. W. Tyler, NT, Kirkland AFB, NM 87117

230. M. A. Uman, Department of Electrical Engineering, University of Florida, Gainesville, FL 32611

231. E. F. Vance, Route 3, Box 268A, Fort Worth, TX 76140

232. D. R. Volzka, Wisconsin Electric Power Company, 231 West Michigan Street, Milwaukee, WI 53201

233. J. Vora, Nuclear Regulatory Commission, MS 5650 NL, Washington, DC 20555

234. C. D. Whitescarber, Martin Marietta Orlando Aerospace, Sandlake Road Complex (SLRC), Mail Point 399, P.O. Box 5837, Orlando, FL 32855

235. W. P. Wigner, 8 Ober Road, Princeton, NJ 08540

236. M. W. Wik, Forsvarets Materielverk, S-11588 Stockholm, Sweden

237. C. B. Williams, IRT Corp., 7650 Convoy Court, P.O. Box 80817, San Diego, CA 92138

238. W. H. Williams, Division Manager, AT&T Information Systems, Building 83, Room 1B23, 100 Southgate Parkway, Morristown, NJ 07960

239. D. D. Wilson, Power Technologies, Inc., P.O. Box 1058, Schenectady, NY 12301

240. U. P. Wissmann, AEG-Telefunken, General Electric Company, 1 River Road, Building 36-444, Schenectady, NY 12345

241. H. W. Zaininger, Zaininger Engineering Company, 3408 Vance Court, San Jose, CA 95132

242. Institute for Energy Analysis, ORAU - Library

243. Assistant Manager for Energy Research & Development, DOE/ORO Oak Ridge, TN 37830

244-897. Given for distribution as shown in DOE/TIC-4500 under Category UC-97a,b,c (Electric Energy Systems)