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THE EFFECTS OF HIGH-ALTITUDE ELECTROMAGNETIC PULSE (HEMP) ON TELECOMMUNICATIONS ASSETS

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**OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
WASHINGTON, D.C. 20305**

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NATIONAL COMMUNICATIONS SYSTEM

**TECHNICAL INFORMATION BULLETIN
88-3**

**THE EFFECTS OF HIGH-ALTITUDE
ELECTROMAGNETIC PULSE (HEMP)
ON TELECOMMUNICATIONS ASSETS**

JUNE 1988

**OFFICE OF THE MANAGER
NATIONAL COMMUNICATIONS SYSTEM
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JUNE 1988

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FOREWORD

The National Communications System (NCS) is an organization of the Federal Government whose membership is comprised of 23 Government entities. Its mission is to assist the President, National Security Council, Office of Science and Technology Policy, and Office of Management and Budget in:

- o The exercise of their wartime and non-wartime emergency functions and their planning and oversight responsibilities.
- o The coordination of the planning for and provision of National Security/Emergency Preparedness communications for the Federal Government under all circumstances including crisis or emergency.

In support of this mission the NCS has initiated and manages the Electromagnetic Pulse (EMP) Mitigation Program. The objective of this program is the removal of EMP as a significant impediment to timely reestablishment of regional and national telecommunications following an attack against the United States that includes high-altitude nuclear detonations. The program approach involves estimating the effects of High-altitude EMP (HEMP) on telecommunication connectivity and traffic handling capabilities, assessing the impact of available HEMP mitigation alternatives, and developing a comprehensive plan for implementing mitigation alternatives. This report summarizes available test results as they apply to the EMP Mitigation Program.

Comments on this TIB are welcome and should be addressed to:

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EXECUTIVE SUMMARY

EXECUTIVE SUMMARY

In response to Executive Order 12472 (E.O. 12472) and National Security Decision Directive 97 (NSDD-97), the Office of the Manager, National Communications System (OMNCS) sponsors the Electromagnetic Pulse (EMP) Mitigation Program. The objective of this program is the removal of EMP as a significant impediment to timely reestablishment of regional and national telecommunications following an attack against the United States that includes high-altitude nuclear detonations. The methodology for developing an EMP Mitigation Program plan was described in the OMNCS report, EMP Mitigation Program Approach of September 1987. The program approach involves estimating the effects of High-altitude EMP (HEMP) on telecommunication connectivity and traffic handling capability, assessing the impact of available HEMP mitigation alternatives, and developing a comprehensive plan for implementing mitigation alternatives. This report summarizes available test results as they apply to the EMP Mitigation Program, and supercedes all previous versions of this report.

PROGRAM APPROACH

The approach to the OMNCS EMP Mitigation Program is illustrated in Exhibit ES-1. This approach is composed of the following activities:

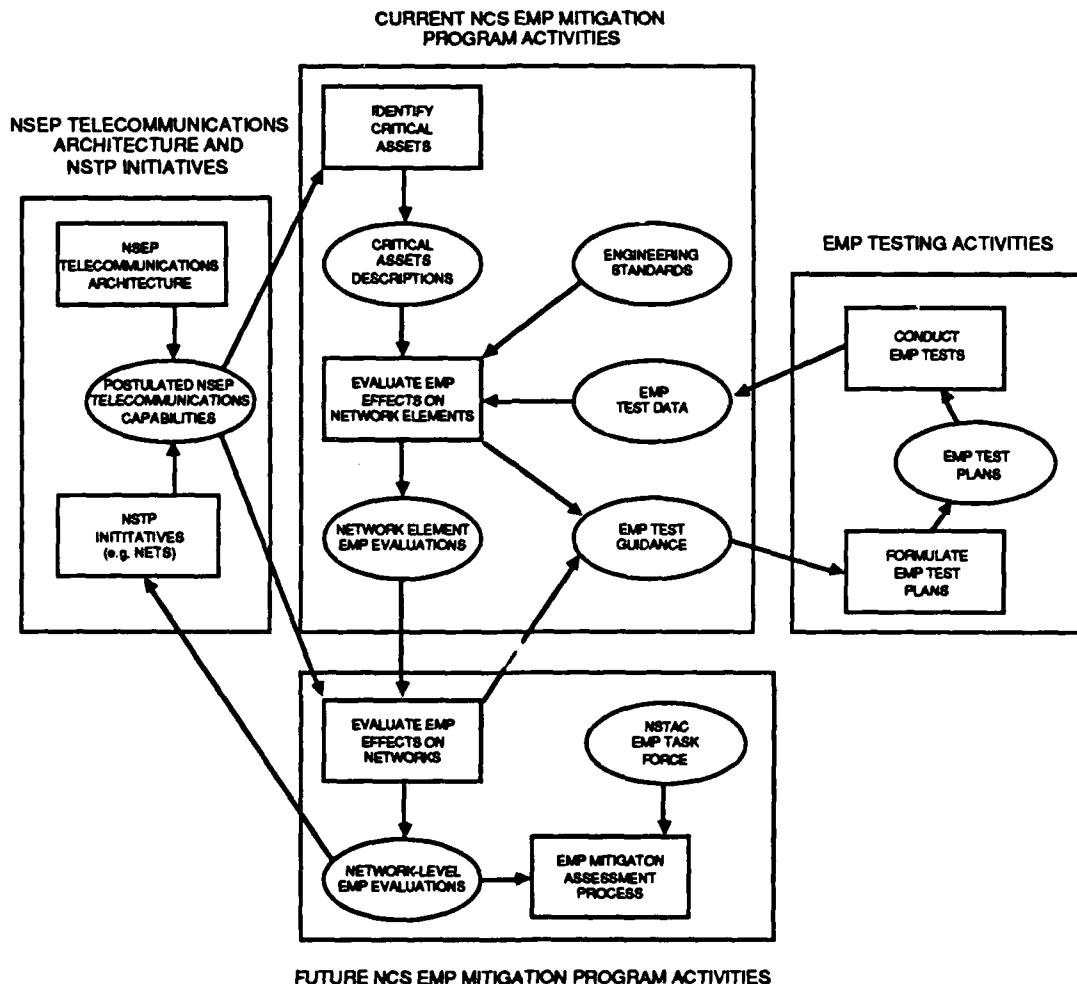
- Identifying critical telecommunication assets
- Evaluating the effects of HEMP on selected network elements
- Evaluating the effects of HEMP on selected telecommunication networks
- Assessing alternative strategies for mitigating the effects of HEMP.

The second activity is the subject of this report. The other three activities are addressed in both current and future efforts.

The first activity is to identify critical telecommunication assets based on postulated National Security Emergency Preparedness (NSEP) telecommunication requirements. These requirements result from consideration of the evolving NSEP Telecommunications Architecture initiatives such as the Nationwide Emergency Telecommunications Service (NETS). Focusing on these requirements emphasizes the assets of greatest concern to OMNCS efforts, bounds the effort required in this assessment, and precludes analysis of nonessential equipment.

The second activity estimates HEMP effects on selected network elements that are among the identified critical telecommunication assets. In this activity, each selected asset is characterized from a HEMP perspective. Applicable HEMP test data and the standards and practices used by the telecommunications industry are analyzed. The results of this activity are

Exhibit ES-1
EMP Mitigation Program Approach



estimates of the HEMP responses of the selected network elements to HEMP and recommendations for further analysis and testing to resolve remaining issues.

The third activity evaluates the effects of HEMP on telecommunication networks. Design approaches of interest to current NSEP initiatives and architectural analyses are reflected in the topologies of the evaluated networks; the results of the second activity are used to determine the HEMP responses of the nodes and links of the evaluated networks. The results of the third activity are estimates of the responses of selected telecommunication networks to HEMP, indications of the inherent

survivability of network topologies of interest to NSEP telecommunication planners, and further guidance to EMP test planners.

The fourth activity assesses alternative HEMP mitigation strategies. Various alternatives for mitigating the effects of HEMP on national telecommunication capabilities can be identified for consideration in the assessment process. Based on the results of the network level HEMP evaluations and inputs from the National Security Telecommunications Advisory Committee, the costs, benefits, and risks of implementing each identified mitigation alternative are determined. This activity results in a recommended composite strategy for mitigating the effects of HEMP on regional and national telecommunication capabilities.

SCOPE OF REPORT

This report focuses on the estimation of the effects of HEMP on telecommunication assets for which available assessment results exist. The threat considered for the EMP effects evaluation is the 50 kV/m double exponential description of the early time portion of the HEMP pulse,¹ which represents the most significant EMP threat to telecommunication assets. Intermediate time EMP and magnetohydrodynamic EMP (MHD EMP) effects are not explicitly evaluated in this report. Some test programs include data for repetitive simulator pulses, where no effort is made to ensure system operability between pulses. These data are not included in this assessment because they lack statistical independence. This report is also limited to typical installations of the selected assets; although versions of some equipment that have been explicitly hardened against EMP effects exist, these versions are not considered for this analysis if the vendor does not intend to include the modifications in standard system design.

CRITICAL ASSET IDENTIFICATION

Assets are chosen for inclusion in this report based on currently available test data and theoretical analyses; the remaining assets will be evaluated as data become available. The switching systems evaluated in this report are the 4ESSTM, 5ESSTM, and DMS100TM systems.² The transmission facilities evaluated in this report are the T1 digital transmission system, the FT3C multi mode and the R-R140 single mode fiber optic transmission systems, the L4 and L5 coaxial cable systems, and the TD-2 microwave system.

¹ Bell Telephone Laboratories, EMP Engineering and Design Principles, Loop Transmission Division, Whippany, N.J.: Technical Publication Department, Whippany, N.J., 1975

² 4ESS and 5ESS are Trademarks of American Telephone & Telegraph Co. (AT&T). DMS100 is a Trademark of Northern Telecommunications Inc. (NTI).

EVALUATION OF HEMP EFFECTS

The evaluation of HEMP effects on the selected assets uses available test data, theoretical analyses, stress level calculations, and the standards and practices of the telecommunications industry. Test reports and analyses are addressed to verify approach, results and conclusions. The HEMP threat description used in these tests is compared to the 50 kV/m double exponential pulse description, and measured or predicted stress levels from these tests are compared to those predicted in this report. The equipment configurations are compared to typical installations of the selected assets. Based on these comparisons, the results of the tests and theoretical analyses are used to draw conclusions about the survivability of typical configurations of assets.

CONCLUSIONS

The conclusions concerning the effects of HEMP on selected network elements follow:

- The unhardened AT&T T1 digital transmission system incorporating splice cases and D4 channel banks is vulnerable to HEMP effects; lightning protected AT&T T1 systems with splice cases and without D4 channel banks are robust to HEMP effects. T1 system elements have been exposed to simulated low-level HEMP fields; the results were then analytically extrapolated to full threat values. Lightning protected repeaters are survivable against HEMP, but repeaters *without* lightning protection are *vulnerable*. D4 channel banks suffered significant damage during testing at transient stress levels that could occur in the central office during a HEMP event; however, further tests and analyses are required to determine the applicability of these results to typical D4 installations. A hardened T1 carrier system, including EMP-protected D4 channel banks and repeaters, was tested at field strengths up to 80 kV/m and proved robust to HEMP effects.
- The AT&T FT3C multi mode fiber optic transmission system is vulnerable to HEMP effects. Threat-level fields and injected currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case; both elements appear to be survivable against the effects of HEMP. Available test data on the survivability of Central Office (CO) and Line Repeater Station (LRS) equipment are inconclusive, since threat-level currents were not injected into all subsystems. Unmodified power converters were shown to be vulnerable to threat-level transients. Power converters incorporating several hardware modifications proved robust, although the test configurations using modified power converters are not typical of

most LRSs and COs. The modified power converters, therefore, cannot be considered survivable to HEMP based on available test data. Because both LRS and CO equipment rely upon the converters to power them, the entire FT3C system must be considered vulnerable.

- The Alcatel R-R140 single mode fiber optic transmission system is robust to HEMP effects. Threat-level fields and injected currents did not produce any service-affecting hardware damage during testing of the repeater, so it appears to be survivable to the effects of HEMP. However, the fiber optic cables were not tested with threat level currents. Because these cables are assumed to be similar to the survivable cables used within the FT3C multi mode system, they are also considered survivable to HEMP effects.
- The AT&T L4 and L5 coaxial cable systems are robust to HEMP effects. These systems are designed for survival in a nuclear environment; all cable is buried and repeaters are well bonded and well grounded. Detailed computer analyses and HEMP simulation tests indicate that although some temporary system outages will occur, no equipment will be damaged as a result of HEMP.
- The AT&T TD-2 microwave radio system is survivable to HEMP effects. Threat level, free-field HEMP simulation testing has produced upsets such as the activation of protection switching and frequency shifting, but it has produced no failures. Low-level current-injection tests caused no failures; high-level current-injection tests have not been performed. However, comparison of predicted HEMP-induced currents to expected lightning-induced transients on microwave towers indicates that TD-2 systems are also survivable against conducted transients.
- The AT&T 5ESS switching system is survivable to HEMP effects, but subject to upset. Several service-affecting hardware failures occurred under exposure to threat-level fields. With several hardware modifications in place, the 5ESS switch suffered no permanent hardware damage, although a significant number of calls (over 90 percent) were dropped and call processing capability was reduced following repeated exposures. Manual recovery is required to restore call processing efficiency to greater than 99 percent; however, most central offices housing 5ESS switches are not staffed and the survivability of remote links has not been demonstrated. To ensure the survivability of a particular 5ESS system requires verification that the identified hardware modifications have been installed and that the site will be staffed or verification that a survivable remote link has been established.

- The Northern Telecommunications Inc. (NTI) DMS100 switching system is survivable to HEMP effects, but subject to upset. Several service-affecting system upsets occurred under exposure to threat-level fields, but no permanent hardware failures were observed. With several hardware modifications in place, the switch was invulnerable to upset. NTI plans to include the changes identified during the test program as part of all future DMS100 switches. Therefore, to ensure the survivability of a particular DMS100 switch requires verification that the identified hardware modifications have been installed or that the site will be staffed.
- Existing test data on the AT&T 4ESS switching system are insufficient to assess its vulnerability to HEMP. No test data or theoretical analysis of the HEMP response of the 4ESS system exist. The results of the 5ESS and DMS100 system assessments cannot be applied to the 4ESS system. It is assumed that of all the systems for which EMP test data are available, the D4 channel bank is technologically most similar to the 4ESS switch, but in the absence of actual 4ESS test data, no definite conclusions regarding survivability can be drawn.

RECOMMENDATIONS

The recommendations concerning future efforts in this program follow:

- The effects of HEMP on the 4ESS switching systems should be determined through test and analysis. The configuration assessed should include typical line termination equipment and appropriately placed lightning protection devices. Typical lengths of the Peripheral Unit Bus (PUB) should also be included.
- The HEMP response of solid state microwave systems should be evaluated through test and analysis. The TD-2 microwave system is based on vacuum tube technology; modern microwave systems are based on solid-state technology. Solid state components tend to be less survivable than their vacuum tube equivalents.³ However, an evaluation of the modern systems is required to determine their survivability to HEMP.
- The HEMP survivability of central office power supply systems should be assessed through analysis and test. The operability of all central office equipment, including switching and transmission

³ Booz•Allen & Hamilton Inc., "State of the Art Report: Electromagnetic Effects Protection for Very Large Scale and Very High Speed Integrated Circuits (VLSIC/VHSIC)," US Army Laboratory Command/Harry Diamond Laboratories, April 1987.

equipment, depends on the availability of central office power. Testing of the 5ESS and DMS100 digital switches indicates that the power systems may be vulnerable to HEMP effects. However, the power systems are not part of the switches but rather are a part of the central office facilities required to support switch operation. They are therefore not included in the assessments of switch survivability. Determining the survivability of the power systems is critical to understanding the potential operability of all major network assets.

- The results of the current study to determine the sensitivity of the network level HEMP-effects model should be used to identify and prioritize critical telecommunication assets. The OMNCS has developed a model to predict the effects of HEMP-induced equipment failures on telecommunication networks. Current efforts include a study to determine the sensitivity of predicted network performance to input data. The telecommunication equipment critical to the NSEP capabilities of the OMNCS should be identified and prioritized based on the results of the sensitivity study. This prioritization should be used as a basis for allocating resources for future tests and analysis of telecommunication equipment in support of this program.
- The HEMP responses of similar equipment from different vendors should be analyzed to evaluate methods of relating test results for one system to the survivability of another. Various vendors manufacture similar equipment for the telecommunication industry, e.g., T1 line termination equipment, channel banks and digital switching systems. The ability to relate the survivability of similar pieces of equipment would minimize the amount of testing required to assess the effects of HEMP on telecommunication networks.
- The HEMP stress level binning procedure used in this program should be reevaluated. The present binning procedure uses three arbitrary stress levels: low (0-30 kV/m), medium (30-50 kV/m) and high (50-70 kV/m). Alternative binning procedures should be reviewed to determine if the accuracy and flexibility of the model used to characterize the HEMP-induced survival probabilities for different types of telecommunications equipment can be improved.

1. INTRODUCTION

1. INTRODUCTION

In response to Executive Order 12472 (E.O. 12472) and National Security Decision Directive 97 (NSDD-97), the Office of the Manager, National Communications System (OMNCS) sponsors the Electromagnetic Pulse (EMP) Mitigation Program. The objective of this program is to remove EMP as a significant impediment to timely reestablishment of regional and national telecommunications following an attack against the United States that includes high-altitude nuclear detonations. The methodology for developing an EMP Mitigation Program plan is described in the OMNCS report EMP Mitigation Program Approach of September 1987.

In that document, essential program steps are defined as: identification of Public Switched Network (PSN) assets critical for reconstitution, estimation of the EMP effects on these assets and the networks in which they are embedded, assessment of the impact of available EMP mitigation alternatives, and development of a comprehensive plan for implementing mitigation alternatives.

1.1 BACKGROUND

The OMNCS approximates the effects of High-altitude Electromagnetic Pulse (HEMP) on the PSN by using two computer models: the Bayesian Survivability Model (BSM)⁴ and the Network Connectivity Analysis Model (NCAM). The BSM is used to generate HEMP-induced survival probability estimates for elements (switches and transmission facilities) in the network, based on the results of HEMP tests on various telecommunications equipment (e.g., 5ESS switch, TD-2 microwave system, FT3C fiber optic transmission system). The NCAM estimates physical and logical connectivity among network switches under different HEMP stress levels using the survival probability estimates generated by the BSM. The functional flow of this approach is shown in Exhibit 1-1.

1.1.1 Bayesian Survivability Model

The BSM is a computer-based application based on Bayesian statistical theory⁵ that characterizes the HEMP-induced survival probabilities for different types of telecommunications equipment (network elements). Exhibit 1-2 illustrates the flow of the BSM. Results from HEMP tests on network elements are input to the model. When test data for a particular

⁴ Bayesian Failure Probability Model Sensitivity Study, National Communications System, May 1986.

⁵ G. Box and G. Tiao, Bayesian Inference in Statistical Analysis, Addison Wesley Publishing Company; Reading, MA, 1973.

Exhibit 1-1
Network Level HEMP Effects Analysis: Functional Flow Diagram

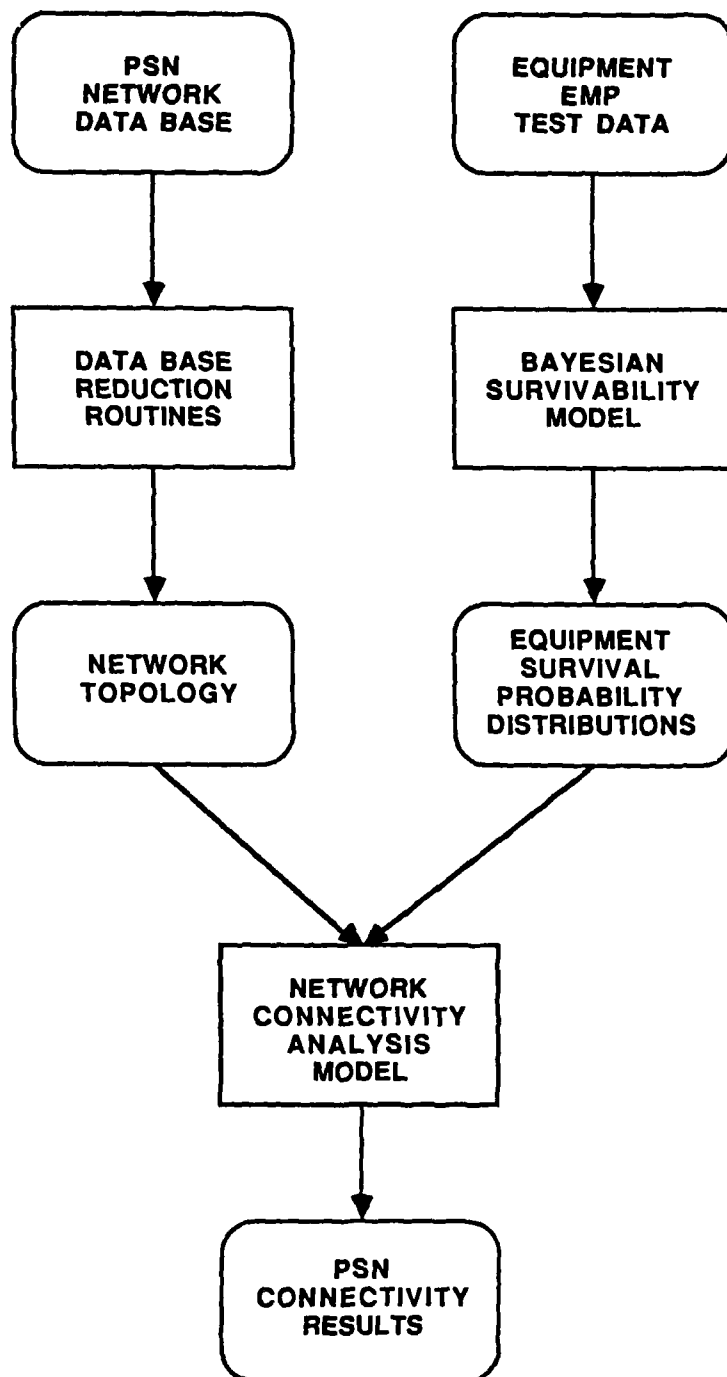
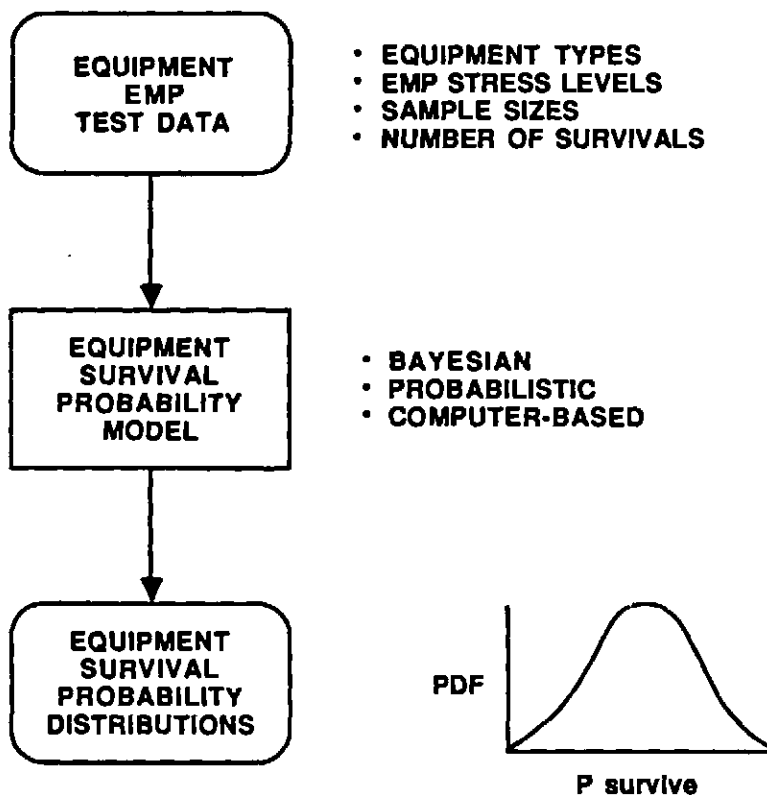


Exhibit 1-2
Bayesian Survivability Model: Functional Flow Diagram



network element are not available, test data from the technologically most similar equipment are used. These results specify the number of times the equipment was tested, and the number of times the equipment survived various stress levels. The Cumulative Distribution Function (CDF) of survival probability is calculated from the beta posterior distribution, which is obtained by performing a Bayesian process on an assumed non-informative prior distribution and the equipment HEMP test data.⁶

For all tested equipment, a unique CDF curve is developed for the HEMP stress levels used in this program: low (10-30 kV/m), medium (30-50 kV/m) and high (50-70 kV/m). These levels are arbitrary categorizations of discrete electric field strengths at which the equipment has been tested. This classification is necessary because not all equipment has been tested at the same discrete HEMP stress levels. In this manner, data from diverse equipment EMP test programs can be assessed consistently. The

⁶ Bayesian Failure Probability Model Sensitivity Study, National Communications System, May 1986.

results of the equipment survivability model are subsequently used as inputs to the NCAM.

1.1.2 Network Connectivity Analysis Model

NCAM can be used to estimate the effects of HEMP on networks that are deemed critical to the OMNCS and that have available topology descriptions. The model measures network performance by the point-pair connectivity metric. The point-pair connectivity metric measures the post-attack connections versus pre-attack connections. Earlier network level analyses performed by the OMNCS have focused on physical connectivity, and quantified network performance with the Baran metric. Baran connectivity is a function of the percentage of switches that both survive and remain connected to the largest "island" of switches following an EMP attack. However, point-pair connectivity is more tractable to calculate for logical connectivity analyses and hence has been adopted by the OMNCS for quantifying network performance.

NCAM performs three tasks. First, it generates a network topology consisting of the switches and transmission facilities that comprise the network of interest. In this analysis, the model identifies the number, location and type of switches and transmission media as specified in the data base. This information is supplied by a 1986 AT&T data base obtained by the OMNCS as part of the Nationwide Emergency Telecommunications Service (NETS) Program. The data base identifies the following information:

- Types and locations of switches
- Types and locations of transmission facilities (also called spans)
- Switch interconnections
- Logical connectivity information.

However, the flexibility of NCAM allows it to address any network structure. This capability is a significant improvement over previous network level EMP efforts, which assessed a simulated network.

Other currently available network descriptions do not supply the required information for NCAM. As the OMNCS obtains more current data bases, complete with the required information, they will be incorporated into EMP analyses.

The second function of the model is to determine which network equipment can survive a disturbance. This analysis assumes the disturbance to be a HEMP stress. Equipment has "survived" if it is fully or partially operable after exposure to a HEMP stress level. For each element (switch or transmission facility), a point estimate of the survival probability is calculated using the BSM-generated survival probability distribution for the particular HEMP stress level. A pseudorandom test is performed on each element of the network to determine whether or not it survives the HEMP stress.

The third task is to calculate the point-pair connectivity metric following the simulated HEMP disturbance. Both physical and logical point-pair connectivity are calculated by the model.

These three tasks are repeated many times using the same statistical and probabilistic input data. For each repetition in this Monte Carlo procedure, the point-pair connectivity metric is computed. At the conclusion of the Monte Carlo process, two primary statistics are calculated: the mean and the standard deviation of the discrete point-pair connectivities. The standard deviation provides insight into the amount of dispersion that is expected among different replications within the same Monte Carlo procedure. Histograms of the replication results can be produced to further illustrate the standard deviation of the process.

1.2 PURPOSE

This report summarizes available assessment results as they apply to the EMP Mitigation Program. The available results are reviewed and summarized in a format suitable for inclusion in the BSM. No attempt is made under this effort to verify predictions and extrapolations presented in the available assessments. To maintain objectivity, the reported test data are used without discrimination based on perceived data quality. This type of review and summary is consistent with the EMP Mitigation Program approach and the development of the BSM and the NCAM.

The available data were collected during multiple tests of telecommunications equipment over a range of HEMP stress levels. Exhibit 1-3 illustrates the format used in this assessment to report test data for inclusion in the BSM for network connectivity assessments. The "actual data" represent data as collected in the various test programs. For example, at the 10-30 kV/m level, there were 9 tests and 0 failures; at the 30-50 kV/m level, there were 6 tests and 0 failures; at the 50-70 kV/m level, there were 7 tests and 3 failures. The "BSM data" are used as the inputs to the BSM for network connectivity assessments. The measured data from some of the bins

Exhibit 1-3
Hypothetical Example of EMP Test Results for a Specific Network Element

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	9	0	15	0
30-50	6	0	6	0
50-70	7	3	7	3

are combined to produce the BSM data , to increase the sample sizes and enhance the value of the model results. Ideally, the data from separate bins would not be combined, but this pooling is necessary due to a lack of sufficient test data samples. As sufficient sample sizes are collected for each bin to support the NCAM assessments, the process of combining data will be eliminated.

The criteria used for combining data from separate bins are as follows:

- When there are *no failures* at a given field level, the data at this level are added to the data at all lower levels. This assumes that when the equipment always survives at the higher level, it will also survive at the lower level.
- When there are *no survivals* at a given field level, the data at this level are added to the data at all higher levels. This assumes that when the equipment always fails at the lower level, it will also fail at the higher level.
- When the test data for a bin include *both failures and survivals*, those data are not combined with data from any other bins.

Transmission facilities included in the current HEMP effects analysis are as follows:

- AT&T T1 digital transmission system (including D4 channel bank)
- AT&T FT3C multi mode fiber optic system
- Alcatel R-R140 single mode fiber optic system
- AT&T L4 and L5 analog coaxial cable system
- AT&T TD-2 microwave system.

These transmission facilities are included in the present HEMP analysis because of their prevalence in the PSN and the availability of applicable test data. The T1 digital carrier system has been tested extensively for HEMP effects, and is representative of the T-carrier technology used for exchange area transmission. The FT3C multi mode and R-R140 single mode systems have also been tested for HEMP effects, and are typical of the fiber optic technologies used for trunk transmission. L-carrier systems are used widely as intertoll facilities, and have been tested for HEMP survivability. Microwave systems are applied to both intertoll and short-haul transmission and constitute over 60 percent of all transmission capability in the existing public networks. The results of the testing of the L4 cable and TD-2 microwave systems are included in the classified appendix to this report.

Switching systems included in the current HEMP effects analysis are as follows:

- AT&T 1ESS (in classified appendix)
- AT&T 4ESS

- AT&T 5ESS
- NTI DMS100.

These switch types are included in the present HEMP analysis because of their importance in the carrier networks, their support of OMNCS technical initiatives (particularly, NETS), the evolutionary prevalence of their technologies, and the availability of applicable test data and analyses. Digital switching systems are of particular interest in this report because they are based on semiconductor components, which are more susceptible to electrical overstress than electromechanical components. The electromechanical predecessors to the digital systems, such as step-by-step, panel and cross-bar systems, are based on technologies that are generally considered to be robust to HEMP effects.

The 1ESS switch was tested for vulnerability to HEMP. The results of that test program appear in the classified appendix to this report. The 4ESS switch is a large, solid-state toll system. Its design includes the extensive use of large-scale integrated circuits. The 5ESS switch is a modern, entirely solid-state system intended primarily for local switching applications. Its design also uses large-scale integrated circuits and incorporates fiber optic cables for interbay connections. The DMS100 switch is a solid-state system that contains a large line/trunk capacity, similar to a toll or central office switch. Although the 4ESS switch has yet to be tested, an engineering analysis of its survivability is included because of the prevalence of the 4ESS in the PSN. The 5ESS and DMS100 switches have been the subject of exhaustive testing and analysis; this report includes a summary of the results of those test programs.

The second step in the overall evaluation centers around HEMP effects on these selected telecommunication assets used by the nation's local and interexchange carriers. Proceeding from the identification of critical assets, the evaluation approach used in this analysis consists of the following basic elements:

- Characterization of assets from an EMP perspective
- Identification of engineering standards and practices
- Evaluation of EMP effects on selected assets.

The result of this analysis is an estimate of the HEMP-induced effects on specific types of equipment (e.g., 4ESS or 5ESS switches, microwave transmission systems) for use in network level analyses of telecommunications network responses to HEMP. Information shortfalls are identified along with recommendations for further analysis and testing to resolve remaining issues. Information shortfalls include those cases where testing has not been conducted and where standards and practices are inadequate for relating untested equipment to available test results with confidence.

The evaluations of network elements will be used as guidance for planning Government-sponsored HEMP testing. These evaluations will also be used in analyses of the network level effects of HEMP on selected telecommunications networks.

1.3 SCOPE

This report focuses on the estimation of HEMP effects on selected telecommunication assets. The threat considered for the HEMP effects evaluation is the double exponential description of the early-time portion of the HEMP pulse, varying in amplitude from 10 to 70 kV/m.⁷ Because intermediate-time EMP and magnetohydrodynamic EMP (MHDEMP) affect fewer types of telecommunication equipment and are considered less severe than HEMP, equipment responses to these EMP components are not evaluated. Some test programs include data for repetitive simulator pulses, where no effort is made to ensure system operability between pulses. These data are not included in this assessment because they lack statistical independence. The discussions in this report are also limited to typical installations of the selected assets; although versions of some equipment that have been explicitly hardened against EMP effects exist, these versions are not considered for this analysis. The test reports include varying levels of detail about the individual test programs, but all available test data are included in this assessment.

1.4 ORGANIZATION

In section 2, transmission facilities are evaluated to estimate HEMP responses; switching systems are evaluated in section 3. In each section, the important HEMP coupling modes and paths are defined and HEMP induced stress levels are estimated; these stress levels are compared to equipment susceptibility levels to assess HEMP effects. These assessments incorporate results of HEMP simulation test programs, results of previous theoretical analyses, and standards and practices used in the telecommunications industry. Conclusions and recommendations are presented in section 4. The classified appendix of this report includes the assessment results for the 1ESS switch, the L4 coaxial cable system, and the TD-2 microwave system.

⁷ Bell Telephone Laboratories, EMP Engineering and Design Principles, Loop Transmission Division, Whippany, NJ: Technical Publication Department, Whippany, NJ, 1975.

2. TRANSMISSION FACILITIES

2. TRANSMISSION FACILITIES

This section presents the HEMP responses of the critical transmission facilities identified in section 1. These facilities include the T1 digital carrier system (both buried and aerial), the FT3C multi mode and R-R140 single mode fiber optic systems, the L4/L5 coaxial cable system, and the TD-2 microwave radio system. For each system, background information on hardware and functions is presented, followed by a discussion of coupling to outside plant equipment, stresses conducted to line repeaters and central office equipment, and exposure of all equipment to direct illumination fields. Relevant tests and analyses are outlined, and the responses of system elements and overall transmission systems to the 50 kV/m double exponential HEMP threat are discussed. In this section, the term central office (CO, Office, Terminal Office) represents a repeated transmission segment end station, which is a PSN building that may be staffed.

2.1 T1 DIGITAL CARRIER SYSTEM

The T1 system has been the subject of several assessments sponsored by the OMNCS. The first test⁸ (referred to as the Buried T1 Carrier Study) assessed the effects of HEMP on components of the buried T1 carrier network. The second test⁹ (referred to as the Aerial T1 Carrier Study) assessed the effects of HEMP on components of the aerial T1 carrier network.

The T1 System was introduced in the early 1960s as a digital carrier of short-haul interoffice traffic. The T1 system transmits 24 two-way voice channels multiplexed as pulse-code-modulated (PCM) 1.544 Mbits/s signals over two pairs of wires. The system has evolved to include subscriber loop and customer premises applications.

A T1 carrier system comprises cable, line repeaters for signal amplification, and central office equipment including main repeaters and protection switching equipment. Channel banks are used when an interface to an analog voice channel is required. Maintenance, trouble isolation and automatic switching are organized on a span basis. An average system is made up of four span lines and is 15 miles long; recent advances in technology allow systems of up to 150 miles in length.

Line repeater fault-locate filters are designed to allow problem isolation from tests conducted in a central office. Additionally, protection switching

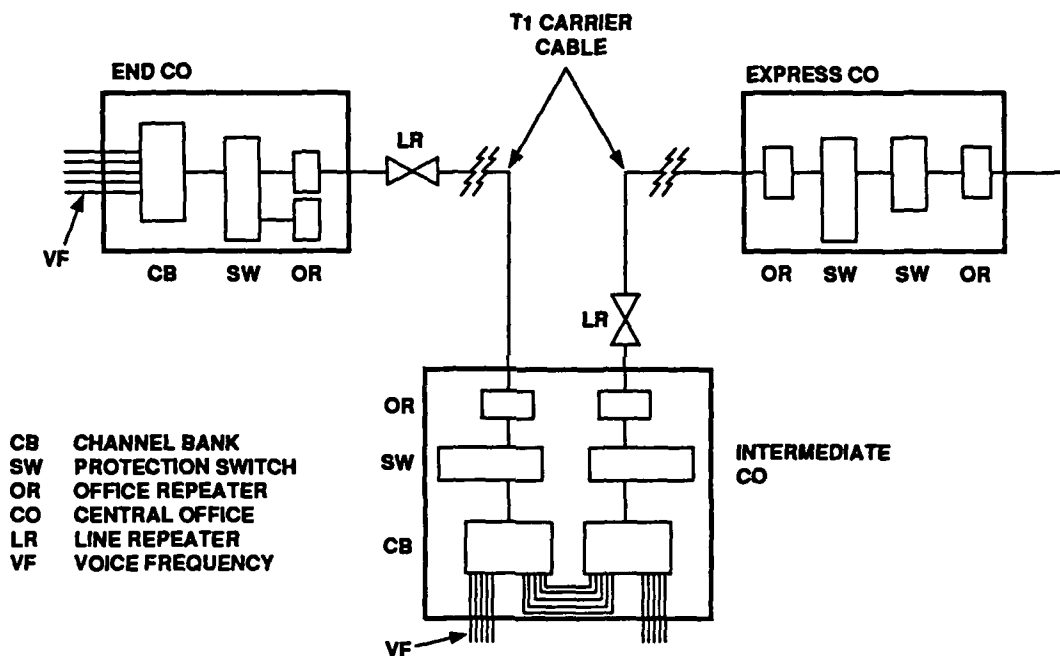
⁸ "T1 EMP/MHD Hardness Assessment and Design," November 1985, a study funded by the OMNCS and administered by AT&T Bell laboratories under contract DAEA-18-75-A-0059-8Z01AC.

⁹ "Aerial T1 EMP Effects Assessment, Volume I," May 1987, a study funded by the OMNCS and administered by Booz • Allen & Hamilton Inc., under contract DCA100-82-C-0034.

equipment is used to automatically reroute multiplexed bit streams from failed pairs to spare pairs carried in each cable.

A typical T1 carrier system might be configured as shown in Exhibit 2-1. At an intermediate CO (e.g., in the lower box) the entire 24-voice-channel group (digroup) is demultiplexed so that some voice-frequency (VF) channels may be directed to a customer while the remaining voice-frequency channels are multiplexed onto the outgoing T1 carrier. The third type of office configuration shown in Exhibit 2-1 (upper right) is used only for supplying power to the T1 carrier line.

Exhibit 2-1
Typical Buried T1 Carrier System Configuration



2.1.1 EMP Effects On The Cable

T1 carrier was originally designed to be used only on twisted pair, voice-frequency transmission cables. Today, other types of cables are used for T1 carrier, some designed specifically for T1 carrier use. The transmission media for T1 can be pulp, air-core PIC, or jelly-filled PIC cables from 16 to 26 gauge. However, expanding the channel capacity of existing voice-frequency cables is still a major application of T1 carrier systems.

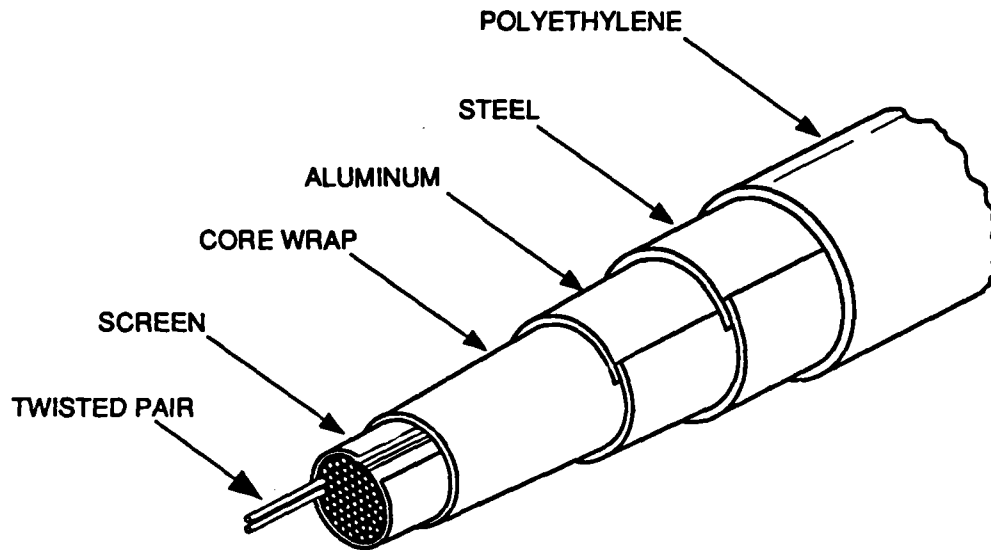
KFAW 158, the cable tested in the Buried T1 Carrier Study, is shown in Exhibit 2-2a. This cable has 158 color-coded twisted pairs of #22 AWG wire arranged in groups of 25 pairs called binder groups. The remaining eight wire pairs are called maintenance pairs and are used as alternate carrier pairs if one

of the other main carriers becomes disabled. Each binder group, as well as each individual wire pair, twists at a uniform rate with respect to the other, but they do not braid. Half of the binder groups are used to transmit the digital T1 signals and half are used to receive the signals. Many T1 cables (including the KFAW 158) have an aluminum screen that separates the receive and transmit binder groups to prevent cross talk. An inner polyethylene jacket surrounds the binder groups and aluminum screen, while the core of the cable is shielded primarily by a corrugated aluminum sheath with a continuous, overlapping, lateral seam. The aluminum sheath is surrounded by a steel casing, which provides additional shielding as well as protection from rodents and inadvertent "dig-ups." The outer jacket is comprised of a weatherproof PVC material. KHAG 106, the cable tested in the Aerial T1 Carrier Study, is shown in Exhibit 2-2b. This cable is similar to the KFAW 158, except that it has 106 twisted pairs of #22 AWG wire. Because of weight constraints, aerial T1 cables do not have an outer steel casing. The KFAW 158 and KHAG 106 were tested because they were considered typical of most buried and aerial cables, respectively, used to interconnect telephone COs throughout the United States.

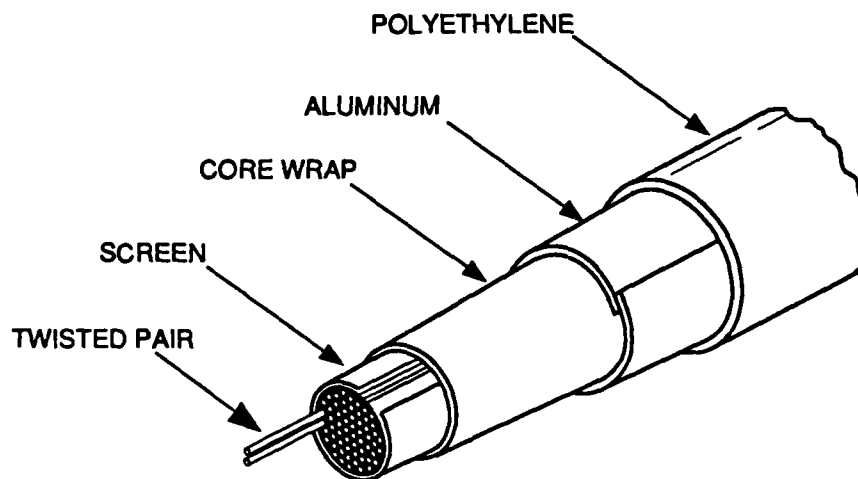
Problems can arise from HEMP energy induced onto long lines by direct illumination. First, induced sheath currents on one-mile segments between repeaters produce very high sheath currents at COs and at repeaters. Such surges might cause direct damage to trunks or to equipment when seeking ground. Additionally, sheath currents diffuse to internal twisted pair conductors and induce surges on signal leads. Currents induced on the leads might cause damage to repeaters or to terminal equipment either as high-frequency, high-voltage transients or as low-frequency, high-voltage surges. These transients on signal leads would be the more serious threat (apart from direct damage to cables) if good bonding practices were not in use. If good bonding practices are not used, and signal leads are openly exposed to induced sheath currents, a major problem would be the direct coupling of transients to signal leads creating a serious threat to repeater and terminal equipment.

In a typical T1 cable in the field, proper EMP cable shielding techniques are not always followed (i.e., the cable sheath is not always continuously bonded). The major violation occurs at cable splice points. In a typical plastic splice case, a copper braid makes a DC sheath-to-sheath connection for safety purposes, running alongside unshielded signal leads. Even when a steel splice case is used, a bonding jumper is carried inside the case. Three common splice cases are shown in Exhibit 2-3. Pigtails (bonding straps) are not usually well-bonded to sheaths, do not provide enough surface for conduction of large amplitude surges, and easily degrade over a period of years. The design of such splice cases allows significant coupling of the sheath current to the signal conductors.

Exhibit 2-2
T1 Carrier Twisted-Pair, Screened Cables

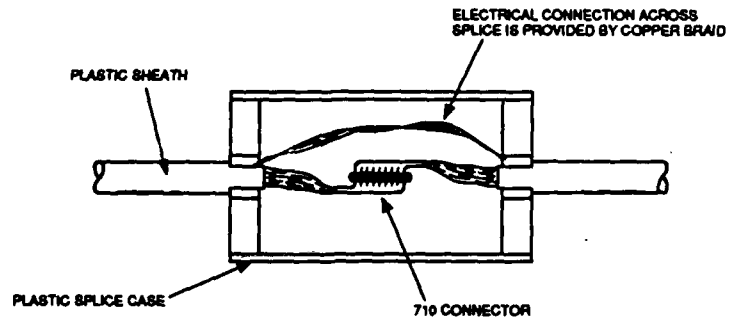


(a). Buried cable

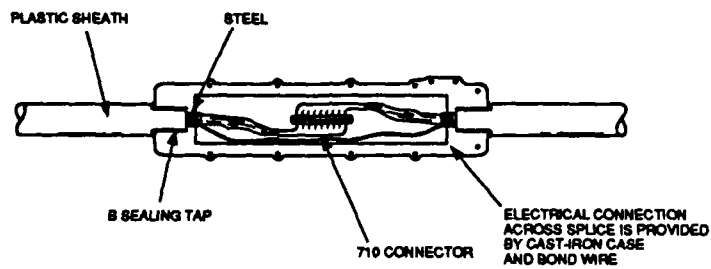


(b). Aerial cable

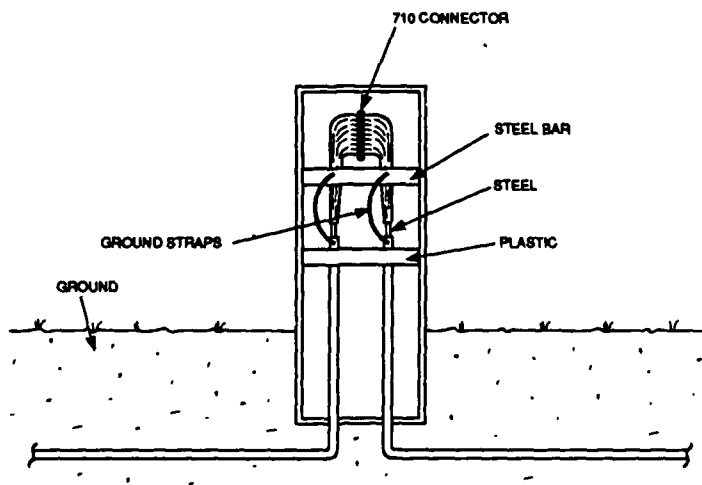
Exhibit 2-3
T1 Carrier Splice Cases



(a). Plastic Splice Case



(b). Cast Iron Splice Case



(c). PC-12 Splice Case

A theoretical prediction of currents induced on a long cable sheath with splice cases inserted has never been performed. Actual long lines cannot be illuminated experimentally, but it is reasonable to assume that actual amplitudes would not be higher, and actual rise times would not be faster, than those calculated for cables without splice cases. However, a few splice cases that allow enhanced coupling to signal leads could cause significantly higher HEMP transients at terminal equipment.

Predicted values for HEMP-induced sheath currents are approximately 2 kA with rise times of 200 ns in buried cable,¹⁰ and approximately 10 kA with rise times of 20 to 2000 ns in aerial cable with splice cases,¹¹ depending on the polarization, angle of incidence, and azimuth of the incident field. The measured values extrapolated to threat level as presented in both the Buried and Aerial T1 Carrier Studies are consistent with these expected values.

2.1.1.1 Buried T1 Cable Test Results. In one test listed in the Buried T1 Carrier Study, a 1,200-foot, 158-pair cable was exposed to the Repetitive EMP Simulator (REPS) at Harry Diamond Labs (HDL) in a simulation of double exponential pulse planewave illumination. Induced currents measured on different parts of the cable are illustrated in Exhibit 2-4. For 760 mA measured on the sheath, 39 mA was measured on the entire core (158 wire pairs). Assuming the relation between the two levels is linear, determined by the transfer impedance, and extrapolating to the worst-case theoretical induced current levels for the full threat (2 kA on buried cable), about 100 A could be induced on the core. The test report goes further to equate this core current to about 0.5 A on each signal lead, and adjusting for the worst case, concludes that not more than 2 A common-mode would be induced on any signal lead for buried cable. For a threat waveform injected or coupled onto buried and aerial signal leads with a 100 Ω load impedance, this corresponds to a voltage at the equipment of 50 V (for 0.5 A), or for the worst-case, 200 V (for 2 A).

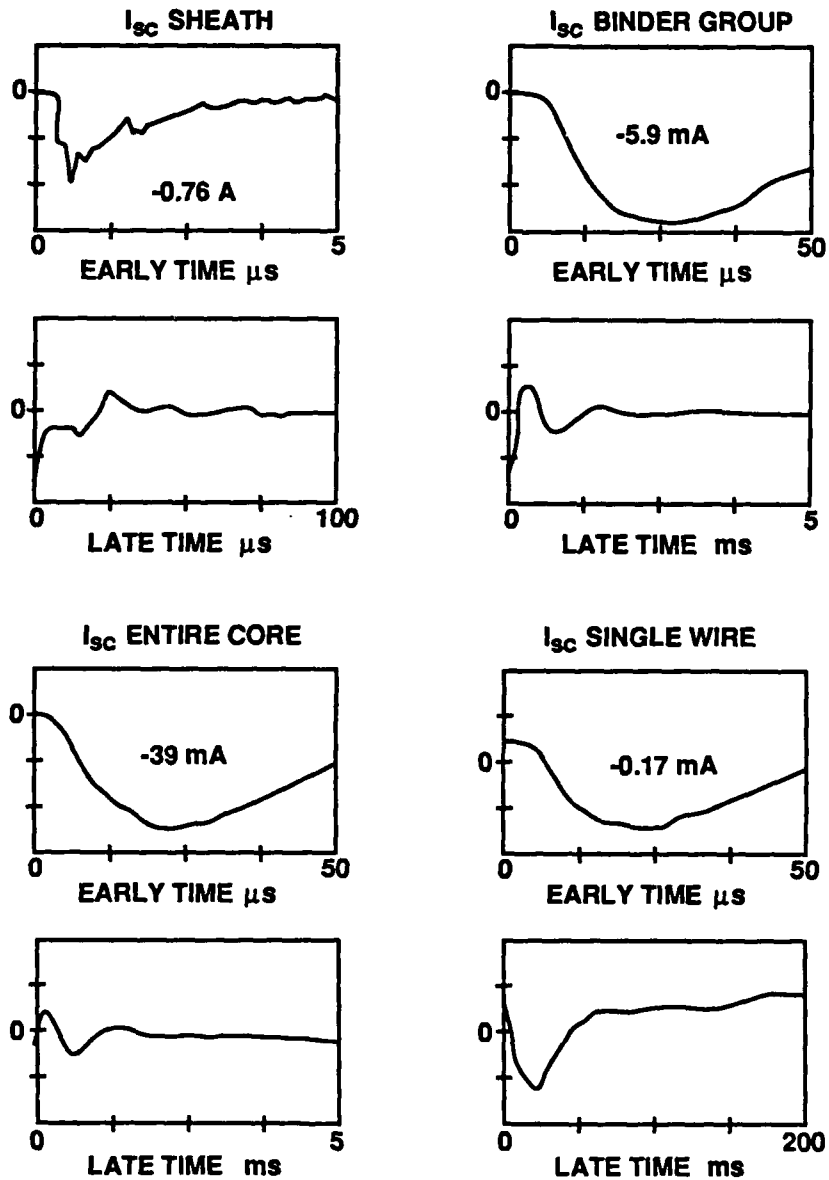
Rise times were measured as 500 ns on the sheath and 20 μ s on a single wire, with double-exponential shaped pulse durations of 50 to 100 μ s. These are within the range of accepted values, and are not expected to change for the full 50 kV double-exponential pulse threat.

Note that on the test setup, the signal leads were shielded for their entire length; this is not a good assumption for typical T1 systems, as leads break out and are exposed to a copper braid (that may be carrying over 4 kA) in splice cases. Therefore, although currents and voltages calculated above give a good quantitative description of diffusion currents, they may not be the most important coupling contributions in typical systems; actual levels may be significantly higher, due to discontinuities such as splice cases.

¹⁰ AT&T Bell Laboratories, "T1 EMP/MHD Hardness Assessment and Design," November 1985.

¹¹ Booz•Allen & Hamilton Inc., "Aerial T1 EMP Effects Assessment, Volume I," May 1987.

Exhibit 2-4
HEMP-Induced Currents on Buried T1 Cables



SHEATH \Rightarrow CORE \Rightarrow BINDER GROUP \Rightarrow WIRE

760 mA \Rightarrow 39 mA \Rightarrow 5.9 mA \Rightarrow 0.17 mA

SHEATH/CORE \sim 20/1

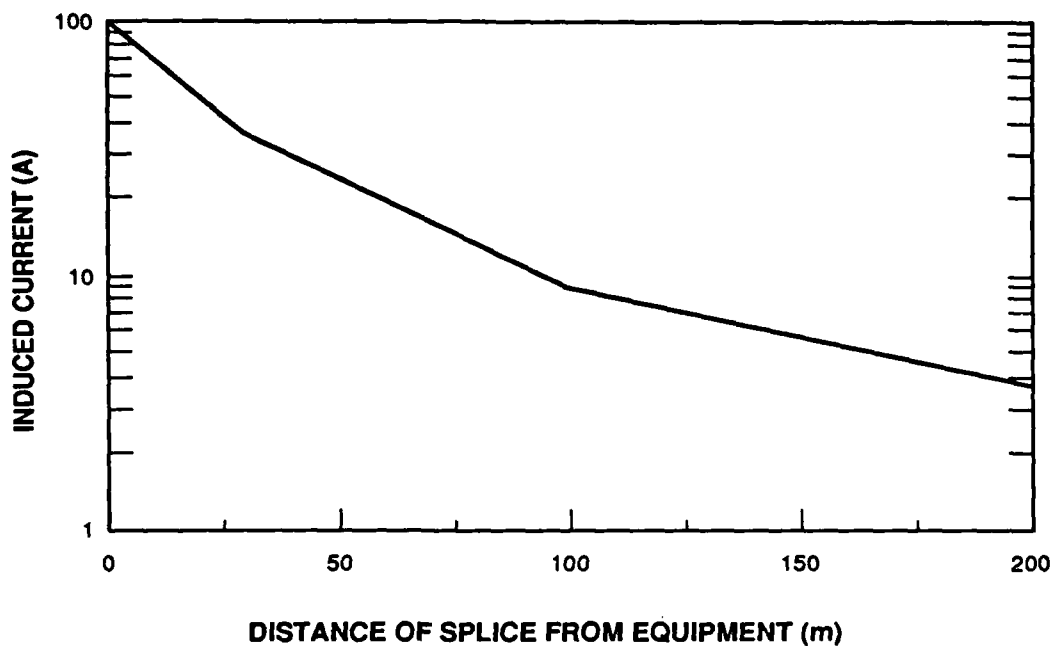
CORE/BINDER GROUP \sim 7/1

BINDER GROUP/WIRE \sim 35/1

2.1.1.2 Aerial T1 Cable Test Results. In the aerial T1 Carrier Study, two 100-foot 106-pair cables were pulsed with a 3 kV Marx-type current pulser at HDL. A decaying exponential current pulse of 1.6 kA peak amplitude was first injected on the sheath of the cable without a splice case. This current induced between 600 and 700 mA on individual signal leads. When extrapolated to a 2 kA sheath current, between 750 and 875 mA should be induced on individual signal leads. The Buried T1 Carrier Study indicates that a 2 kA sheath current will induce about 500 mA on individual signal leads of buried T1 cables. The higher aerial T1 signal lead current is consistent with aerial cable construction, because aerial cables do not have an outer steel casing, thus allowing a more direct coupling from the sheath current on the aluminum screen to the individual signal leads. When a splice case was added in-line with the cable, the same 1.6 kA sheath current induced between 15 and 23 A on the individual signal leads.

A major emphasis of the Aerial T1 Carrier Study is the prediction of currents that would couple to the internal conductors of the cable as a result of in-line splice cases. Exhibit 2-5 shows the predicted HEMP-induced current as a function of splice case distance from T1 equipment. With splice cases less than 10 meters from the equipment, worst-case currents of 100 A may reach the equipment. With splice cases more than about 300 m from the equipment, only about 1 A may reach the equipment.

Exhibit 2-5
HEMP-Induced Currents on Aerial T1 Cables with Splice Cases



2.1.1.3 T1 Cable Test Results Summary. The Aerial T1 Carrier Study concludes that worst-case currents of 100 A may reach T1 equipment from aerial T1 lines, if the equipment is located within about 10 meters of a splice case. Using splice case data generated in this study, it can be assumed from tests conducted in the Buried T1 Carrier Study that worst-case currents of up to 50 A may reach T1 equipment from buried T1 lines, if the equipment is also located within 10 meters of the equipment.

2.1.2 EMP Effects On Repeaters

Regenerative repeaters in the central office and on the line retune and regenerate transmitted bipolar signals. Repeaters are solid state plug-in units suitable for pole mounting or manhole placement. The transmitted digital signal travels on twisted pairs, balanced to ground, which have a nominal source impedance of 100 ohms. Spacing of T1 repeaters ranges up to 6,000 feet. Typical pole-mounted and manhole repeater installations are shown in Exhibit 2-6. The DC power for repeater equipment is supplied over the digital transmission line. Line repeaters are powered in a series loop containing up to 17 repeaters.

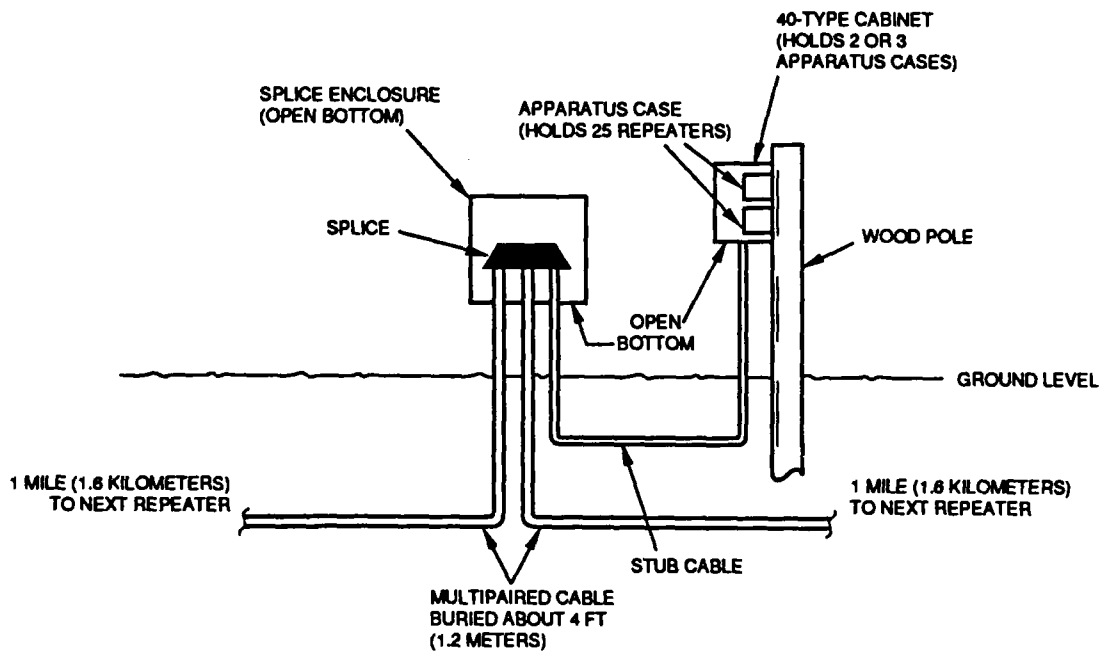
The 818-/819-type repeaters, typical of repeater cases installed on T1 carrier system, were the subject of test and assessment under the Buried T1 Carrier Study. These repeater cases are designed to house 25 T1 carrier repeaters, a fault-locate filter, a pressure contactor, and other apparatus. Repeater cases are molded from fiberglass reinforced plastic. Numerous types of splice cases are in use in T1 systems. Typically, each has a copper braid bridging the gap from sheath to sheath where signal lines break out to the splice connector.

From an EMP perspective, T1 repeaters can be grouped according to their hardness against transients. There are unprotected repeaters, lightning protected repeaters, and 60 Hz hardened repeaters (on lines where power line fault transients can be expected). Technologies vary, and a myriad of repeater types are used; they may contain discrete components, standard or low-power ICs. More robust components are used for protected repeaters, and gas tube protection devices may be installed in the equipment case outside the repeaters.

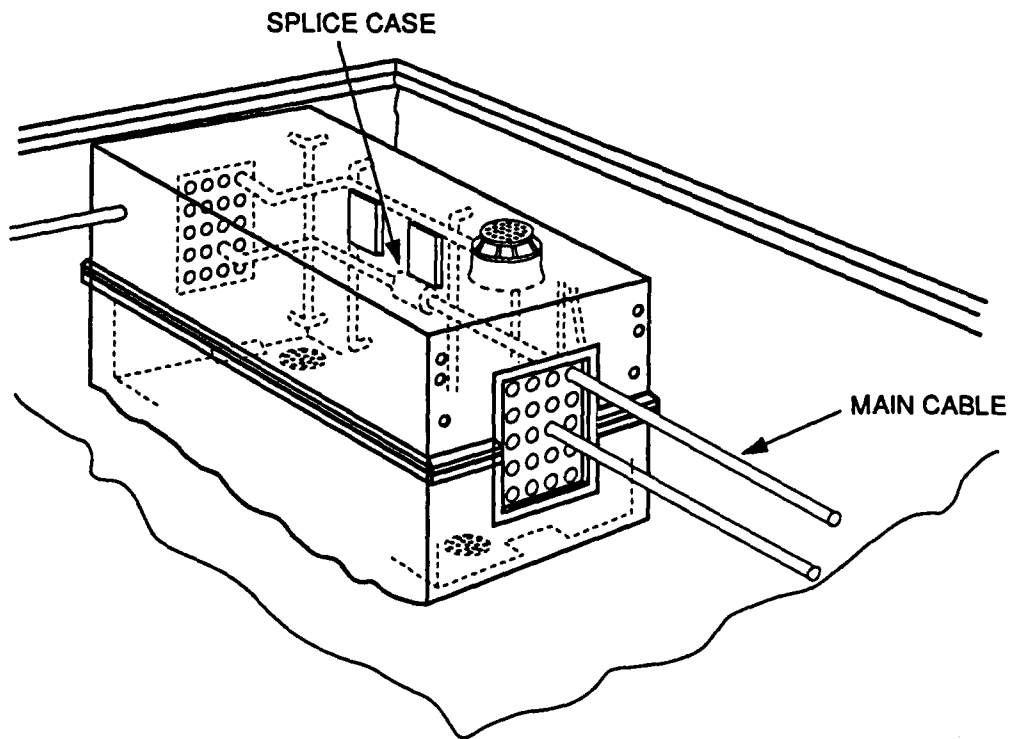
Because T1 signals are digital, and repeaters detect and regenerate rather than amplify them, neither high- nor low-frequency pulse components on signal leads will be amplified and passed along the cable. Therefore, the major concern in repeater susceptibility is whether the circuits will survive when exposed to transients coupled onto signal leads over the one-mile interrepeater lengths.

The Buried T1 Carrier Study describes two series of tests that address repeater susceptibility to the effects of these transients: EMP field-tests and current-injection tests. The first test, at HDL, used the Army EMP Simulator

Exhibit 2-6
Typical Buried T1 Repeater Installations



(a). Pole-Mounted Repeater



(b). Manhole-Installed Repeater

Operation (AESOP) and Office Sinusoidal Simulator (OSSI) combination to pulse fields onto a 2,000-foot T1 trunk with a splice case and pole-mounted repeater at its center. In this test, high-level fields and induced lead currents were simultaneously directed onto the repeater. A lightning-protected repeater and a special EMP-hardened repeater were tested, but only the lightning-protected repeater tests are discussed here.

The typical repeater unit tested is an 800-type plastic case housing two 239 E/F 60 Hz protected repeaters with standard lightning protection devices (208A gas tubes) installed. The splice case is a typical PC-12 mounted above ground. During testing at several field levels up to threat level (about 50 kV/m), outages in equipment operation of 61 μ s to 256 ms were experienced, but no permanent failures were observed.

In addition to subjecting equipment to high-level fields, the tests at HDL provide experimental justification for predicting the coupling of energy from sheaths and sheath termination straps to exposed signal leads. Extrapolation of test observations to worst-case levels indicates three components of induced current depending on the time domain. The first is high-frequency ringing or a double exponential surge, depending on the sheath length, and is quickly damped (in about a microsecond). This high frequency signal is due to the equipment response of the incident HEMP field, and includes signals due to direct field penetration and coupling to the cable. This component might couple more than 100 A peak onto any individual signal lead.

The second induced current component is a slower pulse. In the test report, this pulse is attributed to coupling to the exposed stub cable in the splice case, but it could rise from any discontinuity in the sheath that is near exposed wires. This was predicted to be as high as 20 A at ringing frequencies in the MHz range. The third component is the diffusion current described in section 2.1.1. Pulse characteristics from the Buried T1 Carrier Study regarding these three stress levels are shown in Exhibit 2-7.

The second series of tests involved current-injection on signal leads, performed at Bell Laboratories at Indian Hill, Illinois. Double exponential (DE [50 ns rise-time]) and damped sinusoid (DS [10 ns rise-time]) pulses were injected. Pulses ranging from 100 to 440 A were injected onto gas tube protected repeater and CO equipment leads; between 2 and 84 A were passed through the protector as a result. The only failures seen occurred at 300 A or more, levels above expected HEMP-induced stress levels for both buried and aerial cables. Exhibit 2-8 shows a table of equipment failure and nonfailure versus stress levels.

Exhibit 2-7

HEMP Threat to Buried T1 Carrier Facilities as Recorded in Buried T1 Carrier Study Tests

Response Component	Electromagnetic Environment	Peak Amplitude (Amperes)	Pulse Characteristics	
High-Frequency Early-Time Pulse	Central Office	130	Multiply Damped Sinusoid	
			Ringling Freq.	e-folding Time
			15 MHz 30 MHz	2 μ s 100 ns
	Pole-mounted Line Repeater	25	Multiply Damped Sinusoid	
			Ringling Freq.	e-folding Time
			15, 30 MHz 60, 120 MHz	2 μ s 100 ns
	Manhole-deployed Line Repeater	20	Bipolar Pulse	
			Rise Time	Pulse Width
			150 ns	500 ns
Slow Pulse	All (with buried cable)	20	Bipolar Pulse	
	All (with aerial cable)	untested	Rise Time	Pulse Width
			2 μ s	5-20 μ s
"Diffusion Current"	All (with buried cable)	2	Bipolar Pulse	
	All (with aerial cable)	4	Rise Time	Pulse Width
			20 μ s	40 μ s

Exhibit 2-8
Buried T1 Carrier Repeater Current-Injection Tests at Bell Laboratories

Unit type tested	Line Repeater 239E					Line FLF 1115xx	
Protection type used	SGSL					SGSL	
Type of pulse	DE	DS	DE	DE	DS	DE	D
Peak pulse current per wire (into SGSL)	100 A	115 to 160 A	320 A	360 to 440 A	300 to 400 A	195 A	200 A
Units tested	5	5	4	3	5	1	1
Failures	None	None	None	1	2	None	None

FLF: Fault Locate Filter
SGSL: Sealed Gas Surge Limiter
DE: Double Exponential
DS: Damped Sinusoid

In related experiments during the Buried T1 Carrier Study, Sealed Gas Surge Limiters (SGSLs, or gas tube protectors), were tested separately to determine mean firing times and voltages. Results of tests from the Buried T1 Carrier Study conducted at HDL and at Boeing Aerospace Co. are shown in Exhibit 2-9. Typical PSN applications of the types tested are listed in Exhibit 2-10.

The worst-case HEMP stress coupled onto a signal line might rise as quickly as 10 V/ns at early times; test results show that if limiters fire, they do so within about 60 ns at about 600 to 700 V. An exception is the 208 A (the most commonly used by AT&T T1 repeaters), which fires at about 900 V.

Standard AT&T practices include lightning protection on above-ground T1 repeaters. From the Terminal Protection Device (TPD) test data, repeater system test data, and current-coupling tests and analyses, it is reasonable to conclude that *protected* repeaters are *not* vulnerable to the 50 kV/m double-exponential pulse threat. However, repeaters *without* lightning protection *are* vulnerable. In current-injection tests, line repeaters failed when 38 to 50 A were passed through gas tube protectors. Testing and analysis indicate that surges up to 50 A on buried lines with splice cases and up to 100 A on aerial lines with splice cases can be expected on signal lines at line repeaters.

Exhibit 2-9
Gas Discharge Tube Test Results

SGSL	Mean Firing Time (ns)					Mean Firing Voltage (V)				
	Pulse Rise Times (V/ns)					Pulse Rise Times (V/ns)				
	2,000	100	50	25	16	2,000	100	50	25	16
200A	2.9	5.9	13.5	20.3	23.9	974	900	760	736	684
201A	3	5.1	12.4	17.3	22.3	589	581	692	660	680
205A	3	5	10.6	16	18.9	518	464	534	614	574
208A	3	6.3	18.5	22.7	31.3	1,160	1,080	1,020	507	933

(a) HDL

SGSL	Mean Firing Time (ns)					Mean Firing Voltage (V)				
	Pulse Rise Times (V/ns)					Pulse Rise Times (V/ns)				
	5,000	1,000	100	10	1	5,000	1,000	100	10	1
200A	1.4	2.8	9.0	61	432	2,417	1,395	850	684	531
201A	1.3	2.5	7.5	64	427	2,111	1,023	744	700	531
205A	1.3	2.5	6.1	56	294	1,880	794	560	565	324
208A	1.2	2	11.3	75.1	532.2	2,993	2,217	1,157	888	693

(b) Boeing Aerospace Co.

Exhibit 2-10
Typical Applications of Gas Discharge Tubes in the PSN

Type	Typical Application
200A	Existing T1 Carrier
201A	Outside Plant, Central Office
205A	5ESS Switch
208A	New T1 Carrier Installations

2.1.3 EMP Effects On Central Office Equipment

Central office T1 equipment is conventionally mounted in open bays (equipment racks). An important piece of office equipment is the channel bank (most commonly D4), which provides the voice-frequency interface to the digital line. The channel bank samples the analog voice-frequency signal, converts it to a PCM bit stream, and assembles the digitally encoded voice frequency signals from 24 voice channels and framing information into the 1.544 Mbits/s line signal. In the other transmission direction the channel bank provides the inverse functions. Therefore, D4s are used at the interfaces of analog switches and digital transmission facilities, and digital switches and analog transmission facilities.

A channel bank physically consists of shelves in an equipment frame filled with printed circuit boards. The two basic types of circuit boards in the bank are channel units, devoted to functions involving individual voice channels; and common units, devoted to functions involving the digital line or entire bank. The voice-frequency pairs terminated at a channel unit are balanced to ground and may serve as either two-wire or four-wire circuits. Signaling is accomplished by various DC arrangements over the voice-frequency leads, or by separate signaling pairs. As a result, a single two-way voice-frequency circuit may have as many as eight pairs of leads at the channel bank interface.

The common equipment boards supply maintenance and alarm functions, multiplexing functions, line and office interface functions, and certain other functions such as trunk processing and timing. Common equipment also includes high-frequency circuits, which provide the digital line interface.

In the T1 System, there is essentially no difference between office level stress and stress on line repeaters; as mentioned above, transients will not be propagated by repeaters. As with line repeaters, terminal equipment is either unprotected or protected against lightning and 60 Hz power faults. In a CO, protection may be gas-tube or 3 mil carbon block TPDs. Signal lines entering a building break out of the sheath and run to a Main Distribution Frame (MDF) where the lightning protection is located, then to equipment racks, which contain the office repeaters and channel banks.

Tests similar to the line repeater tests were conducted at HDL on CO terminal equipment and on D4 channel banks. The AESOP and OSSI combination tests on *protected* line systems showed no failures, leading to the conclusion that the office repeaters can sustain up to 130 A simulated HEMP-induced transients without damage.

As part of the assessment of the Buried T1 Carrier system, an EMP-hardened D4 channel bank, enclosed in a shielded cabinet and protected by special TPDs at line interfaces, was subjected to simulated HEMP fields and proved to be survivable. However, when the backplate and door of the

shielded cabinet were left open, or when either the power or voice frequency (VF) TPDs were removed, hardware within the D4 channel bank suffered permanent hardware failure. Because the equipment failed at the lowest field level (35 kV/m) attainable under the simulator at HDL, it was not possible to determine the actual failure threshold or to evaluate the success of alternative methods of protecting the channel bank. A second test,¹² therefore, was undertaken to identify and verify the following:

- The failure threshold for a D4 channel bank
- Methods to protect a D4 channel bank.

To assess its survivability, the D4 channel bank was subjected to simulated HEMP fields.

The tests were conducted at the Air Force Weapons Laboratory (AFWL) using the ALECS facility, which is a bounded wave simulator that produces a vertically polarized electric field, adjustable in strength from 5 to 100 kV/m. The simulated HEMP had a rise-time between 3 and 15 ns and a decay-time of about 200 ns. To assess the channel bank's response to the simulator fields, tests of tone transmission, signal transmission and idle circuit noise were made following each simulator pulse.

This study demonstrated that HEMP affects a D4 channel bank primarily through the injection of large current transients at the interfaces to long connecting cables; fields of only 12 kV/m are sufficient to cause service-affecting hardware failures of unprotected D4 channel banks. EM fields are also coupled directly to wires on the backplane, but these transients are of a much lower amplitude than those at line interfaces. These transients will only cause damage if the field in the vicinity of the bank exceeds 40 kV/m, and only then if maximum coupling occurs to the backplane wires (i.e., the incident field must be planar and roughly parallel to the backplane wires).

The cables used during the testing of the D4 were typical of those found in many COs. The following cables were used:

- Two power cables, each of 6-gauge wire
- One alarm cable with four pairs of 26-gauge wire
- Two ABAM 606B shielded T-carrier cables, each with 12 pairs of 22-gauge wire
- Two VF cables, each with 100 pairs of 26-gauge wire.

The power, T-carrier, and alarm cables were bundled together and separated horizontally by approximately six feet from the VF cable bundle.

¹² The "EMP Assessment of D4 Channel Bank," October 1986, a study funded by the OMNCS and administered by DNA under Contract DNA 001-85-C-0409.

It was assumed for the D4 assessment that a maximum HEMP-induced current of 300 A would couple to the cables connected to the D4 channel bank. At 50 kV/m, the vertical cables connected to the channel bank were adjusted until the current on all but the VF cables reached 300 A. Although 300 A could not be generated on the VF cables, the peak current of 15 A per pair going into the bank was comparable to the 12 A per pair expected in a CO environment.

A standard D4 channel bank without any EMP protection was pulsed 25 times at 5 kV/m without recording a single hardware failure. All channel units were tested at this level. An Alarm Control Unit (ACU) was permanently damaged during the one test pulse at the 12 kV/m level, probably resulting from an overcurrent at the power interface. Based entirely on this one failure, it was concluded that the failure threshold of an unprotected D4 channel bank is probably between 5 and 12 kV/m vertical polarization.

Exhibit 2-11 summarizes the failure thresholds of a standard, unhardened D4 channel bank in terms of the peak transient current induced at each line interface. For the Alarm, VF and T-carrier interfaces, the induced currents are for each twisted pair.

Exhibit 2-11
Failure Thresholds of Unhardened D4 Channel Bank

Interface	I_p (A)	Rise Time (ns)
Alarm	90	~70
VF	3	~70
T-carrier	13-27	75-85
Power	37	~55

It was shown that the D4 channel bank could be protected against threat-level transients by installing TPDs at interfaces to external cables. The minimum protection needed at line interfaces to ensure survivability is as follows:

- Alarm Interface: 845A diodes
- VF Interface: 0.01 μ F capacitor
- T-carrier Interface: 845A diodes
- Power Interface: a 2 μ H inductor and a 60 V voltage clamping diode.

With these TPDs in place, the bank survived 96 simulator pulses between 50 and 100 kV/m (vertical polarization).

Exhibit 2-12 summarizes the maximum induced transient currents at each of the line interfaces to the hardened D4 channel bank (using the EMP TPDs outlined above). For the Alarm, VF and T-carrier interfaces, the induced currents are for each twisted pair. While these current transients did not cause the D4 to fail, they can be used as a conservative lower limit for the failure thresholds of each interface.

Exhibit 2-12
Lower Limit Failure Thresholds for an EMP-Hardened D4 Channel Bank

Interface	I_p (A)	Rise Time (ns)
Alarm	177	95
VF	28	90
T-carrier	64	78
Power	247	90

Further tests measured transient coupling to the backplane wires of the channel bank. The D4 was not connected to any cables other than to a short power cable, protected at the bank interface by a power TPD. To produce maximum coupling, the D4 was configured with no shielding cabinet and was oriented with the backplane wires parallel to the incident field. The D4 was subjected to 3 pulses at 40 kV/m vertical without failure. The same bank (protected on the shelves by EMP plug-in boards) was subjected to one pulse at 80 kV/m, and one channel unit lost its signaling capability. However, when the circuit packs of the channel unit were hardened, no failures were recorded in 3 pulses at the 80 kV/m level. Tests concluded that the failure threshold due to direct illumination is between 40 and 80 kV/m vertical polarization.

For the final test configuration, which included the proposed TPDs, signal errors or interruptions occurred only twice in 33 tests, with durations of 0.1 ms and 10 ms. A synchronization signal was briefly lost in the remaining 94 percent of the tests, but its duration was not long enough to introduce errors into the data. The effect of these signal interruptions on voice communications was nearly imperceptible, although for data communications at 9600 baud, as many as 100 bits may be lost.

2.1.4 T1 System Response To EMP

As stated above, typical T1 cables and repeaters *with* standard (gas tube) protection against lightning and 60 Hz power faults are survivable against the 50 kV/m double exponential HEMP threat, but repeaters *without* this protection are vulnerable.

The results of simulator testing of lightning-protected T1 carrier equipment are summarized in Exhibit 2-13, which indicates that the T1 carrier facilities are robust to HEMP effects. The first set of data represents survivability of line repeaters; the second set of data represents survivability of central office equipment. The "BSM data" are the results that should be used for the BSM (see section 1.1) in OMNCS network connectivity assessments. This data is used because it is assumed that lightning-protected repeaters are typical of most repeaters in the PSN.

Exhibit 2-13
Interpolated Buried T1 Carrier Test Results

Line Repeater Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	11	0	17	0
30-50	2	0	6	0
50-70	4	0	4	0

Central Office Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	2	0	8	0
30-50	2	0	6	0
50-70	4	0	4	0

Test data show that the survivability of the D4 channel bank is highly dependent on the placement of splice cases. Current surges of up to 100 A may reach the channel bank if a splice case is within ten meters of the equipment. Such a surge is above the failure threshold of the D4. The D4 channel will most likely survive HEMP-induced transients as long as splice cases are more than 40 meters from the equipment.

Unprotected D4 channel banks suffered significant damage and complete failure at transient stress levels that could occur in the central office environment. Fields of only 12 kV/m were sufficient to cause service-affecting failures of D4 channel banks. The failures were caused by the injection of large current transients (3 A to 90 A, ~ 70 ns rise-time) at the

interfaces to long cables. By installing TPDs at these interfaces, the bank was able to withstand induced current transients at the various interfaces of between 28 A and 247 A (with rise-times of about 90 ns). Note that the D4 channel bank is used only when interfaced with analog equipment. As the PSN gradually uses less analog equipment, the importance of the D4 will decrease, reducing the vulnerability of the T1 system to this failure potential. However, the elimination of analog equipment at the user interface (i.e., telephone set) is not likely for some time.

The results of simulator testing of the D4 channel bank are summarized in Exhibit 2-14. As previously mentioned, most of the simulator testing focused on the hardened channel bank. A standard (unhardened) channel bank was pulsed 25 times at 5 kV/m without any hardware failures, but this stress level was below the minimum level addressed by this study. The only applicable test data for the unhardened channel bank is the one data point at 12 kV/m.

Exhibit 2-14
Interpolated D4 Channel Bank Test Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	1	1	1	1
30-50	0	0	1	1
50-70	0	0	1	1

Based on these results, the unhardened T1 carrier system incorporating D4 channel banks is vulnerable to HEMP effects. A hardened T1 carrier system, including EMP-protected D4 channel banks and repeaters, was subjected to threat-level fields, and is concluded to be robust to the effects of HEMP. A complete summary of experimental and predicted stress levels is presented in Exhibit 2-15.

Exhibit 2-15
Comparison of Test Levels and Results with Stress Levels for Buried T1 Carrier Equipment

Equipment and Configuration	Test*	Levels Tested			Test Result	Worst-Case Levels Predicted during HEMP	
		Field (kV/m)	Current at Surge Protector (A)	Current at Equipment Lead (A)		Field (kV/m)	Current (A)
D4 channel bank	DI	12	N/A	37 [†]	circuit damage	50	100 at equipment lead [◊]
D4 ch. bank with special hardening ^{††}	CI	N/A	250 at TPD	1	upset**	N/A	100 at TPD
Line Rptrs., typical, lightning power fault protected	DI	80	167 at SGSL input	25	upset	50	40 aerial 20 buried at SGSL input
	CI	N/A	260	40	upset**	N/A	
Line Rptrs., typical, unprotected & with various splice cases	not tested	N/A	N/A	N/A	not tested	50	unknown; at least 20-40 at equipment lead
Office Rptrs., typical, lightning & power fault protected	DI	100	200 at SGSL input	30	upset**	50	130 at SGSL input
	CI	N/A	200 at SGSL input	30	upset**	N/A	

* Direct Illumination (DI) was with AESOP and OSSI at HDL; Current Injection (CI) was with a 15 ns x 1 μ s double exponential pulse or a damped sinusoidal pulse ringing at 30 MHz and folding in 1 μ s at AT&T Bell Labs.

[†] An Alarm Control Unit (ACU) was permanently damaged at 12 kV/m, probably resulting from an overcurrent at the power interface. The damage threshold of the power interface was a 37 A current pulse with a rise-time of ~ 55 ns.

[◊] Lightning protection is installed a considerable distance from D4 inputs; 130 A could couple to wires leading directly to inputs.

** All upsets were outages of < 1 second.

^{††} The experimental EMP-hardened D4 channel bank used a special TPD.

2.2 FT3C MULTI MODE FIBER OPTIC COMMUNICATIONS SYSTEM⁸

The system described in this section is a multi mode fiber optic system developed by AT&T. The FT3C system is a medium to high capacity trunk transmission system that transmits digitally-encoded voice and data information at 90 Mbits/sec through multi mode light pulses. The system contains three basic elements: the optical waveguide cable, the Line Repeater Stations (LRSs) that regenerate the attenuated optical pulses, and the Central Office (CO) equipment that terminates and processes the signal.

A typical FT3C lightwave system might be configured as shown in Exhibit 2-16. The elements of an FT3C system cover a large geographic area; cable splices occur every 1 to 2 km, LRSs may be as far as 44 km apart, and the maintenance span between COs may reach 800 km. The impact of HEMP on any part of the FT3C system must take into account the total electromagnetic energy collected by long cable runs.

2.2.1 EMP Effects on the Cable

The glass fibers used in the FT3C system are very thin, each measuring only 0.125 mm (0.005 inch) in diameter. Individual fibers are grouped into ribbons of 12 fibers, with up to 12 ribbons stacked together for a maximum of 144 fibers per cable. Up to 1344 voice circuits can be transmitted over a pair of lightguide fibers. The ribbons are intertwined to reduce the strain on the fibers due to cable bends, with steel wires incorporated to further distribute the load. The outer sheath contains two layers of high-density polyethylene, with 14 steel wires measuring 17 mils in diameter (approximately 26 gauge) imbedded in each layer. The two sets of wires are helically wrapped in the opposite direction from each other. Exhibit 2-17 shows a cross section of the LGA1-type lightguide cable used in the testing.

The optical fibers of the FT3C cable should not collect electromagnetic energy, so the analysis must focus on the sheath strength members, which will collect electromagnetic energy if they are metallic. If the strength members are analytically modeled as a solid steel sheath, it is possible that current transients of 1-2 kA may be induced on the cable. The cable's response to HEMP can then be verified through physical testing. Three different tests were conducted on the FT3C cable under the EMP simulator (AESOP) at HDL. While the FT3C is a buried system, the cable was tested both

⁸ Significant portions of this section are drawn from NCS TIB 85-12 entitled, "FT3C Multi Mode Optical-Fiber Communications System: EMP Test and Assessment," one of two studies in a program funded by the OMNCS and administered by DNA under Contract DAEA-18-75-A-0059-8Z01AC.

Exhibit 2-16
Typical FT3C System Configuration

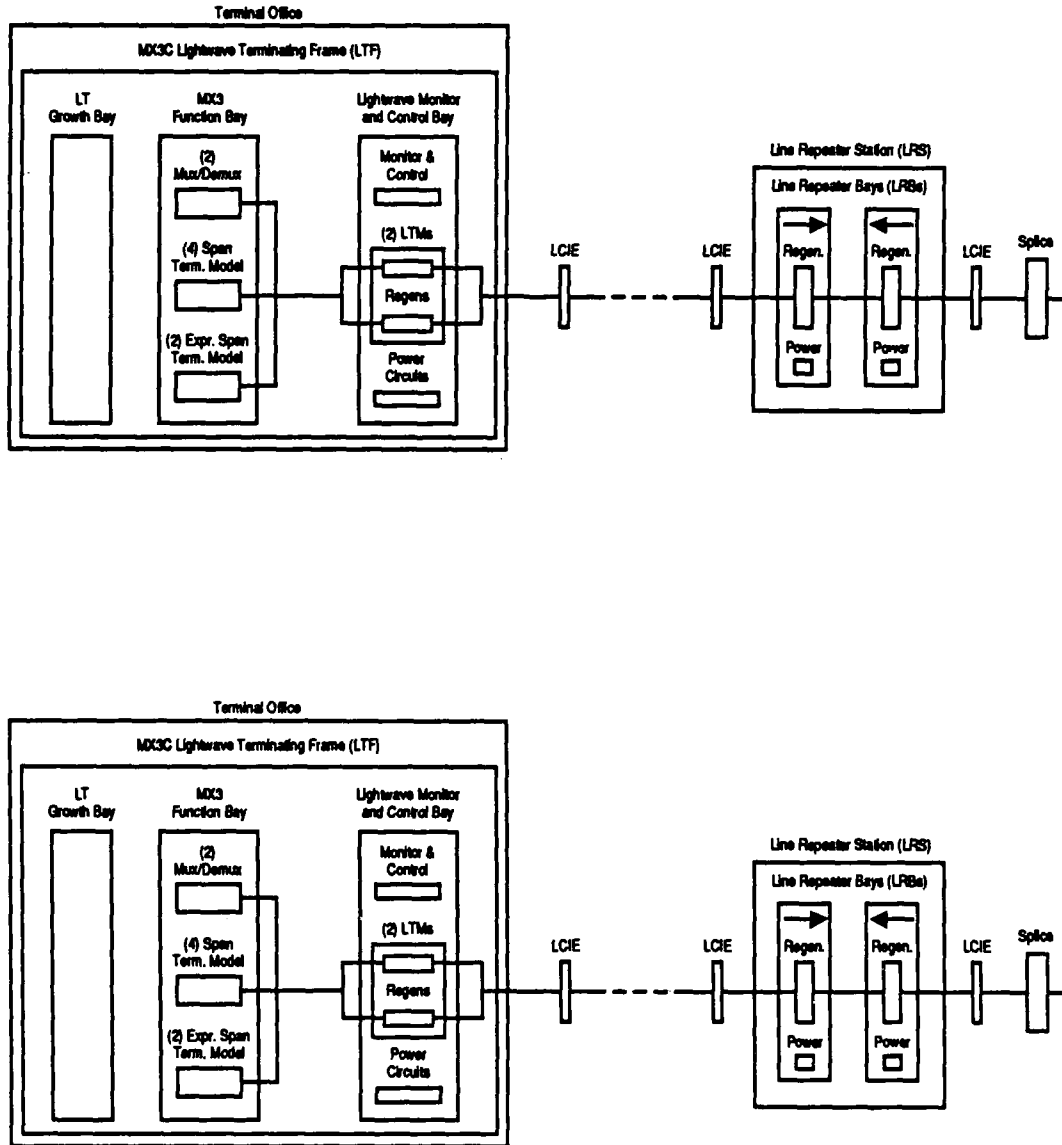
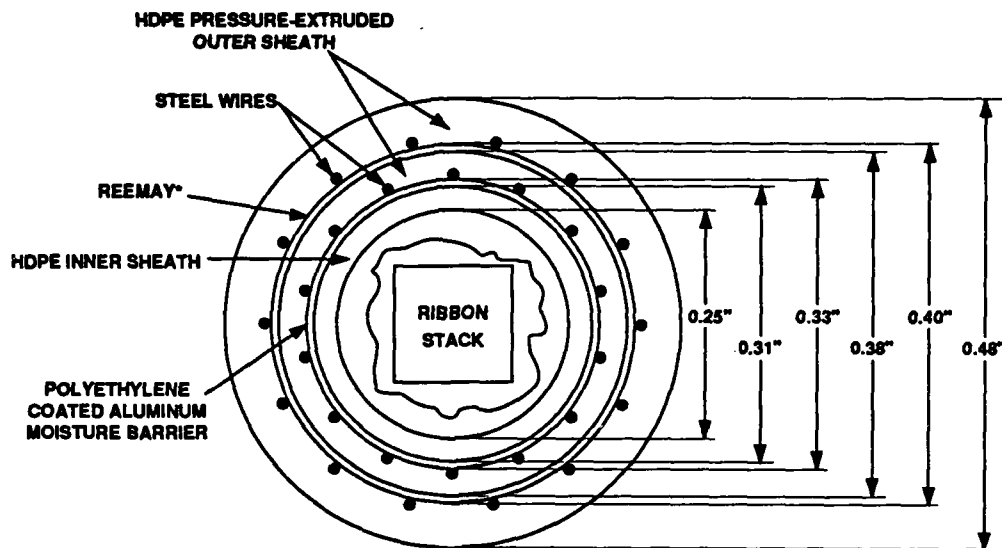


Exhibit 2-17
Cross-section of LGA1-type Lightguide Cable



* REEMAY IS A REGISTERED TRADEMARK OF E.I. DUPONT DE NEMOURS & CO.

on, and six inches above, the ground to facilitate testing. Coupling to aerial cables is much more efficient than coupling to buried cables, so the transients that were induced on the aerial cable had faster rise times, higher peak amplitudes, and larger high-frequency components than the transients expected for an identical buried cable. The incident field, therefore, may have induced worst-case transients on the cable. The electromagnetic coupling test was designed to assist in the quantification of the relation between the incident electromagnetic field and the measured bulk cable current at low incident field levels.

A 308-meter length of cable was laid parallel to the longitudinal axis of AESOP at a distance of 100 meters and was pulsed by the simulator. The peak incident electric field was about 2 kV/m at the cable midpoint. The Sheath Termination Hardware (STH) was alternately left open-circuited or grounded to a copper-clad iron rod, and in each case, the peak current generated at the cable's midpoint was about 27 A. Extrapolation of this low-level coupling predicts a peak induced current of about 700 A at the threat level of 50 kV/m horizontal.⁹ This current is consistent with the 1-2 kA current expected to couple to the solid sheath of a buried T1 cable.

⁹ AT&T, Bell Laboratories, "FT3C Multi Mode Optical Fiber Communications System EMP Test and Assessment," November 1985.

The current-induction test was designed to produce the largest current AESOP could couple to the wire. With the cable laying on the ground and carrying an optical signal in the near field of the simulator (8.5 m), a maximum current transient of 475 A was induced with the centerline grounded, below the predicted threat of 700 A. The test transient caused small "punch-through" holes on the outer sheath of the cable, possibly a result of arcing from the steel wires inside the cable to earth ground. No parity errors or transmission path losses were measured. It is likely that this problem will worsen as currents reach threat levels, possibly causing signal disruption and permanent damage.

The third test measured the distribution of current within the cable. Results show that the outer steel wires carried about one-third of the cable current, with the inner steel wires and vapor barrier carrying the remaining two-thirds.

The AESOP simulator produces an electromagnetic field whose waveform and amplitude approximate those expected from a high-altitude nuclear burst. However, because of the relatively limited spatial extent over which these fields are produced, current injection must be used to reproduce current waveforms of the same magnitude as those induced by HEMP on long cable runs.

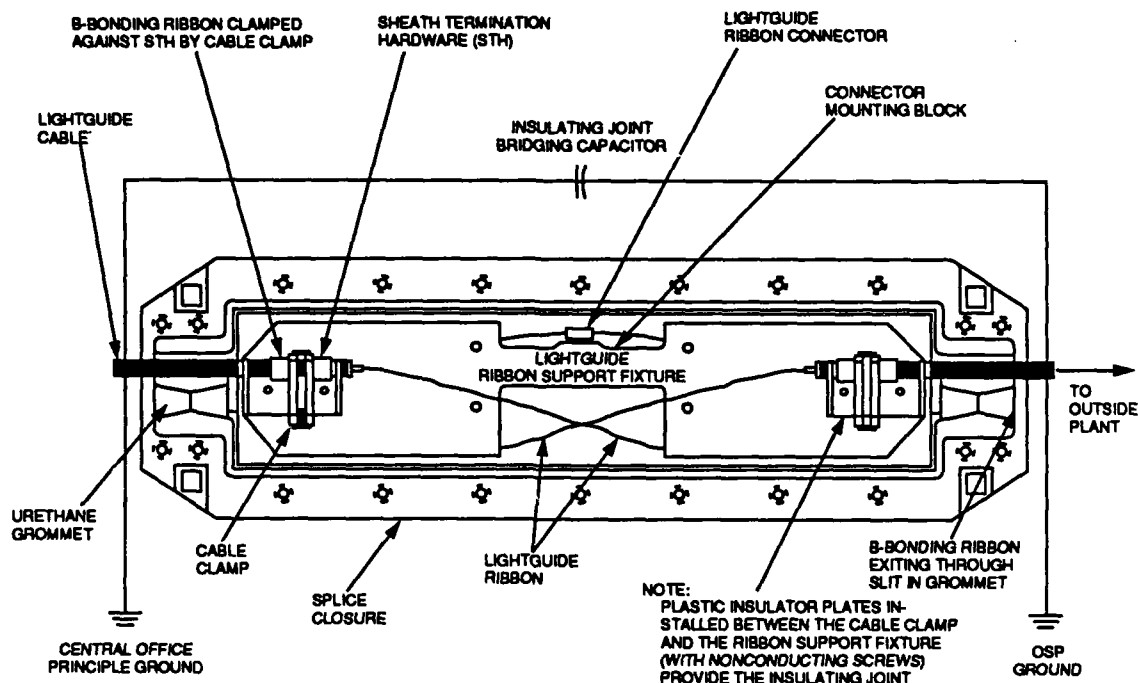
If good bonding practices are not used, induced sheath currents may disrupt the optical signal or damage hardware components; one of the areas most likely to have poor bonding is cable splice points. Current injection was employed to assess the potential signal disruption at cable splice points. Exhibit 2-18 shows a typical optical splice organizer.

For testing purposes, the optical signal was looped through the cable splice and was monitored for parity errors. With the Marx generator charged to 90 kV, peak currents of 900 A were injected through cable stubs into the splice case, and no parity errors were detected. Although not explicitly stated, it is assumed that the stubs were configured with FT3C cable. The rise and fall times of the injected current waveforms are assumed to have accurately represented HEMP-induced transients.

The splice and optical cable were subjected to injected currents above the predicted threat level of 700 A, with no parity errors detected. The 900 A injected current waveform probably caused some physical damage to the cable, because induced current transients of only 475 A were shown to cause minor damage to the outer sheath of the cable. Despite this probable damage, it appears that the cable and splice case are survivable to the effects of HEMP, because the optical signal was not disrupted due to the injected current.

Exhibit 2-18

Grounding and Insulating Joint Connections on Lightguide Splice Organizer in a Vault Splice Closure and at a Central Office CEF

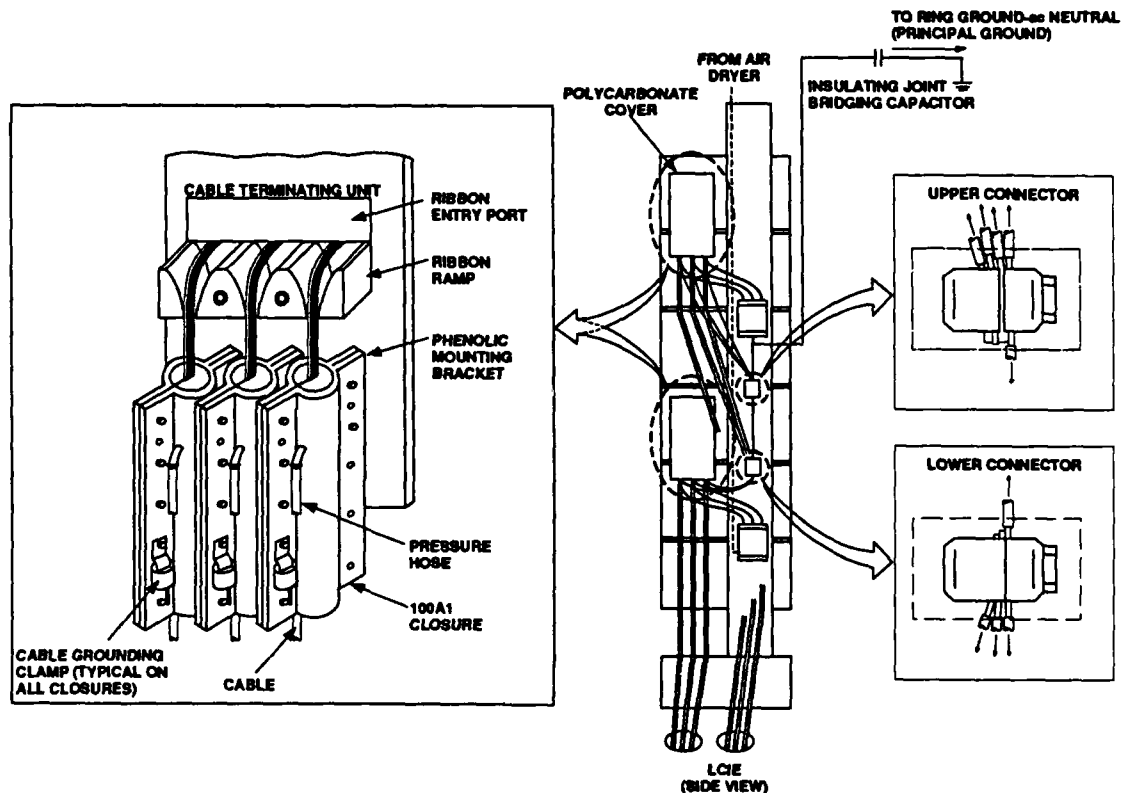


2.2.2 EMP Effects on Line Repeater Stations

The LRS is designed to amplify and retransmit attenuated optical signals between CO facilities. Each LRS contains one or more Line Repeater Bays (LRBs), each of which can accommodate up to 48 FT3C regenerators, with one regenerator required for each direction of transmission. The bays are powered by 131-type power converters, which require 208/240 V single phase AC power input and produce -48 V DC power output for three fully-loaded LRBs. The power converters have a battery backup which can power three fully-loaded LRBs for about eight hours. Long lengths of cable are terminated at the LRS by Lightguide Cable Interconnection Equipment (LCIE). Exhibit 2-19 shows typical cable terminations on the LCIE.

The large current transients that are generated on the steel strength-members of the FT3C cable may enter the LRS through the ground system (which incorporates both the LRS and the LCIE), because the current is terminated to ground through the LCIE. The FT3C power system may be susceptible to spurious shutdown or hardware damage when exposed to these transient ground-system currents.

Exhibit 2-19
Detail Views of Cable Terminations on Lightguide Cable Interconnection Equipment



During testing, the 131C power converters provided the -48 V DC power using one of its two rectifier circuits. While the equipment was exposed to the electric field (E-field) produced by the Marx generators, an optical test signal was generated in the EMP shielded test hut, sent via a 100-foot long cable to the equipment being tested (where it was processed), and sent back to the test hut (where it was checked for parity errors). A maximum charge level of 78 kV produced average E-field components of 55 kV/m horizontal (E_h) and 25 kV/m vertical (E_v) at the equipment.

The two major non-recoverable service affecting failures that occurred during this phase of testing were as follows:

- All three types of power units (131L1A, 131T1, and 131AB1) were subject to deactivation under exposure to simulated-HEMP fields, even at low levels ($E_h \approx 20$ kV/m, $E_v \approx 10$ kV/m). The likelihood of disabling increased at higher field levels.
- One hardware failure occurred in a 131L1A power unit in the LRS at medium field-strength ($E_h \approx 30$ kV/m, $E_v \approx 15$ kV/m).

The deactivation of the power units constitutes a serious problem. When the power units deactivate, power is automatically supplied from the reserve batteries, which will continue to supply power until the deactivated power units are manually restarted. If the power units are not restarted within eight hours, the batteries will be drained, and all service will stop. It is evident that this power system is not survivable to HEMP.

The failure of the 131L1A power unit potentially constitutes a more serious problem, because the failed unit needs to be repaired or replaced (not just restarted) within eight hours if uninterrupted service is to continue. Because only one power unit failed during the testing, and the failure occurred at medium field strength while no failures occurred at threat-level fields, the one recorded failure can be considered an anomaly and is not expected to occur during exposure to HEMP-induced transients.

The power converter shutdowns during the testing of the LRS showed that the overvoltage protection circuitry of all three types of power converters were sensitive to RF noise. The problem was solved by placing a $0.1\ \mu\text{F}$ capacitor between the gate and cathode of the SCR in the overvoltage protection circuitry and placing a $0.01\ \mu\text{F}$ capacitor at the input lead of the overvoltage comparator. The maximum differential current across the supply and return leads of the power converters was measured to be about 40 A, leading to a peak voltage across the output terminals of about 4 kV. With the protective capacitors in place, the modified power converters withstood injected current waveforms with voltages exceeding 4 kV. Several further circuit modifications (similar to those mentioned above) enabled the power converters to withstand repeated peak incident fields of 70 kV/m horizontal and 20 kV/m vertical.

Although the modified power converters of this test configuration survived simulated HEMP transients, they cannot be considered survivable to HEMP. The shutdowns were traced to sensitivity of overvoltage protection circuitry to RF noise, yet this sensitivity was quite likely affected by the configuration of the test setup, which was different from typical LRSs and COs. A more thorough analysis using typical LRS and CO configurations is needed to verify that the modified power converters are survivable to HEMP. Even if the modified power converters are shown to be survivable, there are no plans to incorporate them into either present or future FT3C systems.

Large HEMP-induced current transients may be generated on the cable, leaving the LCIE, LRS, and CO equipment particularly vulnerable, because the LCIE terminates long lengths of cable at both the LRS and CO equipment bays. Because free-field simulation could not generate threat-level currents, current injection was chosen to assess the potential vulnerability of the LCIE to current transients.

With the Marx generator charged to 90 kV, a peak current of 600 A was generated in the LCIE (slightly below the predicted threat of 700 A), and no

parity errors or hardware damage were detected. This current is lower than the current injected into the splice case at the same charging value, because the LCIE has a higher terminating impedance than the splice case. Since no signal disruptions or hardware damage occurred with 600 A of injected current, it is likely that the LCIE will survive injected threat-level currents, but this has yet to be verified.

Except for the damage and shutdown of the power converters, the LCIE and LRS suffered no service-affecting damage or upsets. However, it is possible for threat-level currents to enter the LRS through the ground system, which incorporates both the LCIE and the LRS. Since the survivability of this equipment against threat-level currents on the ground system has not been adequately addressed during testing, the assessment of the modified LRS' vulnerability to HEMP is incomplete.

The power converter shutdown problems incurred during simulator testing of the LRS are quite serious. After a power converter shutdown, power is always supplied by batteries, which last for only eight hours. If the power converters are not manually reactivated within eight hours, then the entire LRS that is powered by the affected power converter will be left without power, and no further calls can be processed. The power converters must therefore be considered vulnerable to HEMP. Because threat-level currents were not injected into all LRS equipment subsystems, no comprehensive conclusions can be drawn regarding the survivability of LRS equipment.

2.2.3 EMP Effects on Central Office Equipment

The FT3C uses MX3 and MX3C equipment at all terminal locations (see Exhibit 2-16). The MX3C LTF consists of a single MX3C lightwave monitor and control bay, a lightwave terminating growth bay (as required), and from one to five MX3 function bays. Various modules may be installed in the MX3 function bay to allow the MX3C lightwave terminating frame (LTF) to operate in one or more of three modes. Each configuration of the MX3C LTF can terminate up to ten two-way FT3C lightwave service lines and up to two two-way FT3C lightwave protection lines. The monitor and control bay lightwave terminating module (LTM) provides an interface between the function bay modules and the optical cable. The regenerators within the LTM multiplex the two 45 Mbits/s input signals and output a 90 Mbits/s electrical signal. This signal drives the regenerator transmitter, which converts the signal to an FT3C lightwave line signal for transmission on the fibers. As with the LRS, long lengths of cable are terminated at the CO by LCIE.

In the FT3C system, there is essentially no difference between stress on CO equipment and stress on line repeaters. Consequently, tests similar to the line repeater tests were conducted at HDL on CO equipment. During testing, CO equipment consisting of a monitor and control bay and an MX3 function bay were subjected to simulated HEMP while powered by batteries. One of the two major non-recoverable service-affecting failures that occurred during the

LRS testing affected the CO equipment as well: all 131-type power converters were again subject to deactivation (causing total service interruptions) when exposed to even low-level simulator pulses.

Threat-level currents can enter the CO equipment ground system from the cable through the LCIE. Because such currents were not injected into CO equipment, the same conclusion can be drawn here as was drawn for the LRSs: CO equipment with unmodified power converters must be considered vulnerable to HEMP. Because threat-level currents were not injected into all CO equipment subsystems, no comprehensive conclusions can be drawn regarding the survivability of CO equipment.

2.2.4 FT3C Multi Mode System Response to EMP

AESOP induced fields and injected threat-level currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case, so both elements appear survivable to the effects of HEMP. Near threat-level currents were injected into the LCIE with no signal disruption or hardware damage detected, so the LCIE will probably survive threat-level transients, but this has yet to be verified.

Unmodified power converters are vulnerable to simulated HEMP transients. Because both the LRS and CO rely on the power converters for power, each must also be considered vulnerable to HEMP.

Although modified power converters are able to survive simulated HEMP fields, testing of the modified power converters did not use a LRS or CO configuration typical of those in the field. It is possible, therefore, that typical equipment configurations incorporating modified power converters would not survive exposure to actual HEMP. While current was injected directly into the LCIE and power converters, it was never injected into the LRS or CO equipment through an LCIE. Because these two issues remain unresolved, the survivability of LRS and CO equipment to HEMP-induced transients is inconclusive.

The results of simulator testing of the FT3C multi mode equipment are summarized in Exhibit 2-20. However, several issues relative to the testing may introduce significant error in using these data. Threat level currents should have been injected into the following:

- The ground system
- All LRS equipment subsystems
- All CO equipment subsystems.

The first set of data presents survivability of line repeaters; the second set of data presents survivability of CO equipment. The "BSM data" are the result estimates that should be used by the OMNCS for inputs to the BSM

Exhibit 2-20
Interpolated FT3C Fiber Optic System Test Results

Line Repeater Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	2	2	2	2
30-50	2	2	4	4
50-70	2	2	6	6

Central Office Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	9	4	9	4
30-50	3	3	3	3
50-70	7	7	10	10

in all network connectivity assessments involving multi mode fiber optic systems. As outlined in section 2.2.2, a major portion of the tests were conducted on an FT3C system with modified power converters, which proved to be robust to HEMP. Because there are no plans to incorporate the modified power converters into either present or future FT3C systems, these results are not used in NCAM. The small sample sizes reflect that only those results incorporating unmodified power converters are used, because they are the only power converters used in the network.

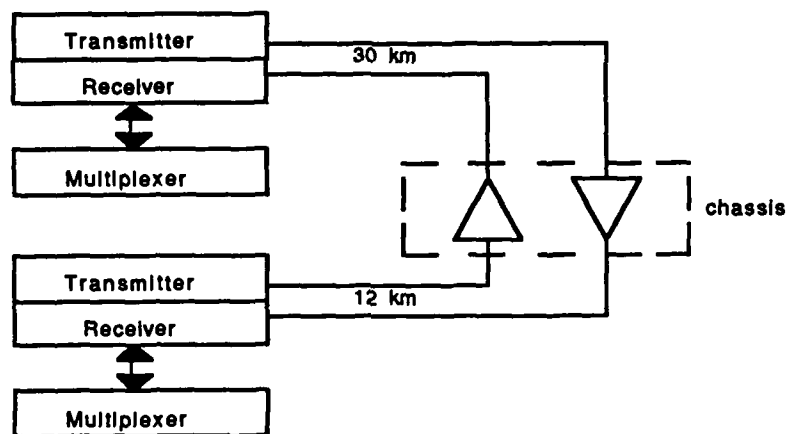
Because of the demonstrated vulnerability of the power system, the entire FT3C multi mode system must be considered vulnerable to HEMP. The primary value derived from these tests is that it has been shown that the FT3C multi mode fiber optic system can be hardened to EMP effects with the incorporation of several hardware modifications.

2.3 R-R140 SINGLE MODE FIBER OPTIC COMMUNICATIONS SYSTEM¹⁰

The system described in this section is a prototype version of a single mode fiber optic system developed by Alcatel of France. While the test report of this system is informative, it gives very limited information concerning system components, so conclusions about the overall survivability of the system to HEMP-induced transients are incomplete. The repeater-regenerator system is a trunk transmission system that transmits information at 140 Mbits/s through single mode light pulses at 1300 nm. The system can be operated with one channel (140 Mbits/s) or with four multiplexed channels (4 x 140 Mbits/s).

For the test, the system was configured as shown in Exhibit 2-21. This setup is considered typical of most repeater-regenerator configurations with the chassis placed in an equipment bay roughly 1 meter above the ground. The chassis contains 2 single-direction repeaters, 1 power supply converter, 1 surrounding alarm card, and 1 TSV attachment card (used to confirm error messages). The chassis was placed in a bounded wave simulator for simulated HEMP testing.

Exhibit 2-21
Typical Repeater-Regenerator System



2.3.1 EMP Effects on the Cable

Because no description of the cable is given in the test report, the cable is assumed to be typical of most buried fiber optic transmission cables (see

¹⁰ Significant portions of this section are drawn from "Compte Rendu Des Essais De Tenue A L'EMN D'un Repeteur-Regenerator En Local 'Noble' Pour Liaison A 140 Et 4x140 MBit/s Sur Fibre Optique Monomode," a study conducted by the French National Center For Telecommunications Study.

section 2.2.1). Therefore, small differences between single and multi mode fiber optic cables should not affect coupled sheath currents. Because the cable used in the FT3C system survived near threat-level injected currents, it is assumed that similar currents (2 kA with 200 ns rise times) will not harm the single mode cable.

2.3.2 EMP Effects on Regenerator Equipment

To measure the operability of the repeater during free-field testing, code and binary errors were monitored. For the 140 Mbit/s mode, the system was configured eight different ways to ensure that a configuration allowing worst-case coupling was achieved. For the system in the 4 x 140 Mbit/s mode, only one test configuration was used, since it was determined to allow worst-case coupling. The line interface was protected with spark gaps mounted on the chassis frame. For each configuration, the system was exposed to fields of 55 - 56 kV/m while operating in each of its two transmission modes.

Prior to testing at the IEMN facility, the 140 and 4 x 140 configurations were monitored for at least 24 hours, and no binary or code errors were detected. During testing, errors were detected in nearly all the configurations, but in all cases no hardware failures occurred.

In one configuration, the lightning protectors were weakened, but the system did not fail (no further information about the lightning protectors is given in the test report). Damped sinusoidal currents of 50 - 325 A were induced on cable sheaths connected regenerator terminals. Exhibit 2-22 depicts a typical sheath current.

Although the current expected to couple to the cable sheaths was not specified in the report, current-injection tests far exceeded expected threat levels. Currents of 2.6 - 6.5 kA were injected at several interfaces, and no errors or hardware failures occurred with the system operating in either mode. Exhibit 2-23 depicts a typical injected current pulse.

At the conclusion of the free-field and current injection tests, the system was monitored for 48 hours, and no errors were detected for either transmission mode. As a result, the electronics of the repeater were concluded to be survivable to HEMP.

2.3.3 Summary

Although the single mode fiber optic cables were not tested, they are assumed to be survivable to HEMP, because they are assumed to be similar to the FT3C multi mode fiber optic cables, which are survivable to HEMP. As for the electronics of the repeater, threat-level simulator fields and injected currents did not produce any service-affecting damage. Temporary transmission errors were detected, but the system returned to full operating capability without manual intervention following testing. This return to full

Exhibit 2-22
Current on Sheath of Cable

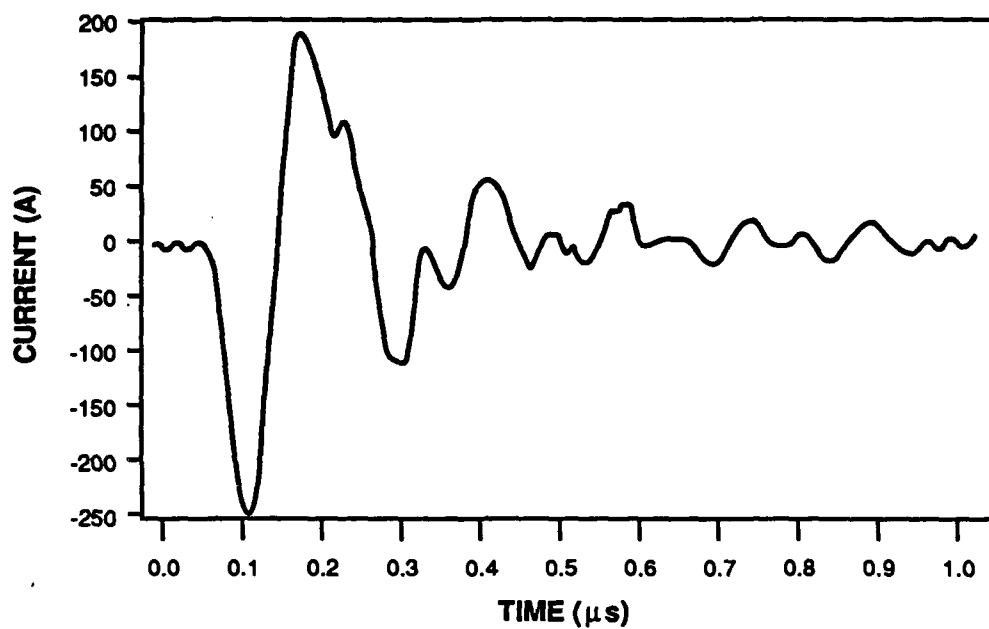
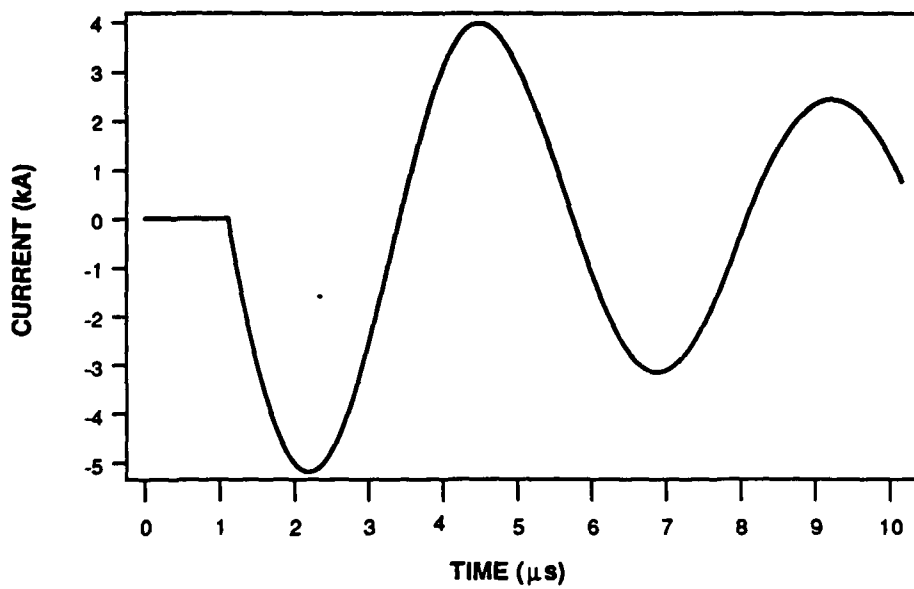


Exhibit 2-23
Typical Injected Current Pulse



operation was systematically confirmed by an observation period of about 48 hours at the end of the tests. The electronics of the regenerator are therefore concluded to be survivable to HEMP.

The results of simulator testing of the single mode equipment are summarized in Exhibit 2-24. The "BSM data" are the results that should be used by the OMNCS for inputs to the BSM for network connectivity assessments involving single mode fiber optic systems. While operating in the 140 Mbit/s mode, the system was pulsed 14 times. While operating in the 4 x 140 Mbit/s mode, the system was pulsed eight times.

Exhibit 2-24
Interpolated 140 and 4 x 140 Physical Test Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	0	0	22	0
30-50	0	0	22	0
50-70	22	0	22	0

2.4 THE L4 AND L5 CARRIER SYSTEMS

The L4 System was introduced in the late 1960s for reliable high-capacity long-haul transmission. L4 is a solid-state system designed to survive in a nuclear environment.¹¹ All cable is buried, and hardened routes have buried main stations and repeaters.

The L4 System comprises cable, terminal office equipment, and three types of line repeaters: basic, regulating, and equalizing. Basic repeaters are nominally spaced 2 miles apart, regulating repeaters 12 miles apart, and equalizing repeaters 50 miles apart. Terminal stations (main stations, COs) perform formatting and switching functions, allow remote control, and supply power to repeaters; they may be attended or unattended, and can be spaced up to 150 miles apart.

The L4 System was retrofitted over L3, introduced in 1953 with 12 coaxial tubes and 9,300 two-way voice channels, which, in turn, had been retrofitted over L2. In addition to carrying more tubes per sheath, each

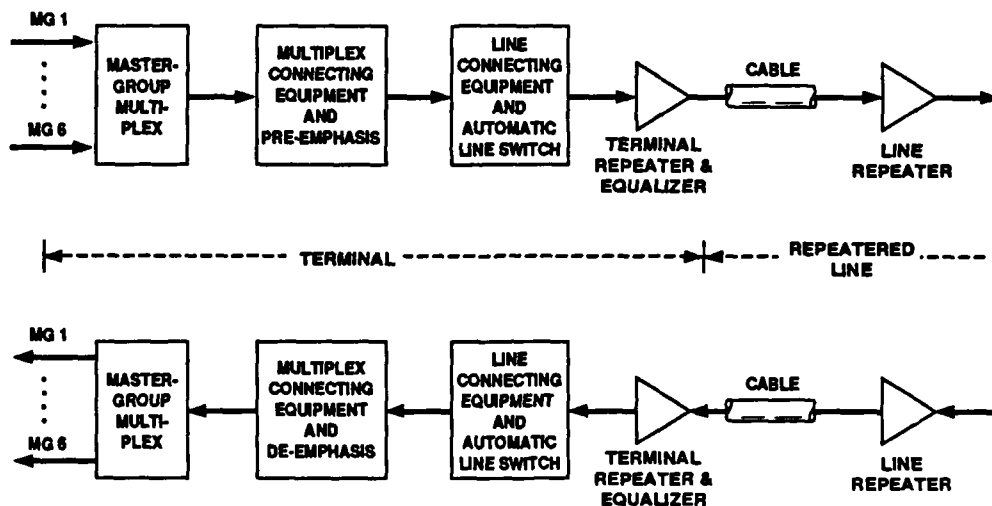
¹¹ E. F. Vance, "L4 Theoretical Cable System Study (U)," SRI, 1971 (SECRET).

successive retrofit multiplexed higher frequencies and cut the previous nominal repeater spacing in half, for example, from 4 miles in L3, to 2 miles in L4.

The first commercial use of L5 was in 1974. L5 was planned for the relief of coaxial and radio systems along major north-south and east-west corridors in intercity networks.¹² The L5 system is retrofitted on L4, and has basic repeaters every mile. Main stations perform the same functions as L4 main stations, but must be spaced 75 miles apart or less.

A high-level block diagram of system terminal equipment is shown in Exhibit 2-25. Main station equipment includes transmitting and receiving equalizing repeaters, and multiplexing equipment for customer message formatting and amplification. Additionally, main station L4 and L5 equipment perform automatic protection switching, remote monitoring and control, fault location and power supply.

Exhibit 2-25
Simplified Block Diagram of L4 Terminal Equipment

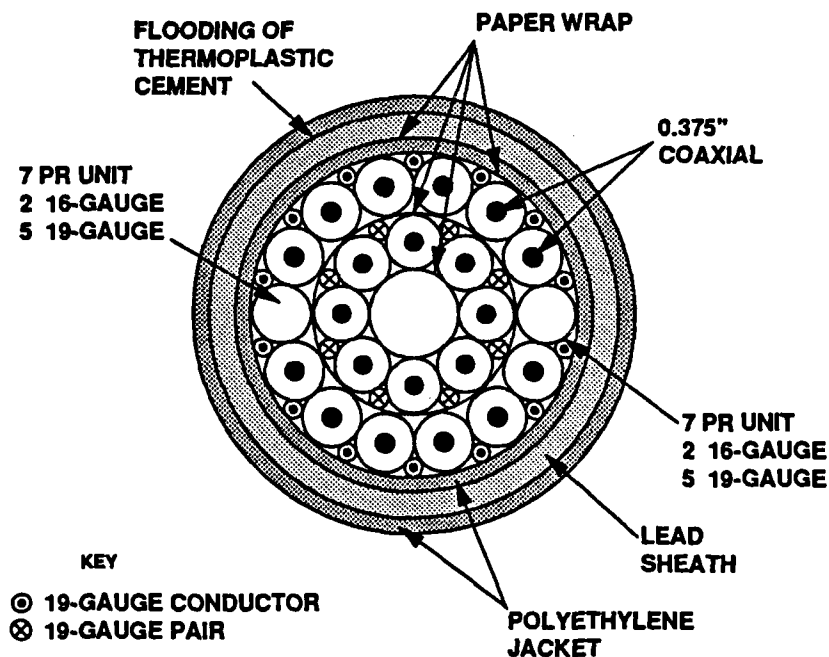


2.4.1 EMP Effects On The Cables

L4 trunks generally are 3-inch shielded cable carrying 20 coaxial tubes and 52 interstitial service pairs. Each coaxial tube carries six frequency-multiplexed master groups (3,600 one-way voice channels), while each pair carries 3,600 two-way (full-duplex) voice channels. Of the 20 tubes, one pair is spare and nine pairs are used, supplying 32,400 two-way message channels per sheath. Exhibit 2-26 shows a typical L4 cable.

¹² AT&T, Engineering and Operations in the Bell System, 1977.

Exhibit 2-26
Typical L4 Cable Characteristics



Trunk cable: WECO "COAX-20", buried, pressurized with dry air.

Standard coaxial line: 0.1" copper conductor insulated from 0.375" cylindrical conductor of 0.012" copper tape seamed lengthwise. Outer conductor wrapped in one or two 0.006" steel tapes for added strength and H-field shielding.

Completed trunk cable core (including core pairs, inner eight coaxials, interstice pairs, outer 12 coaxials, two units of wire pairs, interstice single wires, paper wrapping): 2.13" diameter.

Inner polyethylene jacket: 0.075" thick.

Outer paper wrap (heat barrier): spirally wound, thickness 0.005".

Lead (Pb) sheath: Thickness 0.112", conductivity is 4.5×10^6 mho/m.

Outer polyethylene jacket: 0.079" thick black polyethylene, dielectric constant is 2.3.

Total cable outer diameter: 2.972".

L5 multiplexes three full-duplex jumbogroups (each comprising six mastergroups) per coaxial pair. When new cable is laid, it contains 22 tubes (two are still spare) supplying a total of 108,000 two-way voice channels per sheath.

In addition to the 6 and 18 mastergroups that L4 and L5 trunks respectively carry, they carry line pilot signals, equalizer test and remote control adjustment signals, line-switching signals, command carrier signals, and monitoring oscillator signals. Diagrams of L4 and L5 system frequency allocation are shown in Exhibit 2-27.

If L cables were exposed to HEMP, major concerns would be similar to those for T1 cable: direct damage from large currents, diffusion currents on signal conductors, and high-frequency coupling to exposed cable. However, there are a few differences. Since L systems are analog and repeaters actually amplify signals, the potential amplification of high-frequency HEMP-induced surges is a concern. Additionally, lower-frequency surges could sum along entire 150-mile lengths, since repeater DC power is sent along signal lines and power separation filters are designed to pass low frequencies along the line.

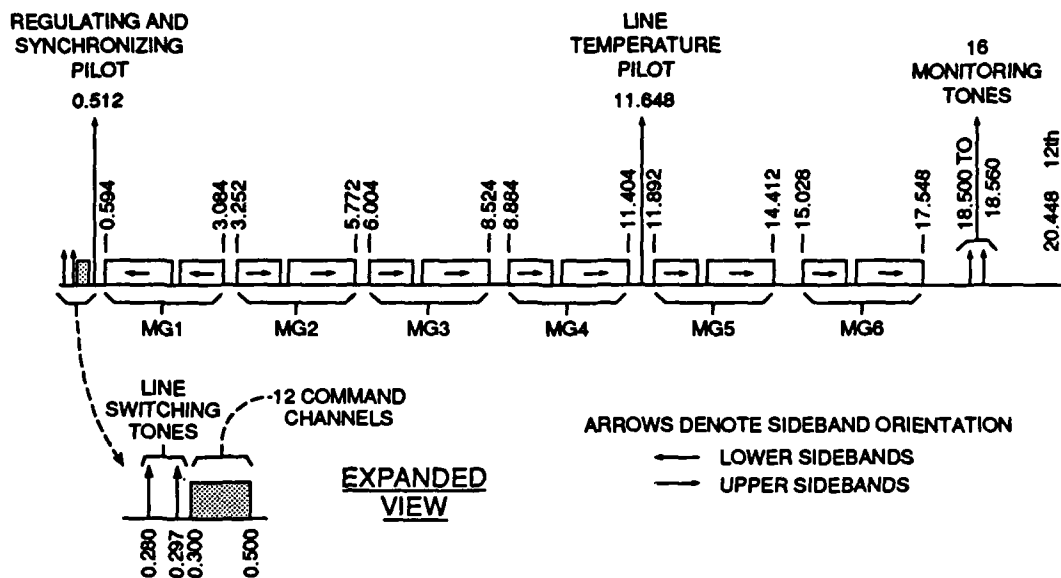
In general, L4 cables are well-protected against direct coupling and its effects. All lines are buried, and there are no splice cases at repeaters. Signal lines in L4 are also much less likely to be exposed to sheath currents than signal lines in twisted pair cables or in T1.

On some routes, guard wires are buried with the cables; guard wires are two 0.165-inch diameter wires, 10 inches apart and 24 inches above the cable. These wires protect cables from direct lightning strikes. The cables are better conductors and carry 90 percent of induced currents at frequencies above 10 kHz (rise times less than 25 μ s), where most HEMP energy is radiated.

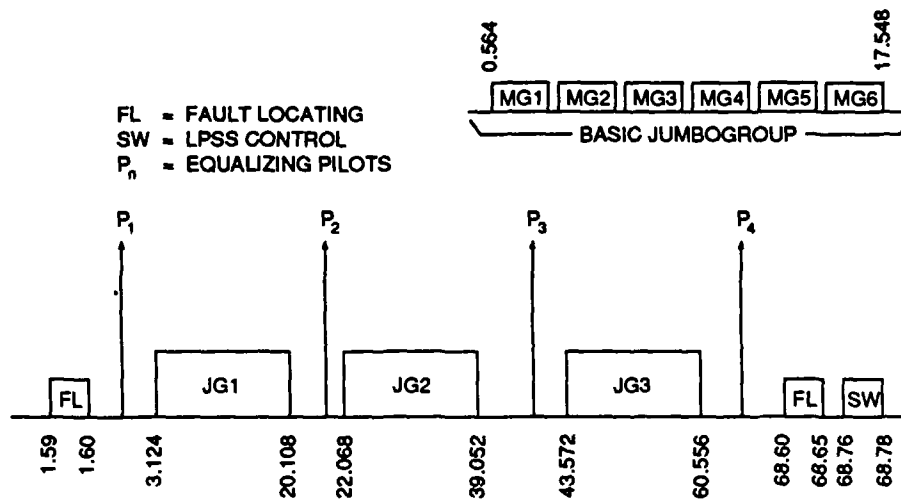
2.4.2 EMP Effects On Repeater

Over a 4,000-mile route, signal loss is 120,000 dB in L4 cable at nominal L4 frequencies. The L4 system is designed to deliver signals to within ± 3 dB amplitude for all circuits. Amplification of the signal is a complex task and must be well controlled. Control of the signal levels is accomplished by three types of repeaters. The basic repeater is a plug-in unit with a shaped gain-frequency characteristic that compensates for two miles of 0.375-inch coaxial cable loss at 55° F. A regulating repeater performs the basic repeater function and provides gain regulation to compensate for changes in cable loss due to variations in soil ambient temperature. An equalizing (mid-span) repeater performs the regulating repeater functions and provides equalization across the L4 band using six networks whose characteristics can be varied remotely by commands from a main station control center.

Exhibit 2-27
L System Frequency Allocation



(a). L4 frequency allocation



(b). L5 frequency allocation

Each repeater has power separation filters (PSFs), a Zener diode for constant voltage drop, and an amplifier circuit. The PSFs supply DC power to the amplifiers and divert frequencies below 70 kHz from amplification. A preamplifier, which accepts frequencies over 100 kHz, and a power amplifier amplify the analog signal, and are separated by Line Build-Out units (LBOs). LBOs are passive lossy networks that mimic cable losses; they are inserted (in 0.1-mile increments) when cables are shorter than nominal. A block diagram of a basic repeater, showing the power separation filters, is shown in Exhibit 2-28. Typical repeater layout according to function is shown for L4 and L5 in Exhibit 2-29.

In general, L4 repeaters (in and out of main stations) are well protected. Transient protection and transformers exist on all interface circuitry. Repeaters, encased in heavy aluminum and installed in manholes, are well-shielded. Protective grounding circuits may also exist at repeater sites.

Because of the configuration of the 150-mile repeater power supply loop, repeaters near the ends of the loop operate at high potentials with respect to ground. This makes high potential surges an even greater concern. L systems do not use TPDs on signal lines (which also carry repeater power); lines terminate in the repeater power separation filter, which is exposed directly to diffusion currents. Nonetheless, L4 repeaters are designed to withstand induced EMP surges, especially along hardened routes—a requirement that may have had the greatest influence on repeater physical design and circuit design.

The low-pass PSF has its break point at 70 kHz in line repeaters and 40 kHz in main office repeaters. High-frequency signals are sent to the preamplifier input filter, a high-pass filter with its break point at 100 kHz in line repeaters and 45 kHz in office repeaters. Low frequency signals are passed to the power supply circuit and directly to the repeater Zener diode. Thus, pulse components below 100 kHz could stress the diode and the preamplifier filter, but they will not be amplified.

Pulses entering through the output terminals are similarly filtered and passed to the power amplifier output. The preamplifier input and power amplifier output are well-protected; the preamplifier input has a transformer and surge protection diodes, and the power amplifier output has a transformer and an RLC filter.⁸ At 20 MHz the preamplifier has a gain of 6 to 17 dB, the power amplifier a gain of 18 to 20 dB.

⁸ Bell System Technical Journal, "L4 Basic and Regulating Repeaters," 1968.

Exhibit 2-28
Simplified Schematic of L4 Basic Repeater

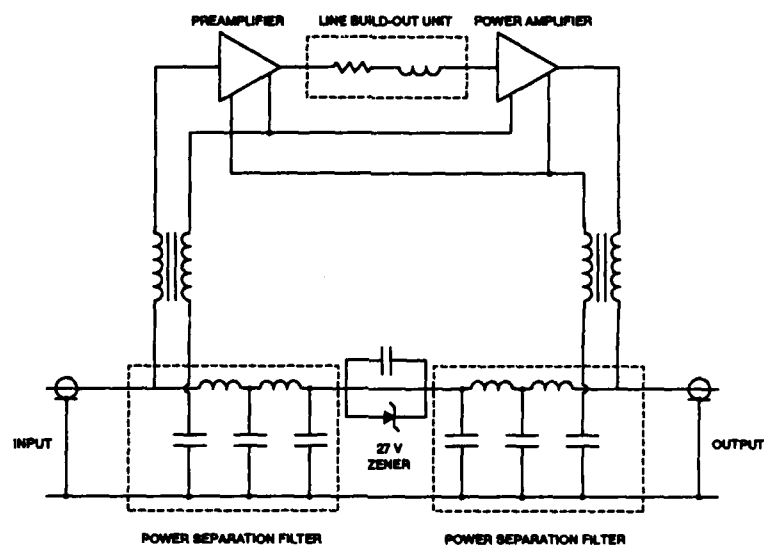
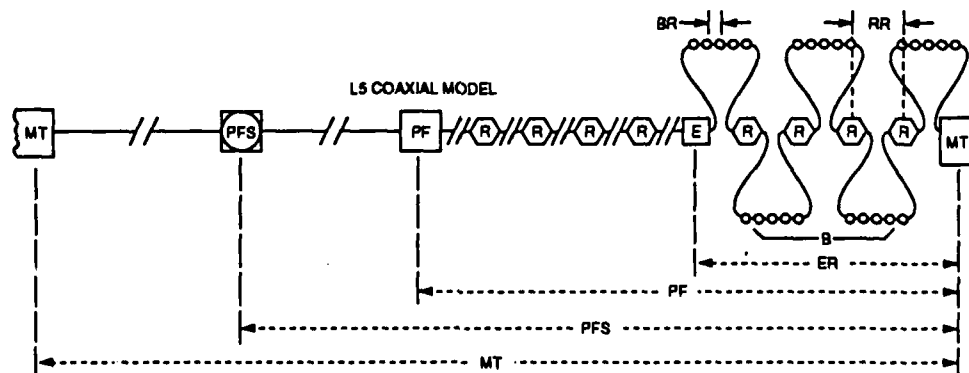
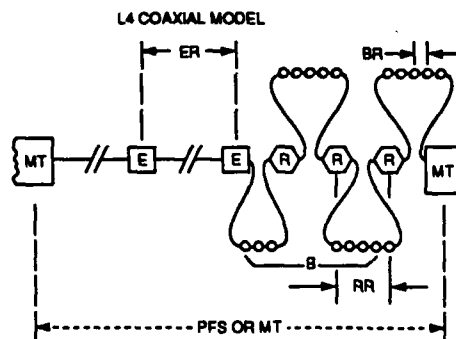


Exhibit 2-29
L System Repeater Spacing

MODEL	MILES *	L4 COAXIAL		L5 COAXIAL	
		AVG	MAX	AVG	MAX
BASIC REPEATER		2	2	1	1
REGULATING RPTR (RR)		12	12	6	7
EQUALIZING RPTR (ER)		44	54	30	38
POWER FEED (PF)		—	—	60	75
POWER FEED/SWITCH (PFS)		120	150	120	150
MAIN TERMINAL (MT)		120	+	240	+

SYSTEM CAPACITIES		L4			L5		
NO. COAX PAIRS	12	20	22	12	18	22	
NO. MGS	30	54	60	96	144	180	
NO. 4 kHz	18,000	32,400	36,000	54,000	86,400	108,000	

* BASED ON THE NATIONAL AVERAGE



Protective silicon diodes are installed across both the primary and secondary windings of the preamplifier input transformer. The preamplifier first stage transistor would be damaged if exposed to too much voltage drop; the protection diodes are designed to limit voltage spikes to a swing of 2 V peak-to-peak for any type of transient, including HEMP.

This combination of repeater protection is proven effective against short circuits, lightning, and 800 V, 60 Hz power fault transients. Before deployment in L4 systems, repeaters are tested with transients peaking at 2 kV in 10 μ s, with up to a millisecond duration injected onto input and output terminals.

Repeater cases are thick aluminum, which is an effective shield. Cases and cables are grounded on a ground bus, which runs to a peripheral ground of 0.75-inch bonded copper-weld rods buried around the manhole. At the repeaters and all along the cable, signal conductors see an estimated 6,000 Ω impedance to their return (the coaxial tubes), essentially an open circuit compared with their 75 Ω source impedance. Thus, they are essentially 150-mile conductors with a continual open circuit to ground. The outer coaxial tubes, on the other hand, are bonded to the lead (Pb) sheath at each repeater, effectively grounding them every two miles. Additionally, cables are laid inside steel pipe for 30 feet as they approach a repeater on each end.

These are good bonding practices, as previously outlined.⁹ Extremely high surge currents might reflect somewhat from the ground bus onto coaxial tubes, but would not be significantly propagated down the line. Ringing that couples onto signal lines would either be damped by amplifier transformers (if high-frequency) or attenuated by the 150-mile isolated signal lead itself (if low-frequency).

Bulk current injected onto the trunk sheath was 1,460 A, somewhat less than the 2 kA that might couple to buried cable. Free-field illumination levels of all equipment were up to 80 kV/m, much higher than the 50 kV/m threat. In addition, equipment was exposed to repetitive pulses of free-field illumination and current injection, spaced 0.5 μ s apart, to simulate multiple HEMP events.

Thus far, the coupling of transient fields to trunk sheaths and the integration of diffused currents over long lines have been discussed, including attenuation by repeater transformers, but ignoring repeater action. In the L4 system, there is also concern about the propagation and amplification of high-frequency (above 100 kHz) surges down the line.

Such limiting action causes a burst of noise to be propagated through the system. In tests, this noise was enough to cause temporary loss of signal

⁹ Harry Diamond Laboratories, "DSN Design Practices for High-Altitude Electromagnetic Pulse (HEMP) Protection," HDL for the Defense Nuclear Agency, June 1981.

to the next repeater in line, but did not cause any damage. Since any amplification of this noise would be attenuated by the next interrepeater cable length, PSF, and preamplifier input filter, it is concluded that high-frequency noise may be spread over time and will not be amplified above the level seen at a single repeater.

2.4.3 EMP Effects on Central Office Equipment

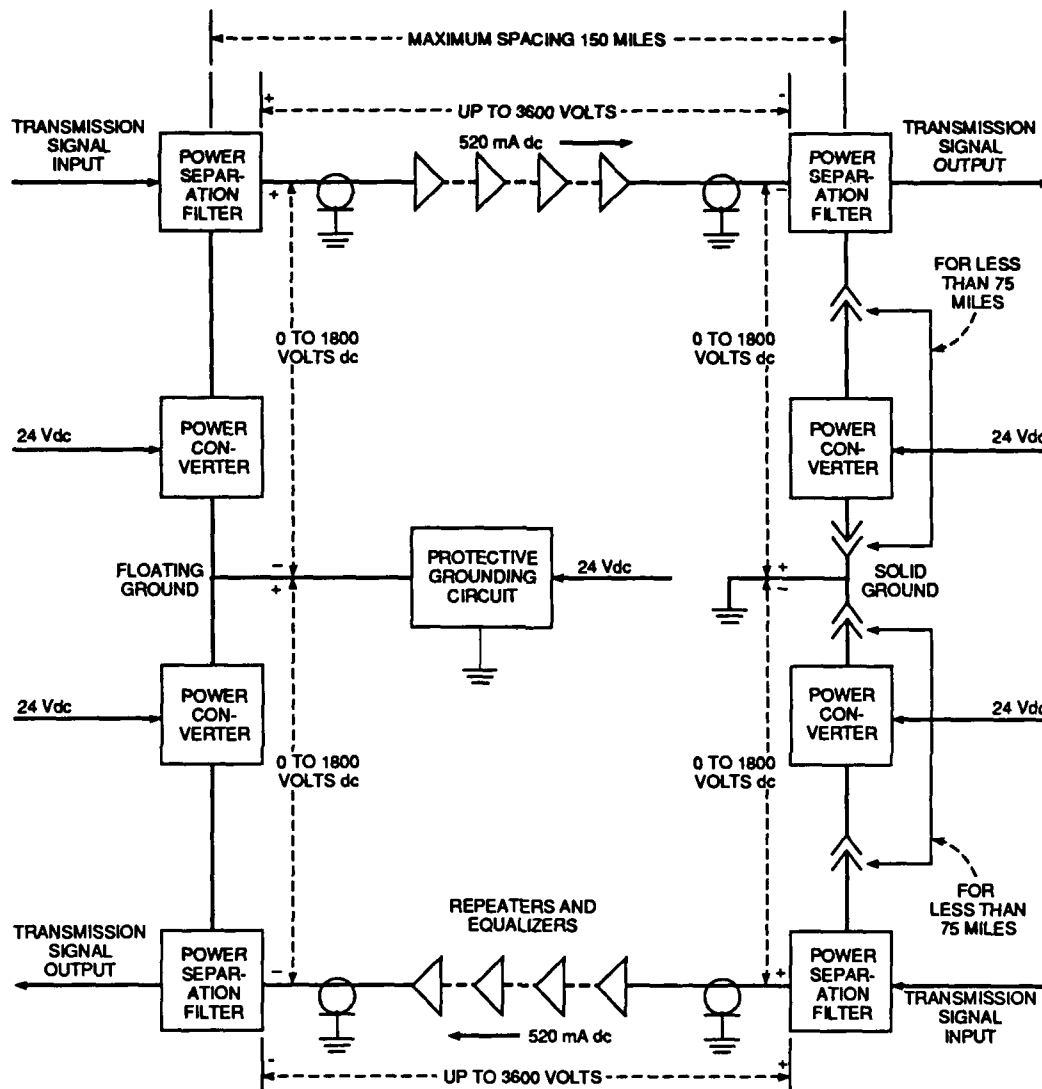
Central offices perform remote control of line systems, protection switching on all transmission trunks, and protective grounding and shutdown of the repeater power supply loop. A control center, located only at certain main stations, is attended and allows performance of remote temperature and gain sensing, adjustment of equalizers, problem location, and interrogation and control of other (slave) main stations, which need not be attended. As an example, problem location might be conducted by remotely turning on test oscillators present in each equalizer and monitoring oscillators present in each repeater. Signal levels would be displayed in a spectrum analyzer at the control center, and amplifier gain deviations would be pinpointed.

Automatic protection switching occurs at each main station, staffed or unstaffed. When a line pilot used for primary frequency synchronization or repeater gain regulation deviates from preset levels, all circuits on that coaxial tube are switched onto the standby pair at the receiving end, and a line protection switching tone is sent to the transmitting end. Any upset in the line pilot tone causes the Line Protection Switching System (LPSS) to switch the standby pair of coaxial tubes into the transmission path.

Main stations contain high-voltage DC converters that furnish power to line repeaters over the center conductor of the coaxial lines and to other remote equipment over the interstitial lines. A line repeater loop (two main terminals and all of the line repeaters between them) is powered from both ends, with one end grounded and the other end floating. The potential drop along each long line is symmetric with respect to ground, with one end positive and the other end negative. In L4 the long-line drop over 150 miles is 3,600 V, maintaining 520 mA DC current; in L5 the drop over 75 miles is 1,150 V, maintaining 910 mA current.

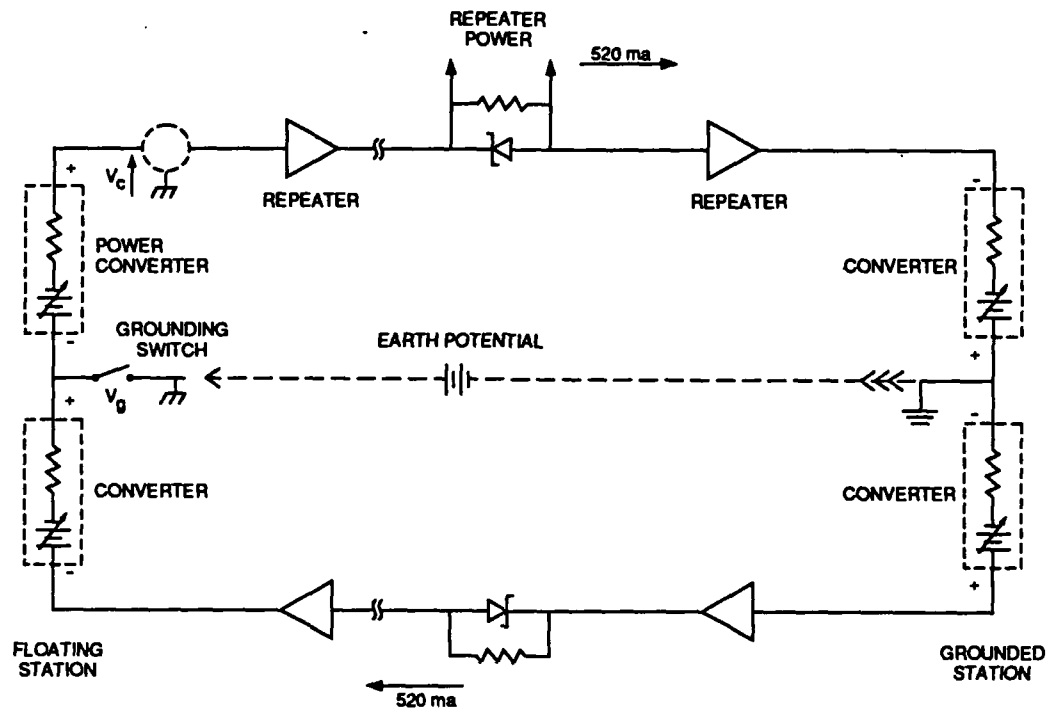
Induced sheath currents or earth potential gradients can cause dangerously high voltages at the floating end of the loop, so a protective earth grounding circuit is tied to floating ground. A block diagram of the L4 repeater power supply loop is shown in Exhibit 2-30, and simpler block diagrams of the grounding protection are shown for L4 and L5 in Exhibit 2-31.

Exhibit 2-30
L4 Repeater Power Supply Loop Block Diagram

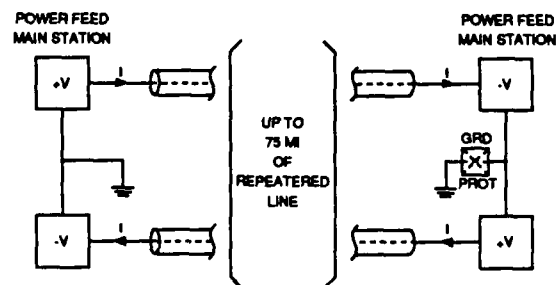


As mentioned in the previous section, surge transients at COs would be equivalent to those expected at repeaters at the ends of a 150-mile segment. On each L4 signal line entering a main station building, surge protection or regulator diodes and a spark gap are provided. Typical spark gaps used are AT&T Technology type 98, 111, or 123 carbon blocks. As part numbers ascend, these carbon blocks are built to carry more current; plant engineers choose a part based on experience with transient problems in their areas. Special high-current protectors, such as AT&T Technology type 198, may be installed where severe power-fault transients could couple to signal lines.

Exhibit 2-31
L System Repeater Power Grounding Protection



(a). L4



(b). L5

Firing tests of the typical spark gaps in use on L4 lines were conducted at Bell Labs.¹⁰ Two pulse types were tested. The first rose to peak in 4 μ s; in two series of tests, the mean and standard deviation firing voltages were 610 ± 70 V and 780 ± 140 V. The second pulse was the 10 μ s \times 1,000 μ s pulse with which repeaters are tested; the observed firing voltage was 700 ± 75 V. For all tests combined, the average delay (charging of the carbon blocks) was 7 to 40 ns at voltages near the threshold (representing the worst case), and 5 to 7 ns at high voltages up to 2,000 V. From these tests, it is apparent that all current in the pulse for at least the first few nanoseconds will be passed on the lines directly into equipment leads.

As mentioned, there is a protective circuit on the repeater power loop floating ground point to protect against induced surges and earth potentials. A schematic and listing of the operational limits of this circuit are shown in Exhibit 2-32. Central offices have additional threats to this power supply loop, particularly from magnetohydrodynamic EMP (MHD EMP).

Shutdown of the power loops through the protective grounding circuit or the power converters is not a failure, but is nonetheless incompatible in an NSEP environment, given that such a failure requires manual intervention. Personnel at the two central offices would have to be communicating to raise the four power converters to operational level in tandem. This communication normally takes place over order wires, the two groups of wires that run in L4 cables near the outer sheath in place of coaxial tubes (see the L4 cross-section, Exhibit 2-26). Communication between PSN personnel is established using voice-frequency analog transmissions repeated at the equalizing repeaters only (in separate amplification circuits from signal amplifiers at the repeaters).

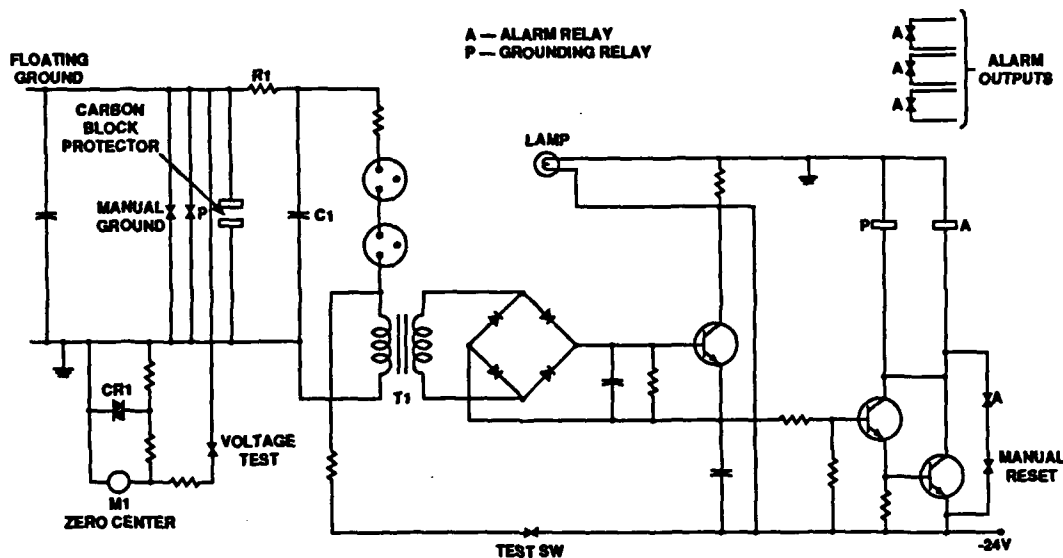
The second potential problem is firing of spark gaps on the separate amplifier power supply lines, system "lockup," and blowing of the fuses. This would mean that power to the 150-mile loop of L4 signal repeaters could not be restored unless personnel can communicate over other routes, or replace the fuses in the field.

2.4.4 Response Of The L4/L5 Carrier Systems To EMP

At the higher stress levels the L4 system was susceptible to shutdowns at the power system due to overcurrent and undercurrent effects. Such an occurrence can be deemed a failure because manual intervention was required to restore system operability even though there was no physical damage. Such manual intervention might be impossible during NSEP conditions.

¹⁰ E. F. Vance, "L4 Theoretical Cable System Study (U)," SRI, 1971 (SECRET).

Exhibit 2-32
Schematic of Power Loop Protective Grounding Circuit



Peak instantaneous limit:	2,600 V total
Peak floating ground voltage:	800 V maximum
Maximum steady-state over-voltage:	2,200 V total
Maximum steady-state floating ground voltage:	400 V maximum
Steady-state shutdown limit for floating ground voltage:	370 V
Delay time for steady-state shutdown:	20 ms

In addition to the cable current, direct illumination and earth potential stresses, current will be carried to L4 COs along other building penetrations. Some analytically predicted levels¹¹ are listed in Exhibit 2-33.

A typical L4 system is sometimes considered a link in a hardened route. Along such a route, cable is hardened to sustain 150 psi overpressure from blast, repeaters to sustain 50 psi, and COs 10 psi. From information available on construction and installation practices along such routes, a typical system as a whole appears to be well-protected. Neither conducted stresses on penetrators nor direct illumination fields are expected to cause failures. This

¹¹ MITRE Corporation, "EMP Effects on the L4 Transmission System (U)," DNA contract F19628-76-C-0001, 1975 (SECRET).

expectation is consistent with test results; no tested L4 component has been

Exhibit 2-33
Analytically Predicted Penetrator Currents

Penetration	Main Station (Amps Pk-Pk)	Repeater Station (Amps Pk-Pk)
Power Cables	2900	-
Aerial Telephone Cable	5200	-
Buried L4 Cable	1000	1000
Sewer/Water Pipes	1000	-

determined to fail at full stress levels. The most serious problems observed have been power or transmission outages for a half second, and power loop automatic protection shutdown, requiring manual intervention.

Exhibit 2-34 summarizes the results of the L4 cable testing. The test data were not analyzed to compare the detailed test conditions for each measurement with each stress level. Throughout the test, both the equipment configuration and the method of applying the stress varied. In addition, the HEMP simulators did not apply appropriate HEMP stress to cables entering the facility, which can result in understressing of the equipment for a given field level. For these reasons it was not possible to separate the data between the low and medium field levels. The low and medium test data results were therefore combined as indicated in Exhibit 2-34.

Exhibit 2-34
Interpolated L4 Cable Test Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	151	1	151	1
30-50	151	1	151	1
50-70	45	24	45	24

In summary, the L4 system appears robust to HEMP effects below 50kV/m and susceptible to HEMP effects above that level. This statement is

based solely on the results of the SAFEGUARD Communications Agency testing program.

2.5 MICROWAVE RADIO SYSTEMS

Long-haul transmission systems frequently use line-of-sight microwave radio. Radio systems, like cable transmission systems, are made up of switching and signaling equipment in central offices, and repeater sites for amplification on long-haul lines. A microwave radio link junction consists of a structural steel tower holding transmitting and receiving antennas, waveguides that run down the tower to a building; and interface, protection, modulation, and multiplexing equipment (or the inverse) inside the building.

A common radio system in the PSN is the Frequency Division Multiplexed - Frequency Modulation (FDM-FM) system, which carries analog signals in the GHz frequencies. Among the most important of these systems are the TD Systems, notably TD-2. TD-2 uses vacuum-tube technology, multiplexes 1,500 circuits per radio channel on vertically and horizontally polarized beams (with interstice channels of the other polarization), and uses horn reflector antennas. Frequency range is 3.7 to 4.2 GHz; average repeater spacing is 26 miles and is decreasing (as circuits per channel increase). The solid-state version, TD-3, is replacing TD-2 on an evolutionary basis.

Another class of FDM-FM analog systems are the TH systems, notably TH-1. These systems transmit over the 5.925 to 6.425 GHz range, but are otherwise similar to the TD systems. TH-3, the solid-state version, is similarly replacing existing TH-1 systems. TH-3 is expected to carry up to 2,400 circuits per radio channel.

Other bands exist centered around 11 and 18 GHz, but the higher frequencies are more problematic. The 11 GHz band is limited to shorthaul traffic, but links can be used as extensions in congested areas or as stand-by protection routes. New technology continues to evolve at higher frequencies, in SSB (single side-band) radio, and in data transmission at lower frequencies.

As mentioned, equipment is housed in ordinary buildings near the microwave tower. Radio transmitters and receivers are usually located as close to the tower as possible to minimize waveguide losses. Consequently, there may be up to another 1,000 feet of coaxial cable leading to multiplex equipment terminals.

Similar to cable systems, FM systems include protection switching in the event of equipment failure. Protection (idle) channels can be switched into the normal transmission path. In addition, patch bays are located at end stations (main stations) for restoration and routing flexibility.

2.5.1 Diffusion And Penetration Stresses

Based on an analysis of the penetration stresses entering a building from a microwave tower and waveguide run,^{12,13,14,15} a worst-case assessment determined that 6 kA peak-to-peak HEMP currents are expected at the waveguide point of entry into the building. Rise times of 100 to 400 ns for typical tower heights in the Bell system are expected. The current rise rate for the worst case is thus determined to be 60 A/ns. Typical lightning transients expected by radio station designers are 10 kA tower currents with 1 μ s rise times.¹⁶ The rate of rise in this case is 10 A/ns, which is of the same order of magnitude as the HEMP rate of rise.

The applied practice of bonding and grounding waveguides and AC power conduits at the building entrance to external and internal ring grounds provides a significant reduction in transients on electromagnetic penetrators. Testing¹⁷ has shown that for signal leads within 10 feet of the penetrator (near zone), induced signals can be reduced by 45 dB or more using this practice. For leads that are farther away than 10 feet (far zone), induced transients can be reduced by more than 65 dB. The transient currents expected in this case are 3 A and 34 A on leads in the far and near zones, respectively. In particular, the coaxial communication cable (in the near zone) connecting the waveguide to the radio bays can carry over 30 A. Such large currents require waveguides and coaxial cables extending 10 feet or more inside a large station and must have multiple grounds inside the building. They should also be multiply grounded at all equipment room entrances.

Power line leads are also expected to produce about 1 A of induced current (see section 3.2.2) at radio equipment leads. Other penetrators such as water pipes, sewer pipes, fuel lines, and conduits for external lighting are not

¹² R. W. Sassman, "The Current Induced in a Finite, Perfectly Conducting, Solid Cylinder in Free Space by an Electromagnetic Pulse," EMP Notes, Air Force Weapons Laboratory, Volume I (Note 11), June 1971.

¹³ S. Dairiki, "Study of a Scale Model of a Common Carrier Communication Station," Final Report, July, 1973.

¹⁴ "Effects of EMP on Bell System Long Haul Transmission Facilities," Bell Laboratory final report on the SAFEGUARD Communications Agency (SAFCA) EMP Program, April, 1974.

¹⁵ "Technical Directors Report of the APACHE Navcams Eastpac Test," DNA 4284FHAS7, December 1979.

¹⁶ AT&T, "Electrical Protection of Radio Stations," Bell System Practices 876-210-100, Issue 4, November 1974.

¹⁷ S. A. Schelkunoff, et. al., Antennas: Theory and Practice, J. Wiley and Sons, New York, 1966.

expected to contribute much current, because these penetrations are usually not routed near equipment bays.

Diffusion fields are also expected to induce significant interbay currents. Simulated HEMP tests have been conducted by Bell Labs on TD-2 microwave relays at several sites.^{18,19,20} The microwave terminal equipment tested includes TD-2 radio bays, protection switching circuits, and multiplexer/demultiplexer subsystems. Exhibit 2-35 lists the test sites used in these studies.

Exhibit 2-35
Simulated HEMP Tests of Microwave Relay Facilities

Location	Building Shielding	Excitation Levels	Responses	Maximum Observed Current Induced
Fargo, North Dakota	10 dB	140 kV/m	Upsets No Damage	2 A
Shiner, Texas	10 dB	50 kV/m	Upsets Some Damage(*)	N/A
Vega, Texas	40-50dB	50 kV/m	Minor Upsets No Damage	N/A
New Hope, Ohio	10 dB	50 kV/m	Upsets No Damage	N/A

* AT&T/Bell Labs studied, identified and recommended fixes

2.5.2 System Response to HEMP

The survivability assessment of the microwave systems requires consideration of penetration currents coupling to radio equipment, multiplexers, and protection switching, as well as diffusion coupling from direct illumination. The present test data base indicates that the TD-2 microwave equipment is survivable to direct illumination to HEMP fields of 50 kV/m. However, this testing did not simulate the direct penetration current expected from the tower and waveguide. Although, the currents induced by direct illumination are less than 2 A, penetration currents (due to

¹⁸ Bell Laboratories, "EMP Tests on Two Bell Systems Communication Centers (U)," December 1968, (SECRET-RESTRICTED DATA).

¹⁹ MITRE Corporation, "Initial Current-Injection Tests at New Hope," MTR 70-92, Vol. 27, Sup. 5, August, 1972.

²⁰ H. Slater, et. al., "Results of RES Test at the Midlothian AT&T Repeater Station Sites 311-327," SAFA, Analysis Report #96, April 23, 1973.

tower transients) can be 30 to 40 A. This suggests that the total stress on microwave equipment will be substantially greater than levels tested to date. Actual stress levels at particular sites, of course, depend on placement of equipment racks (near or far zone) and interior routing of other conductors (i.e., power lines, telephone lines, AM/FM antennas). Tests performed during the PREMPT program provided data concerning damage thresholds for some typical radio and multiplex equipment ranging from 9 to 110 A.

In summary, test data indicate that TD-2 microwave systems are not vulnerable to permanent damage from direct illumination or diffused fields. The dominant conducted stress (potentially damaging) would most likely occur from tower transients. However, the abundance of microwave and radio towers in the PSN and relatively frequent occurrence of lightning transients has led to design practices (i.e., bonding and grounding) that mitigate surges that have rates of rise comparable to HEMP. TD-2 systems are therefore inferred to be survivable to HEMP conducted and diffuse transients. However, the TD-2 system employs vacuum tube technology, which is inherently more survivable to HEMP than systems using solid state technology. Since most newer microwave systems (such as the TD-3) are solid state, they may be more vulnerable to the effects of HEMP than the TD-2 system. The actual test data from the assessment of the TD-2 microwave system are included in the classified appendix to this report.

3. SWITCHING SYSTEMS

3. SWITCHING SYSTEMS

The three switching systems identified in section 1 and their expected HEMP responses are reviewed in this section: 5ESS, 4ESS, and DMS100 switches. In this analysis the following HEMP issues and associated practices are discussed:

- EMP shielding effectiveness of building construction and expected field levels
- EMP-induced surges on power lines and communication cables and the effect of these surges on interface equipment to the switch
- EMP penetrations through ground systems.

The first section describes the central office, with emphasis on the HEMP stress levels for these switching systems. The remaining sections describe in detail the effects of HEMP on each switching system.

3.1 CENTRAL OFFICE STRESS LEVELS

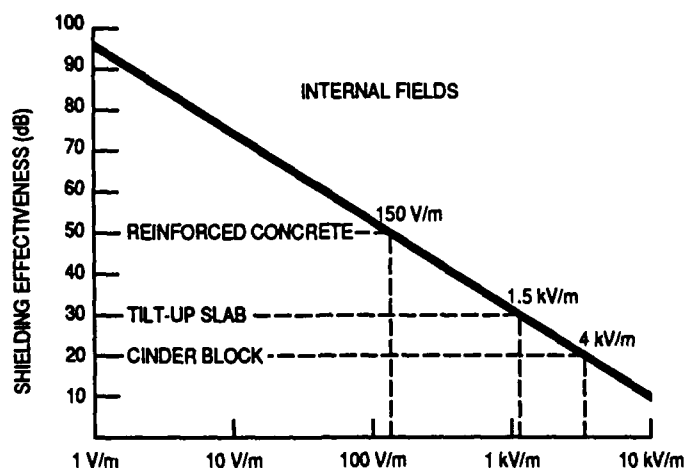
Assessment of the survivability of switching equipment requires the determination of the stresses due to the diffusion field and the conducted stresses on external penetrators (e.g., cables, water pipes, antennas, towers). The sum of all of these stresses is used as the composite stress for a worst-case assessment.

3.1.1 Field Levels

Since the advent of the electronic switch, plant designers have recognized the need to provide a quiet electromagnetic environment for the switch and associated equipment. In an urban area, this environment is typically provided by the use of electromagnetic shielding and filters on power lines to reduce the electromagnetic interference from radio frequency (RF) sources. Switching sites located away from a metropolitan area, however, may be in quiet electromagnetic environments, and require little shielding. Most central offices in the PSN are of this latter type, although the current trend is toward increasing levels of RF interference in both urban and rural areas. AT&T standards and practices indicate that these buildings are normally constructed in one of three ways: reinforced concrete, pre-formed concrete, and cinder block with brick veneer facing.

The high-altitude EMP threat presents a peak electromagnetic field of about 50 kV/m. Given this external field, Exhibit 3-1 presents the field environment inside the walls of a central office as a result of shielding provided by the three types of construction. For example, a reinforced concrete building could reduce the fields inside the walls of the CO to about 150 V/m.

Exhibit 3-1
Building Shielding Effectiveness



**NOMOGRAM FOR INTERNAL ELECTRIC
FIELD ENVIRONMENTS (ZONE 1)**

$$\text{S.E.} = 20 \text{ Log } \left(\frac{E_{\text{ext}}}{E_{\text{int}}} \right)$$

ASSUMED 50 kV/m EMP ENVIRONMENT

At some central offices, additional shielding is required because of EMI considerations. This added shielding may be provided by internal shields in the form of conductive screens inside the plant walls, screen rooms for equipment, or shielded cabinets for sensitive electronics. These shielding practices are not a standard procedure, but are usually incorporated into building design and modification as options, depending on site location and circumstances. For example, if a switching system is located near an airport with radar and air traffic control equipment that radiates high electric fields, equipment may be placed inside a screen room to protect it from this interference.

Internal shielding can be very effective in reducing diffused field EMP. Some estimates of the shielding effectiveness of internal shielding are as follows:³¹

- Screen room (60 dB)
- Wire screens (20 dB)
- Inadvertent shielding (possibly 6 to 10 dB)

³¹ AT&T, "RFI Shielding," Bell System Practices 760-220-100, 1978.

Inadvertent shielding arises from the standard practice of placing switches near the building center where other metallic equipment such as cable trays, water pipes, and heat ducts may shield the switch. Another form of inadvertent shielding is due to the frames, cabinets, and equipment racks of the switch. Testing of a 1ESS at the Apache Junction Autovon Station³² with a parallel plate illuminator showed that 6 ns rise time fields of 35 kV/m were attenuated 15 to 20 dB with rise times slowed to greater than 80 ns. The resultant effect is similar to that of a lossy low-pass filter. Various polarizations were also injected into the switch area and indicated negligible variation in the responses. In addition, fields shielded by building construction are randomly polarized.

Tests at Apache Junction and Fargo microwave stations measured the building transfer functions (shielding effectiveness), where Apache Junction had a 2 psi overpressure construction and Fargo had a 0.5 psi overpressure construction. Since shielding effectiveness is a function of frequency, the measurements were made over a wide range of frequencies (100 kHz to 70 MHz). The minimum shielding observed at each site was 25 dB and 10 dB respectively for electric fields, and 15 dB and 0 dB for magnetic fields. These observations support the correlation of building construction and shielding effectiveness in the HEMP frequency range.^{33,34}

The net shielding of the facility is also influenced by apertures, which include windows, doors, wall seams and joints, air conditioning ducts, and other openings in walls, floors, and ceilings. Apertures allow additional penetration of electromagnetic fields. The size of apertures and their proximity to critical electronics are usually reduced to minimize electromagnetic interferences. Apertures do not significantly affect the shielding of switching facilities. Shielding effectiveness measurements of typical building constructions include the effects of apertures, hence the influence of apertures is already incorporated in the present analysis.

3.1.2 Power Line Transients

The previous sections of this report have presented the typical stress values expected on external penetrations and the stress levels brought into the central office from transmission facilities (cables, waveguides). The power lines entering the control office are also significant penetrators. In fact,

³² Bell Laboratories, "EMP Tests on Two Bell Systems Communication Centers (U)," December 1969, (SECRET-RESTRICTED DATA).

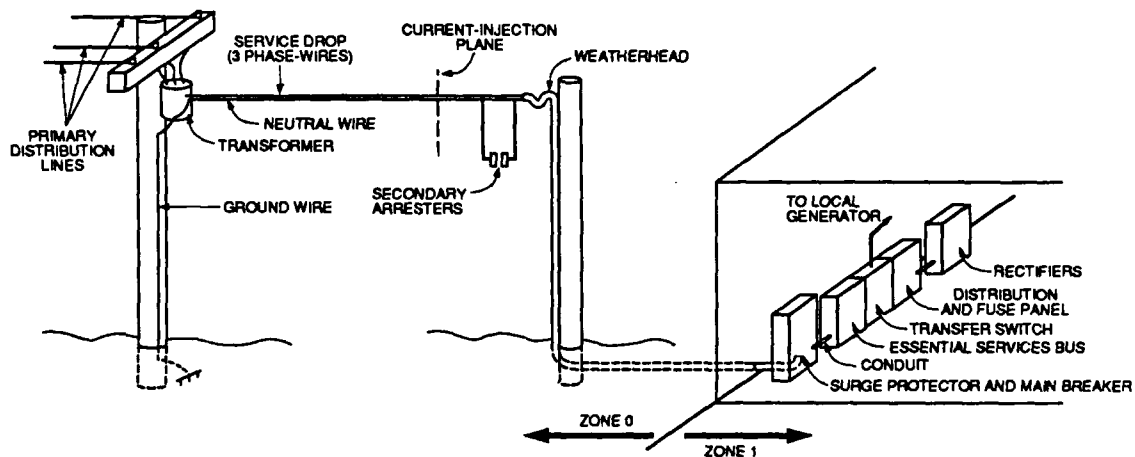
³³ Defense Nuclear Agency, "DNA EMP Handbook Series," Volume II, DNA-H-86-60-V2, 15 November 1986.

³⁴ The BDM Corporation, "DNA EMP Course Study Guide," Module VII, January 1983.

unshielded aerial power lines may result in 4 kA transients at the power entry to the building.^{35,36}

Power lines are unique because they are often routed through the building in conduit and are not exposed inside a building. Outside the building, power lines are terminated in a transformer, reducing the voltage to that required by the site. Exhibit 3-2 shows a typical power line termination at a building. Another typical configuration is placement of the line going to the weatherhead pole in an underground conduit.

Exhibit 3-2
Typical Power Line Termination



TYPICAL COMMERCIAL POWER FEED AND DISTRIBUTION
BOUNDARY ONE AT THE MAIN BREAKER BOX

Inside the building, the power first passes through the main circuit breaker and then branches to essential and nonessential (i.e., lighting) service buses. From the essential service bus, the power goes to a transfer switch (actuated when power fails), then to a fuse panel and power distribution board (the rectifiers powering the facility are fed directly from this board). These circuits are almost always protected from lightning by the power company serving the physical plant. The power company places lightning arrestors (usually carbon block or gas tube) at the transformer on the load side of the power lines. Also, in virtually all physical plants, the telephone company places its own (secondary) lightning arrestors in the form of carbon

³⁵ Bell Telephone Laboratories, EMP Engineering and Design Principles, Loop Transmission Division, Whippany, NJ: Technical Publication Department, Whippany, NJ, 1975.

³⁶ E. F. Vance, "Coupling to Cables," DNA-2114 EMP Handbook, Chapter 11, Defense Nuclear Agency, Washington, DC, December 1974.

block or gas discharge tubes at the weatherhead or at the main breaker when no weatherhead is used.

The coupling through the transformer does not take place by normal transformer action. Common mode currents couple through the capacitance between the transformer windings and through the inductance of the bushings and the leads.³⁷ Since this coupling effect is not well understood, no reduction in current on the power line is assumed when passing through the transformer.

Lightning arrestors may also affect the incoming surge, though insufficient data are available about their effectiveness in limiting the fast-rising HEMP transients. This is especially true for carbon blocks where the response time for "clamping" may be too slow to be effective. Tests by the Stanford Research Institute and Bell Labs^{38,39} on secondary arrestors show reductions in currents of 6 to 15 dB. In view of the uncertainties and limited data, a 6 dB reduction in current is assumed when arrestors are present.

The coupling of the 4 kA signals to equipment at and beyond the rectifiers has been determined through several tests.^{40,41,42} Current injection tests were used to measure the coupling-loss factor to transform exterior currents to interior load currents. (The coupling-loss factor is the ratio of measured peak equipment lead current to peak injected current.) The results of the tests conclude that at the rectifiers, a 4 kA signal is reduced by 40 dB (or 40 A). For nonrectifier leads, the coupling-loss factor is 70 dB (or 1.5 A). Thus, power lines generally contribute little to total induced lead currents (with the exception of rectifier leads) in the buildings tested.

³⁷ R. T. Bly, Jr., and E. F. Vance, "High-Voltage Transient Tests of Service Transformers Lightning Arrestors, and an Automatic Switching Unit," SRI Technical Report 10, SDI Project 7995, October 1973.

³⁸ E. F. Vance, S. Dairiki, "Analysis of Coupling to the Commercial Power System," Stanford Research Institute, Technical Report, October 1971.

³⁹ J. B. Hays, D. W. Bodle, "Electrical Protection of Tactical Communication Systems," Bell Laboratories Engineering Services on Task Studies of Military Communication Systems, Technical Report No. 6, December 1963.

⁴⁰ MITRE Corporation, "Initial Current-Injection Tests at New Hope," MTR 70-92, Vol. 27, Sup. 5, August 1972.

⁴¹ MITRE Corporation, "Midlothian Power-Line Injection Test Plan," M70-92, Vol. 21 Sup. 3, January 9, 1973.

⁴² SRI, "HEMP Hardening Assessment of 16 CONUS/Canada ARCO AUTOVON Switch Centers (U)," May 1976, (CONFIDENTIAL).

3.1.3 Ground System Transients

The central office ground is a common point to which all ground connections are made to avoid potential differences. The central office ground is typically obtained by connection to the metallic water system. Driven ground rods may be used in addition to, or in lieu of, the water pipe. Inside the central office, low resistance connections to the central office ground are provided throughout the building. The low resistance connections are attained through the use of large diameter cables, copper or aluminum bars, or structural steel. All groundable metallic penetrators entering the central office are required to be well bonded to the central office ground. All equipment racks and other metallic surfaces are bonded to the central office ground. Emphasis is placed on maintaining potential equalization between equipment ground, power ground, cable shields, protection ground, and the central office ground.

Modern digital switching equipment is typically bonded to the central office ground using a single point ground; all equipment grounds for the switch are electrically isolated from all other grounds except through a single point. Because HEMP transients will cause large potential differences between points in the grounding system due to its self-inductance, large potentials may exist between pieces of equipment that are grounded to different points in the grounding system. Single-point grounding ensures that all of the equipment in the switch is referencing the same ground potential, regardless of the potential between that point and remote earth.

The amplitude of current transients in the ground system are difficult to predict. The currents on all well-bonded penetrators (e.g., waveguides, well-bonded cable sheaths, water pipes) are all injected into the ground system. Portions of the currents on singly-bonded penetrations also contribute to ground system transients. The transients on power lines and all of the currents diverted through surge protection devices are placed on the ground system. The combination of all of these currents (possibly 100 kA or greater) may cause large potential differences to exist between subsystems unless good bonding and grounding practices are used.

3.1.4 Equipment Lead Transients

HEMP-induced transients on the signal leads to switching system equipment include components arising from two sources: conducted transients on conductors external to the central office; and coupling to long conductors inside the central office. This section summarizes the procedure for estimating the transients on switching system leads based on these two effects.

External conductors (both signal lines and power lines) are attached to various pieces of interface equipment before entering the switching equipment. The interface equipment includes modulators/demodulators, multiplexers/demultiplexers, equalizers, office repeaters, lightning protection

devices, and other terminations. The interface equipment attenuates the transient on the line, providing some amount of protection for the switching equipment. However, the attenuation is extremely difficult to predict without detailed knowledge of the circuit design of the interface equipment, and few test data exist. A worst case attenuation of 0 dB (no attenuation) is assumed unless measured attenuation data exist for a particular piece of equipment. The transient levels on transmission facilities are described in detail in section 2 and are summarized in Exhibit 3-3. These levels are assumed to also exist at switching system input leads that connect to these transmission facilities.

Exhibit 3-3
Central Office Stress Levels on Transmission Facilities

Transmission Facility	Peak Current (A_{pp})
T1	2
TD-2	1

As seen in previous sections, coupling to conductors within the central office has two sources: the EMP fields within the building (direct illumination); and coupling due to the currents induced on external conductors that are brought into the building (penetrations). A summary of the diffused EMP field coupling to wires within the central office is presented in Exhibit 3-4.⁴³

Exhibit 3-4
Induced Current Waveforms from Direct Illumination

			Peak-to-Peak Current(A)	
	f_0 (MHz)	$t_{1/e}$ (μs)	Concrete Block	Poured in Place
Average	7.2	4.6	10.0	0.3
Median	6.3	4.3	6.0	0.3
Range	1-16	1-8	3-20	0.2-5.0

⁴³ Bell Telephone Laboratories, EMP Engineering and Design Principles, Loop Transmission Division, Whippany, NJ: Technical Publication Department, Whippany, NJ, 1975.

Coupling from penetrations depends on penetrator transients, routing of the penetrations within the building, routing of the equipment lead of interest, and bonding of conductors. However, the currents induced on the equipment leads as a result of the penetrators may be estimated through existing data bases of EMP test results.^{44,45,46}

The estimation of currents on equipment leads is a two-step process. The first step is the estimation of the current induced on the penetrator. Measured coupling-loss factors from HEMP testing are used to calculate the induced current on equipment lead as a result of the current on the penetrators. The coupling-loss factor is defined by $\alpha = 20 \log (I_p/I_e)$, where α is the coupling-loss factor, I_p is the peak-to-peak amplitude of the current on the penetrator, and I_e is the peak-to-peak amplitude of the current on the equipment lead.

Measured coupling-loss factors are greatly affected by bonding to the central office ground system and proximity of equipment leads to the penetrators. Penetrators that are well bonded to the building ground, including waveguides, coaxial cable sheaths, some aerial cable sheaths, water pipes, and sewer pipes, exhibit relatively large coupling-loss factors; unbonded or singly-bonded penetrators exhibit relatively small coupling-loss factors. An example of a singly-bonded penetrator is an unshielded telephone line with a surge arrestor for lightning protection. Unbonded penetrators include unbonded twisted pair cables and commercial radio antennas.

For simplification of the estimation procedure, the proximity of equipment leads and penetrators is separated into two cases: near zone and far zone. The equipment leads are considered to be in the near zone if the switching equipment is within 3 m of the penetrator. If there are more than 3 m of separation, it is considered to be in the far zone.

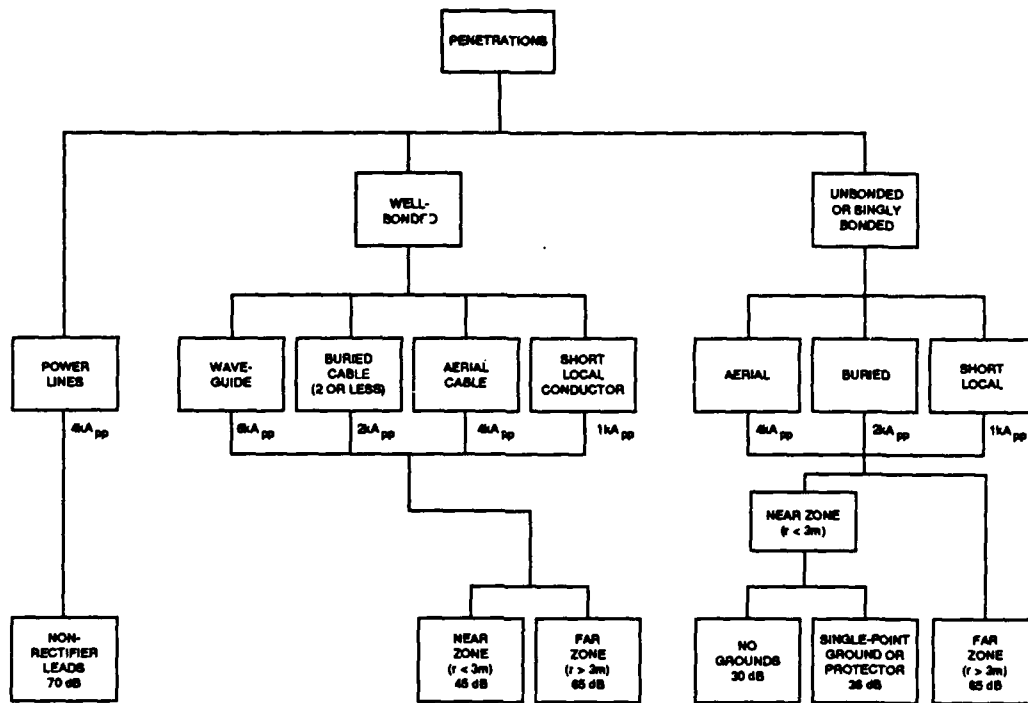
The peak-to-peak amplitudes of penetrator currents and the measured coupling-loss factors for equipment leads are summarized in Exhibit 3-5. The coupling-loss factor for power lines to all equipment other than switching system equipment leads is 70 dB. The coupling-loss factor between equipment leads for all well-bonded penetrators is 45 dB for the near zone, and 65 dB for the far zone. The coupling-loss factor between equipment leads and singly bonded penetrators is 36 dB for the near zone and 65 dB for the far

⁴⁴ "Effects of EMP on Bell System Long Haul Transmission Facilities," Bell Laboratory final report on the SAFEGUARD Communications Agency (SAFCA) EMP Program, April 1974.

⁴⁵ "Technical Directors Report on the APACHE Navcams Eastpac Test," DNA 4284FHAS7, December 1979.

⁴⁶ "Technical Test Directors Report on Delta, Utah Autovon 1 PREMT," HDL for the Defense Nuclear Agency, DNA 3808F, April 1975.

Exhibit 3-5
Summary of Penetrator Currents and Coupling-Loss Factors



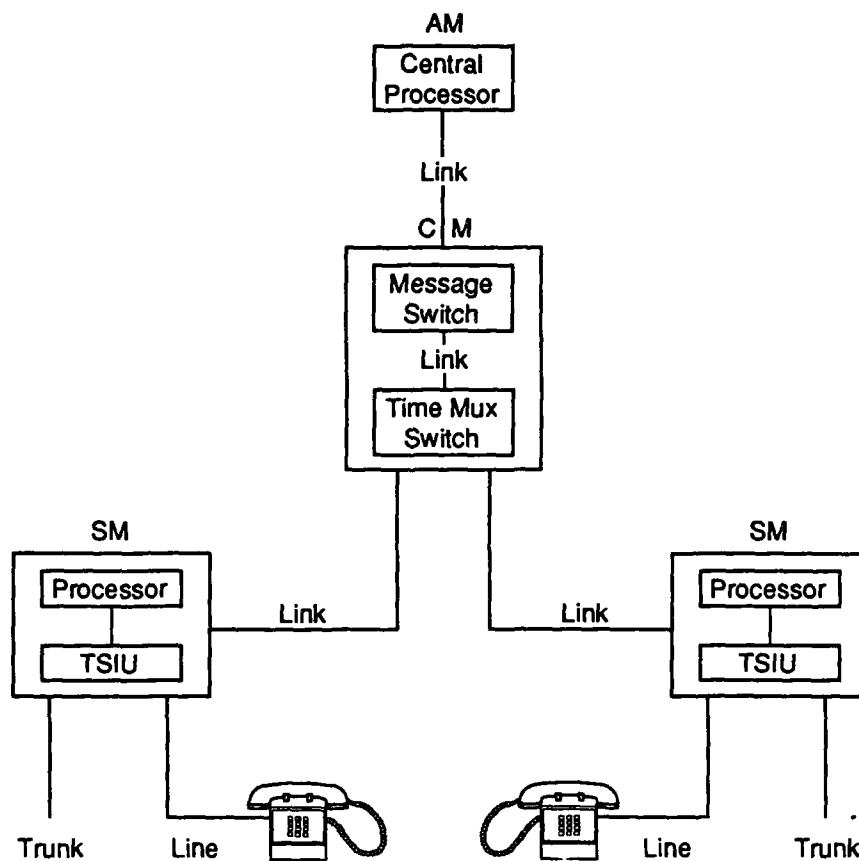
zone. The coupling-loss factor between equipment leads and unbonded penetrators is 30 dB in the near zone and 65 dB in the far zone.

The estimated peak-to-peak amplitude of the transient current on the switching system equipment leads is the sum of all of the contributing effects described above. For example, consider a switching system located in a concrete block central office. If the lead of interest is connected to T1 carrier, the direct contribution from the external cable is 15 A (from Exhibit 3-3). The current from direct illumination is 20 A (from Exhibit 3-4). If the system is in the near zone of the well bonded T1 carrier, the current contribution from the sheath current of the T1 is 22 A (from Exhibit 3-5, 4 kA decreased by 45 dB). The contribution from a waveguide (far zone) is 3 A (from Exhibit 3-5, 6 kA decreased by 65 dB). The current from the power lines is 1 A (from Exhibit 3-5, 4 kA decreased by 70 dB). Finally, the current induced by the water line that enters the building (far zone) is 0.6 A (from Exhibit 3-5, 1 kA decreased by 65 dB). The estimated total transient on the signal leads is the sum of each of these components, or 62 A, peak-to-peak.

3.2 5ESS SWITCHING SYSTEM⁴⁷

The AT&T 5ESS switch is a time-division, digital switching system, consisting of a complex combination of hardware and software. A 5ESS switch has three major hardware components: the Administrative Module (AM), the Communications Module (CM), and the Switching Module (SM). A block diagram of a 5ESS switch is shown in Exhibit 3-6; the exact configuration is customized to meet the requirements of each office.

Exhibit 3-6
Functional Diagram of the 5ESS Switching System



⁴⁷ Significant portions of this section are drawn from OMNCS TIB 86-3 entitled "Nuclear Weapons Effects Studies for the 5ESS Switch," September 1986, a study funded by the OMNCS and administered by AT&T under Contract DCA 100-85-C-0094.

At the heart of the AM is the central processor, an AT&T 3B20D fully-duplexed computer; this CPU is equivalent in complexity to the Vax 11/780. The central processor handles allocation of resources, overall maintenance, and interface with operation support systems. The two major components in the CM are the Message Switch (MSG) and the Time Multiplexed Switch (TMS). The MSG directs the routing of control, maintenance, and administrative messages between the AM and the SMs. The TMS performs time-multiplexed, space-division switching of digitized voice signals, internal system messages, and synchronization pulses.

The SMs are microprocessor-based units that provide the majority of normal call-processing functions. They serve as the terminations of all transmission facilities entering the switch, including both lines and trunks. Such terminations include all required equalization, amplification, and digital-to-analog and analog-to-digital conversions. Each SM also contains its own Time Slot Interchange Unit (TSIU) that performs time division switching for all connections required between two channels within the module. Connections involving two SMs use the TSIUs of both of the SMs and the TMS to form a time-space-time (TST) network.

The 5ESS system supports the use of Remote Switching Modules (RSMs) similar in design to 5ESS interface modules. The main difference is that RSMs may be located up to 100 miles from the main (host) 5ESS system, usually connected by T1 lines. The RSM terminates up to 4,000 customer lines and performs all switching functions between lines that are terminated by the same module. All other connections are passed through the TMS of the host system.

Stored programs run by the distributed microprocessors in the AM, CM, and SMs control the 5ESS switch. The distributed memories in a switch store both office-specific data and program software ("generics"), which is common to a whole class of switches. 5ESS switch software controls the operating system, call processing, and system administration and maintenance.

Fiber optic cables are used for all communication between the control processor, the MSG, the TMS, and all of the SMs within the central processor. The format of the lines is a serial PCM digital signal transmitted at 32.768 Mbits/s. This format contains 256 time slots per optical fiber. Because fiber optic cables do not directly couple to electric fields, the signals internal to the switch itself are relatively isolated from HEMP interference.

3.2.1 System Response to Direct Illumination

The 5ESS switch does not require any special electromagnetic shielding techniques in the central office; therefore, the incident electric field is as described in section 3.1.1. The EMP field tests of the 5ESS switch were conducted at the AFWL test facility in Albuquerque, New Mexico. The model office was tested under two EMP simulators. At the first facility, known as the

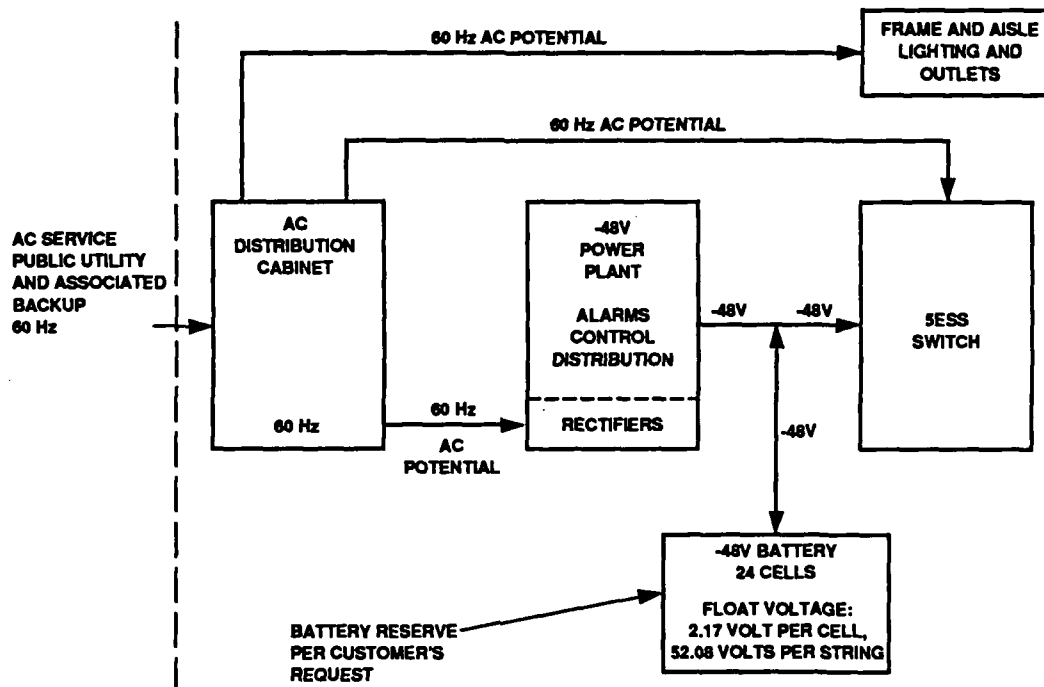
ALECS facility, the equipment was exposed to planar, vertically polarized fields of between 5 kV/m and 80 kV/m. At the second facility, known as the Horizontally Polarized Dipole (HPD), the switch was exposed to spherical, horizontally polarized fields of 35 kV/m. The fields produced by ALECS exceeded the 15 kV/m vertically-polarized component of the threat specified for this assessment. The fields produced at the HPD did not meet the 50 kV/m horizontally-polarized component of the threat waveform, although the 35 kV/m field exceeded the field expected inside many buildings. A 50 kV/m pulse incident on a building offering only 3 dB of shielding would result in a 35 kV/m pulse inside the building. The results of the HPD tests are consistent with the results of the ALECS tests, verifying that the results for the vertically polarized ALECS fields held for horizontal polarizations as well.

At all levels of testing, some form of system upset occurred. The faults and upsets that occurred are separated into three categories: "hardware failures," which result in physical damage requiring replacement of hardware; "manually recoverable hardware upsets," which require human intervention to restore switch functionality; and "recoverable logic upsets," which result in temporary switch disruption, with the switch returning itself to full operation without human intervention. The main focus of this test was to determine whether exposure to simulated HEMP would result in a loss of service; temporary, automatically recoverable upsets (requiring no human intervention) were of lesser concern.

3.2.1.1 Hardware Failures. The 48 V power system for the 5ESS system (shown in Exhibit 3-7) is consistent with the discussion of power systems in section 3.1.3. The commercial AC power is rectified by three 200 A Lineage 2000 rectifiers (model J87439A) arranged in parallel with the 48 V battery set and a battery plant controller. Whenever a loss of AC power occurs, the controller transfers the electrical load from the rectifiers to the battery set. Each rectifier alone was capable of fully powering the switch, although the three rectifiers are generally placed on-line together to share the load, providing the system with a redundant power supply capability.

Several pulses above 50 kV/m caused the failure of several power diodes in the rectifiers, leaving the affected rectifier(s) inoperative. One test pulse caused the AC circuit-breakers of all three rectifiers to trip, resulting in a switch to battery power. Every DC-to-DC power converter in the 5ESS switch also shut down, causing the operation of the entire switch to stop. The diode failure was probably in response to voltage transients which exceeded the 200 V Peak Reverse Voltage (PRV) rating of the diodes. Diodes rated at 800 V PRV were installed, and the modified rectifiers were exposed to pulses at ALECS up to 80 kV/m vertical without a single diode failure or power shutdown, although they were never exposed to the horizontally-polarized fields of the HPD. The massive power-down shows that the unmodified

Exhibit 3-7
Power System of the 5ESS Switching System



rectifiers cannot be considered survivable to the effects of HEMP. Even a switch to battery power is unacceptable, because the batteries will only provide power for about eight hours. Backup generators can provide power after the batteries fail, but the generators will run out of fuel in several days. If the failed rectifiers are not repaired before the generators run out of fuel, operation of the entire 5ESS switch will cease.

AT&T plans to use the 800 V PRV diodes in all Lineage 2000 rectifiers produced as of September, 1986. The modified model J87439A rectifiers survived the effects of the vertically polarized fields of ALECS, but because they were never subjected to the horizontally polarized fields of the HPD, their survivability to HEMP is not fully determined. Model J87439A rectifiers are currently being replaced with a new model. Other models rated at 100 A and 400 A will soon be introduced, as will a line of lower-capacity rectifiers. Because these new rectifiers vary considerably in design from the model used in this study, further testing is needed to assess their vulnerability to HEMP; however, these new rectifiers can be tested without testing an entire switch.

Induced transients also caused damage to battery plant controller (Microprocessor and Conventional Controller Systems) components and

shutdown of a single rectifier. The occurrence of the particular problems were highly variable, although it was suspected that the shutdowns were caused by a rectifier problem. No solution was suggested for these problems, so it is likely that they will occur again during exposure to actual EMP. While these problems did not cause the switch to stop operating or to lose its call processing capability, further testing is needed to determine their cause and to verify that the battery plant controller is survivable to EMP.

The Master Control Center (MCC) terminal or printer communicates with the 5ESS switch AM through an RS-232C copper-braid shielded cable. Current injection testing of the TTY interface showed that transients as small as 175 V and 4 A were sufficient to damage the RS-232C receive circuit. Therefore during testing, the cables were replaced with RS-232C optical fiber links, which do not conduct large transients. On the final day of testing, the optical fiber links were replaced with the shielded cables, and permanent hardware failure occurred after just three pulses, verifying the predicted vulnerability. The susceptibility of the MCC and MTTYC interface to HEMP-induced damage when using hard-wire cable connections makes it essential to provide protection if equipment is to survive. While optical links and modems are available as a well-tested option, they are not normally used in most 5ESS switches because they are more expensive than conventional copper-braid shielded cable.

3.2.1.2 Manually Recoverable Hardware Upsets. Unless an EMP-hardened link connects the switch to a central office, certain types of faults will require manual intervention to restore full service. This is a very serious problem, because manual intervention with switches in remote or isolated locations cannot be guaranteed.

Pulses as low as 5 kV/m vertical caused several units within the AM to hang-up due to logic upsets within the Power Control and Display Circuits. The problem was solved by reducing the value of a pull-up resistor. Slightly higher field levels caused power converter and interface circuits in the switching module to deactivate. The power converter problem was solved by replacing power control circuitry with a newer, less noise-sensitive version. The interface circuit problem was solved by placing a single filter capacitor across a latch input. A similar correction prevented shutdown of the power supplies to the AM moving head disks (MHDs). Additional testing at fields as high as 80 kV/m vertical and 35 kV/m horizontal verified that all the modifications successfully eliminated the faults (only one upset was observed during the 2550 tests of the modified circuitry). AT&T has adopted these circuit modifications for use in production models of the 5ESS switch; the modifications appear to solve the sensitivity problems, but assuring survivability of a particular system requires ensuring that these circuit modifications are used in that system.

3.2.1.3 Recoverable Logic Upsets. The operation of many different electronic circuits in the AM, CM, and SM were disrupted by exposure to E-fields of all

levels, causing stable calls to be dropped and the call processing capability of the switch to be reduced. The mean fraction of stable calls dropped after a single exposure (as shown in Exhibit 3-8a) is between 16 and 46 percent. The vertical bars represent a one-standard-deviation variation in the fraction of stable calls dropped. Following several repeated exposures, a mean fraction of 93 percent of the stable calls were dropped, while at field levels over 45 kV/m, virtually no calls could be completed for several minutes.

Immediately following exposure to simulated HEMP fields, the switch began automatic fault recovery to isolate the fault and to restore the call processing ability of the switch. As shown in Exhibit 3-8b, the efficiency of the switch in completing calls gradually increased as the time from exposure increased, but the switch never achieved full recovery, with the efficiency lowest following repeated exposures. With the efficiency less than 100 percent, service was not restored to some loops or trunks, and the likelihood of call blocking increased.

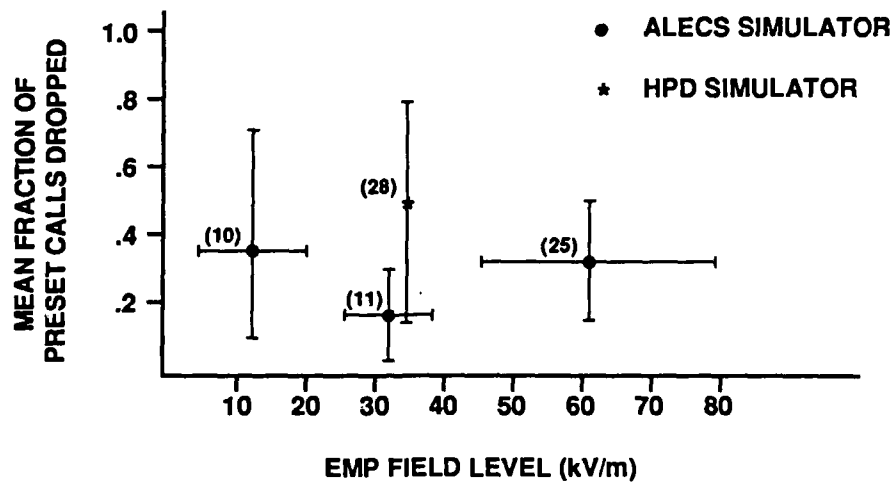
With assistance from an operator at the MCC, the call completion efficiency reached greater than 99 percent after about 30 minutes, provided an optical link connected the MCC and 5ESS switch. Because many central offices with 5ESS switches are not staffed, prompt restoration of service could not be guaranteed unless staffed, remote Switching Control Centers (SCCs) exist, with survivable links to the CO.

3.2.2 Interpretation of Test Results

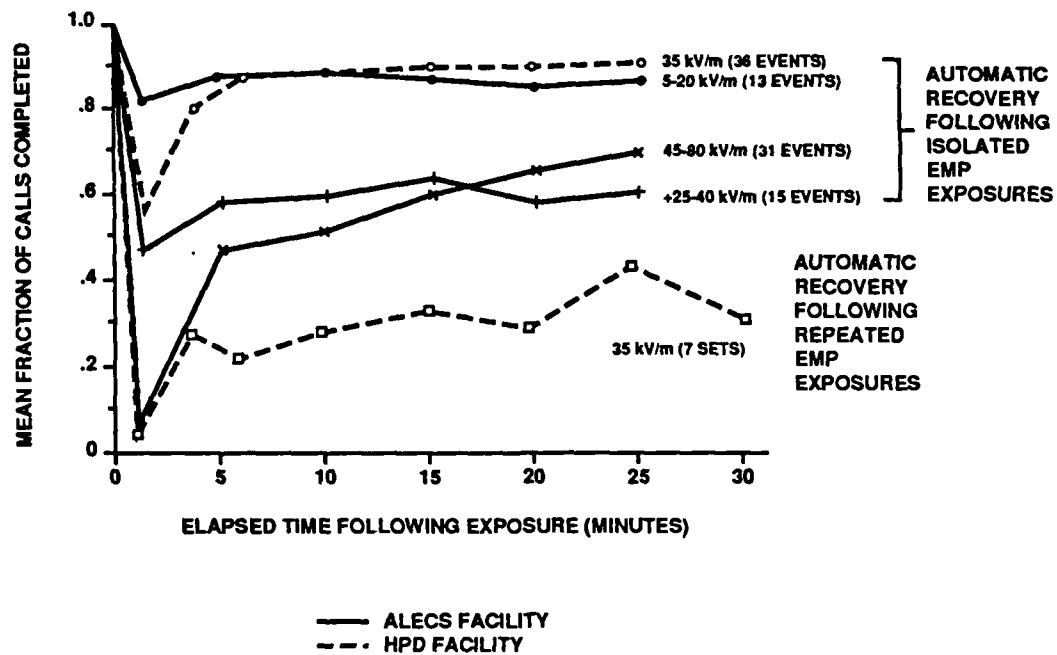
Following exposure to simulated-HEMP fields, data were collected every five minutes over a half hour period to monitor the automatic recovery of call processing of the 5ESS switch. Immediately following the test pulse, few, if any, calls were processed. Automatic fault recovery improved the call processing capability of the switch over time, but after 20 to 30 minutes, automatic fault recovery stabilized (reached a steady-state). Using the call-completion data, the call processing capability of the 5ESS switch is estimated as the percentage of calls that were completed during all the tests at the end of the half hour test period. Testing was conducted using the HPD and ALECS simulators.

Exhibit 3-9 summarizes the 5ESS switch steady-state test results that should be used by the OMNCS as inputs to the BSM for network connectivity assessments. Each data point in the exhibit represents the total fraction of pulses at a given field level for which the switch returned to the given percentage of active call processing. For example, following 2 out of the 13 test pulses at 10-30 kV/m, the switch reached a steady state active call processing of 85 percent. This data format more accurately reflects the response of the switch than data formats from other test programs, because the 5ESS switch never returned to full operating capability following exposure to simulated HEMP fields. Testing under the ALECS simulator was

Exhibit 3-8
Transient-Induced Effects on Telecommunications Network



(a). Mean Fraction of Preset Calls Dropped Due to Induced Transients



(b). Automatic Recovery of Call Processing Following Simulator Exposure

Exhibit 3-9
5ESS Switch Physical Test Results

Stress Level	Total Percentage Recovery of Active Call Processing								
(kV/m)	15	25	35	45	55	65	75	85	95
10-30		$\frac{1}{13}$					$\frac{1}{13}$	$\frac{2}{13}$	$\frac{9}{13}$
30-50	$\frac{1}{47}$	$\frac{2}{47}$	$\frac{2}{47}$	$\frac{2}{47}$	$\frac{1}{47}$	$\frac{1}{47}$	$\frac{1}{47}$	$\frac{4}{47}$	$\frac{33}{47}$
50-70		$\frac{3}{27}$	$\frac{2}{27}$	$\frac{3}{27}$	$\frac{3}{27}$		$\frac{2}{27}$	$\frac{4}{27}$	$\frac{10}{27}$

conducted at three field levels: low (5-20 kV/m, 13 events), medium (25-40 kV/m, 15 events), and high (45-80 kV/m, 31 events). Testing under the HPD simulator was conducted at 35 kV/m (36 events). To be consistent with the data format from previous test programs, all data were grouped into three bins: low (10-30 kV/m), medium (30-50 kV/m), and high (50-70 kV/m). It is assumed that the low-level data (5-20 kV/m) for ALECS could be used in the low-level bin for the BSM (10-30 kV/m). The same assumption holds true for the medium and high-level test data from ALECS. Although the E-fields produced by the HPD are polarized differently than the ALECS fields, the data from the HPD was also included in the medium-level BSM bin. Data from most (but not all) test events were recorded, so the number of events presented in Exhibit 3-9 differs slightly from that presented in Exhibit 3-8.

Although the switch did not have a single physical failure at any of the simulated HEMP exposures, careful interpretation is required in using these results. It must be stressed that the results presented in Exhibit 3-9 are for a 5ESS switch incorporating the hardware modifications outlined above. All these modifications, with the exception of the optical link to the MCC, will be incorporated in new 5ESS switches. As mentioned above, some form of upset occurred at all levels of testing: a significant fraction of calls were dropped, call processing capability was reduced during fault recovery, and automatic restoration of all switch resources was not fully completed. Despite these upsets, the hardware failures experienced did not affect call processing capability. The optical link to the MCC will not be a standard offering on future 5ESS switches. Damage to the TTY interface caused by current transients on the MCC cables would not affect call processing ability of the switch, but personnel at remote sites would not be able to control and monitor the switch after a HEMP.

The primary reason for the immediate reduced call processing capability is reinitialization of the AM. Through automatic fault recovery, the switch regains some call processing capability, but this capability never reaches 100 percent without manual intervention. When the switch reaches

a constant call processing level, the reduced capability is believed to be due to failures in the SMs.

The failures in the SMs can only be fixed by a reinitialization of the switch. Such a manual reinitialization is not guaranteed in an NSEP environment. In the SM, there are believed to be two types of failures: those in the module processor and those in the periphery equipment (line and trunk units). Processor failures result in an overall reduced call processing capability of the switch; however, it is possible that each end user may obtain a connection through the switch. Periphery line and trunk failures imply that certain users will be completely unable to access the switch. Unfortunately, the data taken in the testing program does not support differentiation of periphery failures from processor failures.

3.3 4ESS SWITCHING SYSTEM

The AT&T 4ESS is a time-division, digital switching system designed for use in toll applications. As discussed in section 1.2, the 4ESS has not yet been tested, but a theoretical engineering analysis of its survivability against HEMP effects is included in this report because of the prevalence of the 4ESS in the PSN. The importance of the 4ESS within the PSN was further illustrated in a previous network level sensitivity study.⁴⁸ Similar to the 5ESS, the switching network of the 4ESS switch is comprised of Time Slot Interchange (TSI) and Time Multiplexed Switch (TMS) frames interconnected to form a time-space-space-space-time (TSSSST) network.

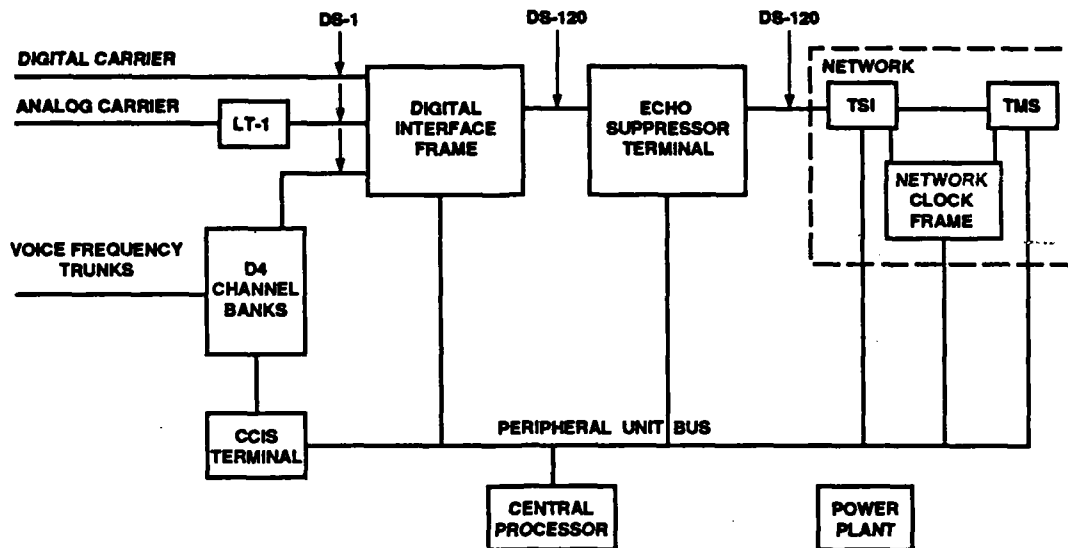
The 4ESS switch (shown in Exhibit 3-10) contains several frames that terminate trunks and convert signals to suitable format for input to the TSI. The Digital Interface Frame (DIF) terminates up to 160 DS-1 format signals and multiplexes them onto 32 lines. DS-1 format signals include T1 carrier and the output of other frames used for trunk terminations. In contrast to the electromechanical switches, the 4ESS system is designed to use the digital carrier signals directly, without conversion to analog signals.

The LT-1 connector terminates two 12-channel analog group signals and transmultiplexes them onto one 24-channel DS-1 signal. This connector is used to terminate analog carrier systems in the 60 to 108 kHz frequency band. The output of the LT-1 connector is suitable for connection to the DIF.

Metallic trunks, international format analog carrier trunks, and other miscellaneous voice frequency circuits are terminated in a D4 channel bank. A D4 channel bank terminates the lines, performs analog to digital conversion, and multiplexes the digital signals onto a DS-1 format line, which is connected directly to the DIF.

⁴⁸ Booz•Allen & Hamilton Inc., "Network Level EMP Effects Sensitivity Study on Selected Telecommunications Equipment," National Communications System, March 1987.

Exhibit 3-10
Functional Diagram of the 4ESS Switching System



The entire 4ESS system is controlled by the 1A processor. The processor monitors and controls the operation of the other subsystems, establishes and maintains trunk interconnections, and performs self-checking to locate faulty circuits. As a stored program control system, the 4ESS system maintains all of the instructions for the processor in semipermanent memory to maximize flexibility and to facilitate rapid implementation of new instruction sets.

All of the frames communicate with the processor via the peripheral unit bus (PUB). The processor uses the PUB to send commands to the other subsystems, to receive responses from them, and to collect maintenance information. The DIF and D4 channel bank both use the PUB to transmit signaling information that is extracted from the trunk lines.

3.3.1 System Response to Direct Illumination

The 4ESS system does not require any special electromagnetic shielding techniques in the central office; therefore, the incident electric field is as described in section 3.1.1. The 4ESS switch is designed to the requirements of the Local Switching System General Requirements (LSSGR) to operate without degradation while subjected to an electric field with a peak amplitude of 10 V/m for any frequency between 10 kHz and 1 GHz. This electric field specification is consistent with the Bell System Practice (BSP) dealing with radio frequency interference of switching systems.⁴⁹ This electric field specification is the guaranteed minimum operational upset threshold; for

⁴⁹ AT&T, "RFI Shielding," Bell System Practices 760-220-100, 1978.

this assessment, the damage threshold is of interest. As stated previously, a margin of 30 to 40 dB can be expected between the upset threshold specification and the damage threshold. Therefore, the damage threshold of the 4ESS can be estimated to be at least 300 V/m.

The 4ESS system has not been subjected to EMP testing to determine actual susceptibility to electric fields. The equipment is contained in open equipment racks, which offer minimal electromagnetic shielding for the equipment. Several internal conductors may be long enough to couple sufficient energy to cause equipment damage. The signal lines between the DIF and the TSI, and those between the TSI and the TMS are coaxial cables; the shielding of these lines should prevent appreciable transients from being induced on the center conductor and causing damage. The PUB consists of unshielded twisted pair cables that must be connected to each frame within the switch, possibly reaching a length in excess of 100 m. The PUB is never in the near field of any of the penetrators described in section 3.1.4; however, the current due to the diffused electric field may be as high as 20 A, peak-to-peak. The PUB is connected to line driver/receiver circuit pacs, which are designed to withstand transient overvoltages associated with transmission lines. However, detailed analysis and/or testing is required to accurately assess the survivability of a 4ESS system subjected to HEMP fields.

3.3.2 System Response to Power Lead Transients

Power for the 4ESS subsystems is passed through the AC distribution equipment, transfer switch, and rectifier described in section 3.1.2; the output of the rectifier charges a 140-V battery plant that supplies power to the 4ESS system. The output of the battery plant is connected to bulk DC-to-DC converters in the switch. The 24- or 48-V output of these converters is distributed to in-frame DC-to-DC converters located in each rack of 4ESS equipment. The output voltage of the in-frame converters ranges from -28 to +28 V, depending on the requirements of the equipment in the racks.

As described in section 3.1.2, little of the 1 kA current transient on commercial power lines is expected to pass through the rectifier to the battery plant. Any transient passing through the battery plant is then attenuated by the large capacitances of the two DC-to-DC converters before entering any circuit pacs in the equipment. For these reasons, transients on the power leads of the 4ESS system are not likely to be large enough to cause permanent damage; however, HEMP testing of the power system is required to verify this conclusion.

3.3.3 System Response to Signal Lead Transients

Estimation of the signal lead transients for switching systems is discussed in section 3.1.4. The 4ESS system is typically placed in the center of the central office, as far away from any electromagnetic penetrators as practical. Therefore, the equipment attached to signal leads is assumed to be in the far zone from all penetrators. Although the actual estimation depends

on which penetrators are present in the central office, reasonable estimates of the transients on signal lines are 40 A for concrete block construction and 25 A for reinforced concrete construction.

The vulnerability of the D4 channel bank is addressed in section 2.1.4. Based on field testing, both the digital inputs (receive units) and the voice frequency inputs were found to be vulnerable to damage as a result of HEMP transients. The DIF is similar in technology, function, and application to the D4, and may be presumed similar in survivability. The LT-1 connector inputs are sufficiently different from any D4 inputs that no conclusions can be drawn about their survivability. Detailed analysis and EMP testing are required to conclusively assess the survivability of these interfaces for the 4ESS switch.

3.3.4 System Response to Ground System Transients

Transients in the central office ground system are described in section 3.1.3. As with the 5ESS system, the 4ESS switch utilizes a single point ground, which provides isolation from transients in the ground system. Large current transients in the ground system may cause differences in potential between the ground connection of the switch and that of the peripheral equipment. Such potentials may cause large voltage differences between the leads on the peripheral equipment and those on the switch; the resultant current may damage the equipment attached to the leads. Much of the equipment required to convert signals to the internal format of the 4ESS switch is included in the switching system itself; this equipment shares the single point ground with the rest of the system. As more peripheral equipment is included within the switch itself, the single point ground system is increasingly effective at mitigating the effects of transients in the ground system.

3.3.5 Interpolated Results

Exhibit 3-11 presents the test data that should be used by the OMNCS as inputs to the BSM to characterize the performance of the 4ESS switch for network connectivity assessments. Because the 4ESS has not yet been tested, data from the D4 channel bank test program are used instead. The D4 channel bank is used in many 4ESS switches and the DIF is similar to the digital portion of the D4. Therefore, it is assumed that of all the systems for which EMP test data are available, the D4 channel bank is technologically most similar to the 4ESS.

Exhibit 3-11
Interpolated Test Results for Predicting 4ESS Performance

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	1	1	1	1
30-50	0	0	1	1
50-70	0	0	1	1

3.4 DMS100 TELECOMMUNICATIONS SWITCH⁵⁰

The DMS100 telecommunications switch, developed by Northern Telecommunications Inc. (NTI), is a switching system that contains a large line/trunk capacity, similar to a toll or central office switch. A DMS100 switch has four major components: the Central Control Complex (CCC), the Maintenance and Administration, the Network, and the Peripheral Modules (PM). A block diagram illustrating the interconnections of some equipment of each major component is shown in Exhibit 3-12.

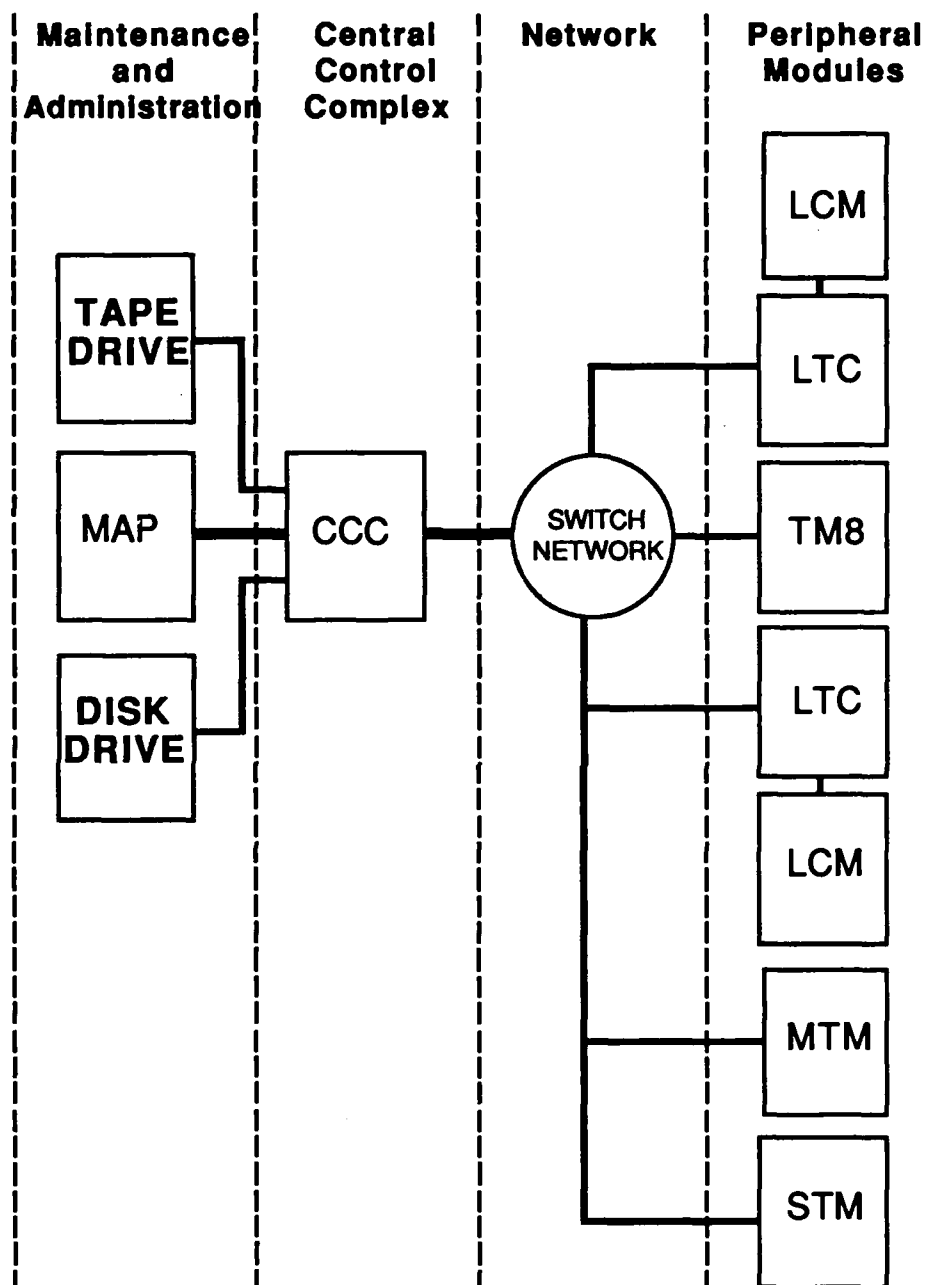
The CCC is a duplicated group of four modules: the Central Message Controller (CMC), the Central Processor Unit (CPU), the Program Store (PS) and the Data Store (DS). The CMC, located in a Message and Device Controller (MDC) shelf, controls the message flow between the network, maintenance, and administration areas, and the CPU. The CPU, located in the Central Processor and Memory (CPM) shelf, controls all operations of the switch. The PS, located in the CPM shelf, is associated exclusively with one CPU, and contains program instructions required by that CPU for call processing, maintenance, and administrative tasks. The DS, located on the DS shelf, is also associated with one CPU and contains transient information on a per-call basis, as well as customer data and office parameters. These four modules act together to evaluate incoming messages, format the proper response, and issue instructions to subsidiary units.

Maintenance and Administration is made up of the I/O Controller (IOC) and the I/O terminals, such as visual display unit (VDU), printer, magnetic tape drive (MTD), and disk drive unit (DDU). The Network's main function is the electronic switching of speech parts between users. This is accomplished through a four-stage time-switching technique employed by the Network. The Network Module is made up of two shelves: the Network Interface Shelf and the Network Crosspoint Shelf. The Network Interface Shelf contains the cards that allow the Network to interface externally with the CCC and the Peripheral Modules. The Network Crosspoint Shelf contains the cards that perform the electronic switching.

The PM is the component that allows the DMS100 system to interface with the outside world, or external lines. Three major types of Peripheral Modules are used: the Trunk Module (TM), the Line Concentrating Module (LCM), and the Line Trunk Controller (LTC). These Modules and the simulated traffic distribution implemented in the DMS-100 test are shown in Exhibit 3-13. The TM accepts 30 analog trunk circuits and performs

⁵⁰ Significant portions of this section are drawn from "DMS100 HEMP Test Final Report, Volume II," a study funded by the OMNCS with test support by the Army's Harry Diamond Laboratories, in preparation.

Exhibit 3-12
Major DMS100 Component Interconnections

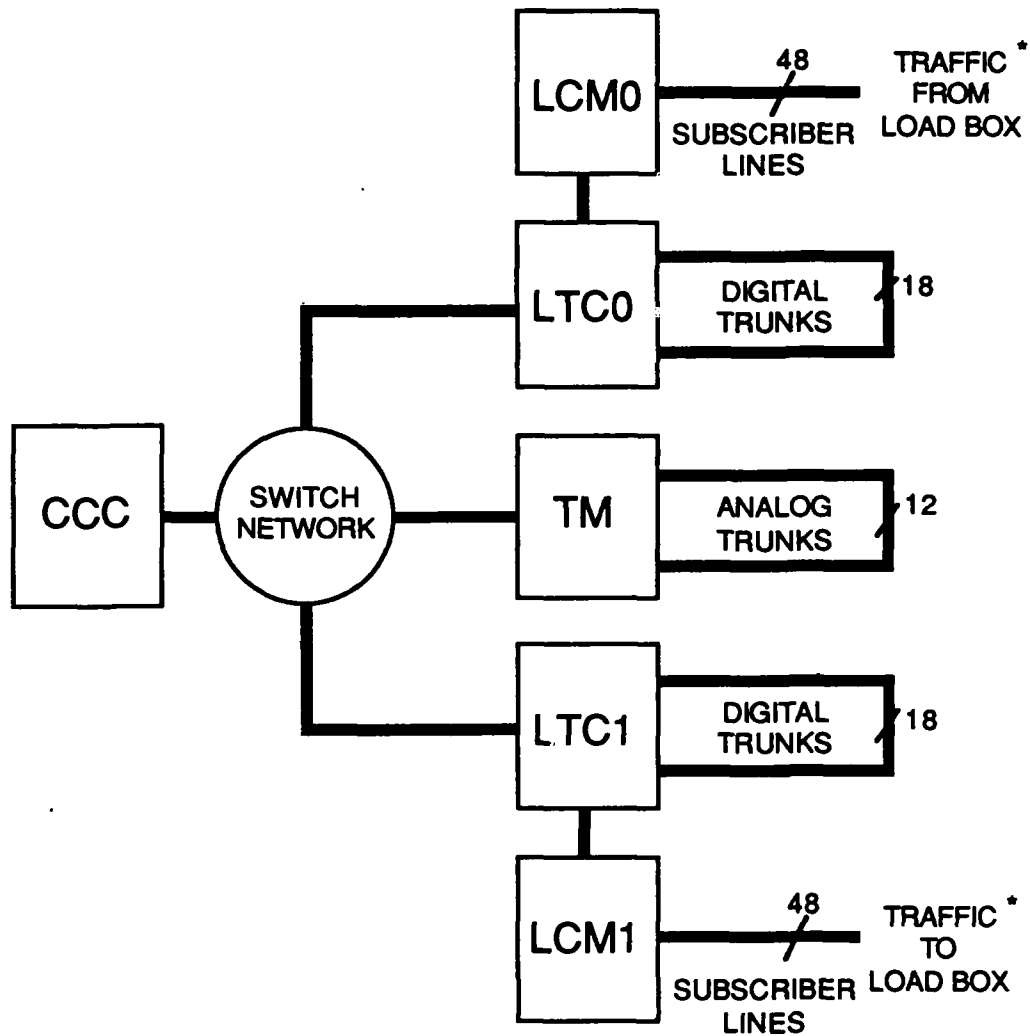


LEGEND:

TM8 - Trunk Module, 8-wire
 MTM - Maintenance Trunk Module
 STM - Service Trunk Module

LCM - Line Concentrating Module
 LTC - Line Trunk Controller
 MAP - Maintenance & Administration Position

Exhibit 3-13
Traffic Link Distribution for the EMP test



LEGENDS:

LCM - Line Concentrating Module (Subscriber Line Interface)

LTC - Line Trunk Controller (Digital Trunk Interface)

TM - Trunk Module (Analog Trunk Interface)

* Only 36 out of the 48 links were operational in Ottawa.

32-channel, time-division Pulse Code Modulation (PCM) of speech and control signals for conversion to DS-30 links. The LCM provides an interface to telephones, attendant consoles, low-speed and high-speed data units, RS-422A compatible devices, and personal computers. The LTC provides interfaces to T1 digital trunks. All external line signals are processed by the PMs and converted to DS-30 signals, which are then processed (switched, routed) by the Network Module.

3.4.1 Test Performance

Prior to free-field testing of the DMS100 switch, TEM cell radiation and low-level current injection experiments were conducted at the Bell Northern Research (BNR) facility in Ottawa, Canada. A PM frame, the Remote Line Concentrating Module (RLCM), was selected and tested in the experiment, because most of its components resembled those of other PMs. The RLCM survived repeated injections of currents of about 110 A into the power and signal interfaces without any hardware failures. The TEM cell experiment showed a field threshold level of 35 kV/m for RLCM upsets. Hardware failure did not occur, even at field levels up to 110 kV/m. However, because the injected currents never reached the expected threat level (4 kA) and the RLCM is not representative of the switch as a whole, no conclusions can be drawn regarding the survivability of the switch based on this testing.

Free-field testing of the DMS100 switch was conducted at the National Research Council (NRC) facility in Ottawa and the HDL facility in Woodbridge, VA. The unit was first tested at the Ottawa facility, where a portable 300 kV pulser was used to generate simulated-HEMP fields of 2.5 kV/m at the switch. The switch was then tested at the HDL facility, where the REPS simulator was first used to generate fields of 10 kV/m, and the AESOP simulator was then used to generate fields between 33 and 69 kV/m at the switch.

The shielding configuration of the switch was varied at each field level. The configuration defines the degree of EMI shielding and protection that was installed during the free-field testing. The shielded switch, which is offered by NTI as an option, had EMI frame panels on front and back and filters on all power, subscriber, and trunk lines. The unshielded switch had all front and rear EMI frame panels removed and all subscriber and trunk line filters bypassed. Four other shielding configurations, which were subject to limited testing, indicated that the filters had little impact on the upsets. Because most DMS100 switches currently in operation are not shielded, only the test results of the switch in *unshielded* configurations are included in this assessment.

Prior to every pulse, the switch was processing all calls. A load box simulated call traffic through the switch during testing, and was capable of establishing 48 concurrent telephone connections. After each pulse or series of pulses, the operation of the switch was evaluated by two devices: the load box and the Maintenance and Administration Position (MAP). The load box

measured each line connection for successful or failed call attempts. Diagnostic information was generated for failed attempts. The MAP, consisting of the VDU and line printers, provides diagnostic information to the MAP operator, who can perform service routines for repairing and maintaining the switch.

3.4.2 Test Results

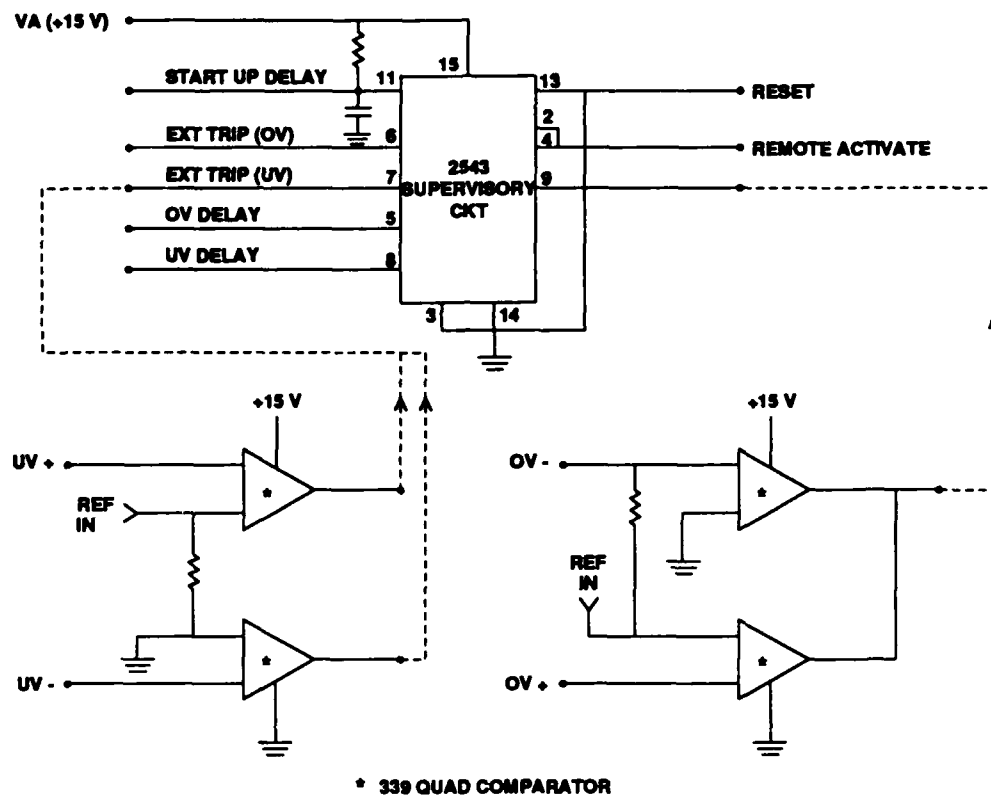
For the unshielded switch, some form of system upset occurred at all levels of testing. Some upsets resulted in temporary switch disruption, while other upsets required manual intervention to return to full operation. The shielded switch proved robust at all levels of testing. The main focus of the test was to determine vulnerable areas within the system that showed damage or upset when exposed to simulated HEMP environments.

3.4.2.1 Recoverable Logic Upsets. The switch was first exposed to 1016 simulator pulses at the Ottawa facility. The call processing capability of the switch was unaffected following all but two of the pulses. However, two of the test pulses caused upset (where call processing capability of the switch was temporarily lost), but switch recovery was automatic and complete. To remain consistent with the format used to report data for input to the BSM for network connectivity assessments, the data from the Ottawa test are not included in this assessment because of the low field levels (2.5 kV/m).

3.4.2.2 Manually Recoverable System Upsets. After testing in Ottawa, the switch was transported to HDL. While shielded, the switch was pulsed 36 times under REPS and 46 times under AESOP (up to 69 kV/m), with only one call processing upset observed (at 60 kV/m). However, when the switch was tested in an unshielded configuration, numerous operational upsets occurred. During testing under REPS, the upsets were traced to transient effects on the LTC's power converter units, as shown in Exhibit 3-14. During testing, a capacitor was installed at the interface pins of the supervisory chip (2543). This modification did not fully solve the problem, but it decreased the frequency of the upsets to about 50 percent. Call processing capability returned to full capacity following each call processing upset though manual power reset and data downloading from disk to the LTC.

Prior to testing of the unshielded switch under the AESOP simulator, the sensitive supervisory chip was replaced by a less sensitive chip produced by another manufacturer to preclude manually resetting the switch after each test pulse. During testing at the 33 kV/m level, call processing continued to break down following each of the pulses. This problem was due to two effects: sensitivity of other supervisory circuit chips located in the LCM's power converter, and logic corruption in the PMs (e.g., LCM, LTC, & TM8). Call processing capability returned to full capacity through manual power reset and data downloading from disk. The affected chips were eventually replaced with less sensitive chips during testing at the 60 kV/m level at

Exhibit 3-14
Power Converter Monitor Module



AESOP. In addition, an "autoload" software pack was installed to provide automatic data downloading from disk. Four sets of multiple pulses (60 kV/m), ranging from 6 to 14 pulses per set, illuminated the modified switch, and call processing automatically recovered following each multiple set.

Exhibit 3-15 graphically depicts the recovery time of switch call-processing capability following exposure to single simulator pulses of 30-50 kV/m. Exhibit 3-16 presents switch recovery time following exposure to single pulses of 50-70 kV/m. These exhibits include data taken from all the AESOP pulses for which recovery time data exist, with the switch in an unshielded configuration with modified and unmodified hardware. When one of the two LCMs (LCM0 or LCM1) returned on-line following a test pulse, the switch was said to be operating at 50 percent capability. When both LCMs returned on-line, the switch was said to be operating at 100 percent capability. This definition is entirely a function of the test architecture as described in Exhibit 3-13.

Exhibit 3-15
Recovery Time Distribution for 30-50 kV/m

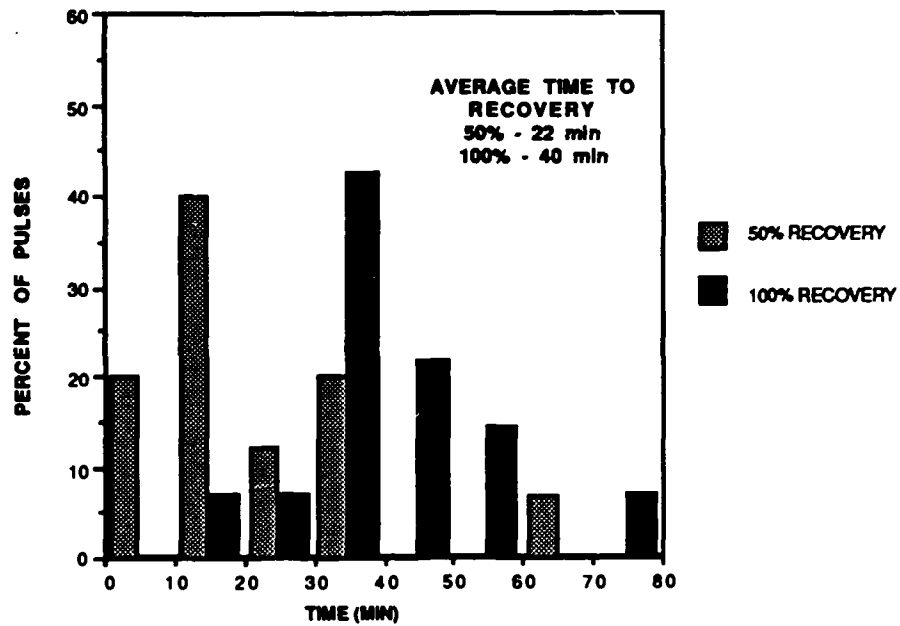
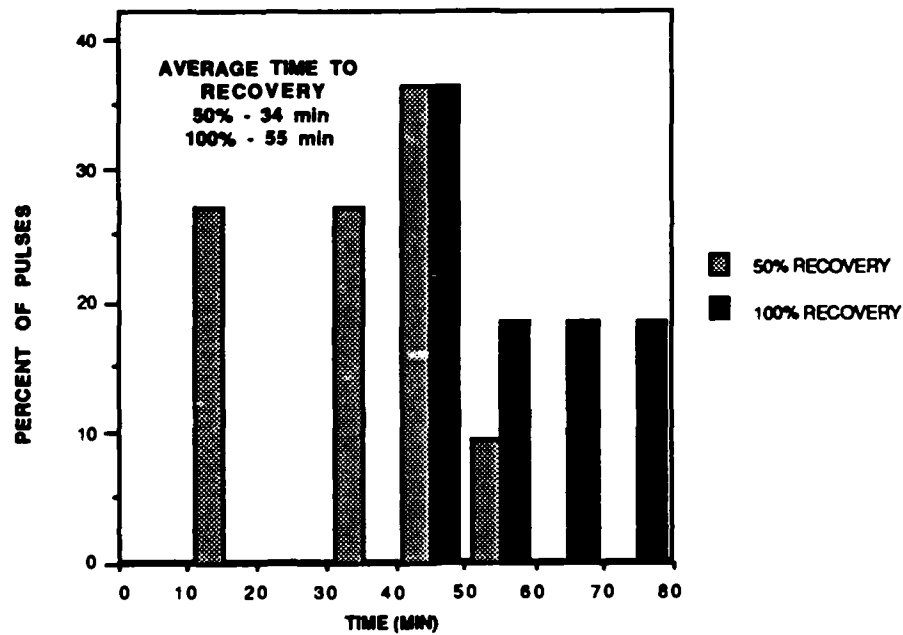


Exhibit 3-16
Recovery Time Distribution for 50-70 kV/m



3.4.2.3 Upsets and Failures Without Immediate System Effects. Other upsets, which did not affect call processing, were discovered in the rectifiers. There were 5 AC rectifiers used for the switch. The AC rectifiers converted the 120 VAC to 48 VDC power which was required to supply constant charge to the battery, which in turn supplied power to the switch. During all the AESOP field levels, the rectifiers were affected by the pulse illuminations. An overvoltage condition had been detected by the control circuitry of the rectifier causing the "reset" switch to turn off and disable the rectifier unit. Rectifier operation was regained by manually resetting the switch. At 33 kV/m, 2 rectifiers were affected. At 45 kV/m, 3 rectifiers were affected, while at 60 kV/m, 4 rectifiers were affected. The battery supply maintained power to the switch, thus switch operation was not affected. A ceramic capacitor (0.01 μ f) was eventually installed at an IC interface pin inside each rectifier to filter out the coupled current that caused the overvoltage condition. This modification cured the rectifier upset problem. However, three of five rectifiers must be on-line at any time to power the switch without battery assistance. Whenever a loss of AC power occurs, the batteries can supply power to the switch for only several hours. After the batteries completely discharge, the operation of the switch will cease.

Hardware failure occurred in the keyboard of the MAP video terminal. This failure had no direct impact on the call processing function of the test article, assuming that call processing was regained automatically. Two keyboard damages occurred at field levels greater than 60 kV/m. The keyboard was the DEC LK201AA model that had a 6-foot coiled cord which plugged into the video terminal through an RJ11C connector. Thus, the keyboard could easily be replaced with a spare keyboard in case of a hardware failure.

3.4.3 Interpretation of Test Results

During testing, manual intervention was frequently required to return the call processing capability of the switch to 100 per cent. To maintain scenario-independent results, the OMNCS requires the ability to perform network level assessments for scenarios where manual intervention is assumed, as well as for those that assume no manual intervention. Exhibit 3-17 presents the data that should be used by the OMNCS as input data for DMS100 switches in NCAM simulations. These data include only test pulses for the switch in an unshielded configuration (i.e., EMI panels removed and filters bypassed).

Without all the hardware and software modifications that NTI plans to include as part of all future switches, the DMS100 switch is survivable to HEMP effects but vulnerable to upset. Exhibit 3-17(a) includes all data to be used for NCAM statistical assessments where switch locations are assumed to be staffed and manual intervention is available. This exhibit presents all data recorded during testing of the unshielded switch and includes data from both single and multiple pulses.

With all the hardware and software modifications in place, the DMS100 switch automatically recovered to 100 percent call processing capability within 20 minutes. Exhibit 3-17(b) includes all data to be used for NCAM statistical assessments where switch locations are not assumed to be staffed and manual intervention is not available. This exhibit includes all data for the switch in the final (modified) configuration. The switch was only tested with multiple pulses under AESOP at 60 kV/m in this configuration. As a result of the modifications, call processing was unaffected or returned to 100 percent without manual intervention.

Exhibit 3-17
DMS100 Test Results

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	59	0	191	0
30-50	78	0	132	0
50-70	54	0	54	0

a. manual intervention available

Stress Level (kV/m)	Actual Data		BSM Data	
	Sample size	Failures	Sample size	Failures
10-30	0	0	33	0
30-50	0	0	33	0
50-70	33	0	33	0

b. no manual intervention required

3.5 SUMMARY

The 5ESS switch is survivable to HEMP effects, but subject to upset. 5ESS power systems produced before September, 1986, were shown to be susceptible to induced transients. Modified power system rectifiers were shown able to survive threat-level, vertically polarized fields, but because they were never subjected to threat-level horizontally polarized fields, their survivability remains undetermined. Power is supplied by batteries as a result of a complete shutdown of the rectifiers, but this is only a temporary solution to the problem; once battery power is lost, the 5ESS ceases to operate.

With the hardware modifications discussed in section 3.2 in place, the 5ESS switch suffered no permanent hardware damage. The switch remained operational following exposure to threat-level fields, but a significant fraction of calls were dropped and the call processing capability was reduced. Automatic recovery slowly restored call processing efficiency but never to 100 percent.

For upsets not caused by hardware failures, the switch can be restored to full operation in two ways: by an operator at the MCC, provided the switching office is staffed; or by an operator at the SCC, provided the SCC and its link to the CO are survivable. It must be emphasized, though, that many COs are not staffed, and projections call for even less staffing in the future. The links between remote SCCs and COs have not been shown to be generally survivable, and there are no plans to either retrofit existing links with survivable ones or install survivable links in new systems.

Available data are insufficient to determine the effects of HEMP on the 4ESS switching system. Conclusions about the survivability of the 5ESS and DMS100 switching systems cannot be directly applied to the 4ESS system, because their technologies are fundamentally different. Because no HEMP test data exist for the 4ESS system, conclusions about the survivability of the 4ESS switching system must be based on implications of related EMP test data and the use of electromagnetic protection practices. However, available data are sufficient to make observations concerning potential strengths and weaknesses of the systems.

The survivability of the 4ESS switching system against HEMP fields is greatly affected by the use of open equipment racks and long, unshielded wires for the PUB. The use of extensive filtering in the power distribution system and the use of a single point ground system should provide significant protection for the 4ESS equipment. The D4 was shown to be vulnerable to typical HEMP conducted transients; in the absence of test data the DIF must be presumed similar in vulnerability to the D4.

The observations presented here only indicate potential strengths and weaknesses of the 4ESS system in a HEMP environment. Conclusions about

its response to HEMP require more detailed analysis and the results of HEMP simulation testing of typical configurations of this system.

The DMS100 switch is survivable to HEMP effects, but subject to upset. Several service affecting system upsets occurred under exposure to threat-level fields, but no permanent hardware failures were observed.

The power converter of the DMS100 switch was shown to be sensitive to simulator-induced overvoltages. Power converters modified with a less-sensitive integrated circuit were shown able to survive threat-level fields. In addition, the rectifiers tripped when they sensed overvoltages on the power line. As with the 5ESS switch, power is supplied by batteries when the rectifiers shut down, but once battery power is lost (after several hours), the DMS100 ceases to operate. Rectifiers modified with filter capacitors were also shown to survive threat-level fields. With these hardware modifications in place, the switch was invulnerable to upset. NTI plans to include these changes as part of all future DSM100 switches. Therefore, to ensure the survivability of a particular DMS100 switch requires that the identified hardware modifications have been installed or that the site will be staffed.

4. CONCLUSIONS AND RECOMMENDATIONS

4. CONCLUSIONS AND RECOMMENDATIONS

Section 4.1 summarizes conclusions drawn throughout this report about the performance of the assessed systems after exposure to HEMP fields; Section 4.2 makes recommendations concerning future activities for the OMNCS EMP Mitigation Program.

4.1 CONCLUSIONS

The conclusions concerning the effects of HEMP on selected network elements follow:

- **The unhardened AT&T T1 digital transmission system incorporating splice cases and D4 channel banks is vulnerable to HEMP effects; lightning protected AT&T T1 systems with splice cases and without D4 channel banks are robust to HEMP effects.** T1 system elements have been exposed to simulated low-level HEMP fields; the results were then analytically extrapolated to full threat values. Lightning protected repeaters are survivable against HEMP, but repeaters without lightning protection are vulnerable. D4 channel banks suffered significant damage during testing at transient stress levels that could occur in the central office during a HEMP event; however, further tests and analyses are required to determine the applicability of these results to typical D4 installations. A hardened T1 carrier system, including EMP-protected D4 channel banks and repeaters, was tested at field strengths up to 80 kV/m and proved robust to HEMP effects.
- **The AT&T FT3C multi mode fiber optic transmission system is vulnerable to HEMP effects.** Threat-level fields and injected currents did not produce any signal disruptions or service-affecting hardware damage during testing of the optical cable and splice case; both elements appear to be survivable against the effects of HEMP. Available test data on the survivability of Central Office (CO) and Line Repeater Station (LRS) equipment are inconclusive, since threat-level currents were not injected into all subsystems. Unmodified power converters were shown to be vulnerable to threat-level transients. Power converters incorporating several hardware modifications proved robust, although the test configurations using modified power converters are not typical of most LRSs and COs. The modified power converters, therefore, cannot be considered survivable to HEMP based on available test data. Because both LRS and CO equipment rely upon the converters to power them, the entire FT3C system must be considered vulnerable.
- **The Alcatel R-R140 single mode fiber optic transmission system is robust to HEMP effects.** Threat-level fields and injected currents

did not produce any service-affecting hardware damage during testing of the repeater, so it appears to be survivable to the effects of HEMP. However, the fiber optic cables were not tested with threat level currents. Because these cables are assumed to be similar to cables used within the survivable FT3C multi mode system, they are also considered survivable to HEMP effects.

- **The AT&T L4 and L5 coaxial cable systems are robust to HEMP effects.** These systems are designed for survival in a nuclear environment; all cable is buried and repeaters are well bonded and well grounded. Detailed computer analyses and HEMP simulation tests indicate that although some temporary system outages will occur, no equipment will be damaged as a result of HEMP.
- **The AT&T TD-2 microwave radio system is survivable to HEMP effects.** Threat level, free-field HEMP simulation testing has produced upsets such as the activation of protection switching and frequency shifting, but it has produced no failures. Low-level current-injection tests caused no failures; high-level current-injection tests have not been performed. However, comparison of predicted HEMP-induced currents to expected lightning-induced transients on microwave towers indicates that TD-2 systems are also survivable against conducted transients.
- **The AT&T 5ESS switching system is survivable to HEMP effects, but subject to upset.** Several service-affecting hardware failures occurred under exposure to threat-level fields. With several hardware modifications in place, the 5ESS switch suffered no permanent hardware damage, although a significant number of calls (over 90 percent) were dropped and call processing capability was reduced following repeated exposures. Manual recovery is required to restore call processing efficiency to greater than 99 percent; however, most central offices housing 5ESS switches are not staffed and the survivability of remote links has not been demonstrated. To ensure the survivability of a particular 5ESS system requires verification that the identified hardware modifications have been installed and that the site will be staffed or verification that a survivable remote link has been established.
- **The Northern Telecommunications Inc. (NTI) DMS100 switching system is survivable to HEMP effects, but subject to upset.** Several service-affecting system upsets occurred under exposure to threat-level fields, but no permanent hardware failures were observed. With several hardware modifications in place, the switch was invulnerable to upset. NTI plans to include the changes identified during the test program as part of all future DMS100 switches. Therefore, to ensure the survivability of a particular

DMS100 switch requires verification that the identified hardware modifications have been installed or that the site will be staffed.

- Existing test data on the AT&T 4ESS switching system are insufficient to assess its vulnerability to HEMP. No test data or theoretical analysis of the HEMP response of the 4ESS system exist. The results of the 5ESS and DMS100 system assessments cannot be applied to the 4ESS system. It is assumed that of all the systems for which EMP test data are available, the D4 channel bank is technologically most similar to the 4ESS switch, but in the absence of actual 4ESS test data, no definite conclusions regarding survivability can be drawn.

4.2 RECOMMENDATIONS

The recommendations concerning future efforts in this program follow:

- The effects of HEMP on the 4ESS switching systems should be determined through test and analysis. The configuration assessed should include typical line termination equipment and appropriately placed lightning protection devices. Typical lengths of the Peripheral Unit Bus (PUB) should also be included.
- The HEMP response of solid state microwave systems should be evaluated through test and analysis. The TD-2 microwave system is based on vacuum tube technology; modern microwave systems are based on solid-state technology. Solid state components tend to be less survivable than their vacuum tube equivalents.⁵¹ However, an evaluation of the modern systems is required to determine their survivability to HEMP.
- The HEMP survivability of central office power supply systems should be assessed through analysis and test. The operability of all central office equipment, including switching and transmission equipment, depends on the availability of central office power. Testing of the 5ESS and DMS100 digital switches indicates that the power systems may be vulnerable to HEMP effects. However, the power systems are not part of the switches but rather are a part of the central office facilities required to support switch operation. They are therefore not included in the assessments of switch survivability. Determining the survivability of the power systems is critical to understanding the potential operability of all major network assets.

⁵¹ Booz, Allen & Hamilton, Inc., "State of the Art Report: Electromagnetic Effects Protection for Very Large Scale and Very High Speed Integrated Circuits (VLSIC/VHSIC)," US Army Laboratory Command/Harry Diamond Laboratories, April 1987.

- The results of the current study to determine the sensitivity of the network level HEMP-effects model should be used to identify and prioritize critical telecommunication assets. The OMNCS has developed a model to predict the effects of HEMP-induced equipment failures on telecommunication networks. Current efforts include a study to determine the sensitivity of predicted network performance to input data. The telecommunication equipment critical to the NSEP capabilities of the OMNCS should be identified and prioritized based on the results of the sensitivity study. This prioritization should be used as a basis for allocating resources for future tests and analysis of telecommunication equipment in support of this program.
- The HEMP responses of similar equipment from different vendors should be analyzed to evaluate methods of relating test results for one system to the survivability of another. Various vendors manufacture similar equipment for the telecommunication industry, e.g., T1 line termination equipment, channel banks and digital switching systems. The ability to relate the survivability of similar pieces of equipment would minimize the amount of testing required to assess the effects of HEMP on telecommunication networks.
- The HEMP stress level binning procedure used in this program should be reevaluated. The present binning procedure uses three arbitrary stress levels: low (0-30 kV/m), medium (30-50 kV/m) and high (50-70 kV/m). Alternative binning procedures should be reviewed to determine if the accuracy and flexibility of the model used to characterize the HEMP-induced survival probabilities for different types of telecommunications equipment can be improved.

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