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Multitier Specification for NSEP Enhancement of Fiber Optic Long-Distance Telecommunication Networks

Volume II: Multitier Specification Background and Technical Support Information

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PREFACE

This report is submitted as the primary deliverable for a study conducted for the National Communications System (NCS), Office of the Manager, Technology and Standards Office, Washington, DC, under Reimbursable Order 6-10038. Several other reports are submitted as part of this study to provide background information for the Multitier Specification described in this report. Those reports are listed below, and the reports by Ingram (1987) and Nesenbergs (1987) are referenced in this report.

Hull, J. A. (1987), NSEP fiber optics system study background report: Nuclear effects on fiber optic transmission systems, NTIA Report 87-227/NCS TIB 87-26, 115 pp, NTIS Order No. not yet available.

Ingram, W. J. (1987), A program description of FIBRAM: A radiation attenuation model for optical fibers, NTIA Report 87-216/NCS TIB 87-22, 120 pp., NTIS Order No. PB 87-230686 (report only), NTIS Order No. PB 87-230678 (report and flexible disk).

Nesenbergs, M. (1987), Fiber optic networks and their service survival, NTIA Report 87-214/NCS TIB 87-9, 121 pp., NTIS Order No. PB 87-186706/AS.

Englert, T. J. (1987), Effects of radiation damage in optical fibers--A tutorial, 55 pp., May, NTIA Contractor Report 87-38, NTIS Order No. PB 87-210308.

This report is issued in two volumes. Volume I contains a summary of a Multitier Specification for stress hardening long-haul fiber optic telecommunications systems. This volume is intended for those who wish an executive summary of the specification. Volume II provides a more detailed analysis of the levels of protection defined in the Multitier Specification.

This report includes data and information from industry, Government agencies, and literature. Certain commercial names are identified in this report to specify and describe some of the necessary information. Such identification does not imply exclusive recommendation or endorsement of the companies or products by NTIA or NCS. The views, opinions, and/or findings contained in this report are those of the author and should not be construed as an official NTIA or NCS position or decision unless designated by other official documentation.

The author wishes to express his appreciation to those industry representatives who offered information and ideas for inclusion in the report. He extends thanks to the following ITS colleagues: Mr. Joseph Hull, Program Manager, for his sharing of background knowledge; Dr. William Kissick and Mr. Robert Adair for their technical reviews; Mrs. Lenora Cahoon for her editorial review; and Ms. Karen Marvin for her word-processing assistance. Mr. David Blaylock, Federal Emergency Management Agency (FEMA) Regional VIII Engineering Office, and Dr. Thad Englert, University of Wyoming Department of Electrical Engineering, also contributed through their technical reviews.

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LIST OF ACRONYMS

AT&T	- American Telephone and Telegraph Company
AT&T-IS	- AT&T Information Systems
CCITT	- International Telephone and Telegraph Consultative Committee
CNS	- Commercial Network Survivability
DCA	- Defense Communications Agency
DOD	- Department of Defense
EMI	- electromagnetic interference
EMP	- electromagnetic pulse
EOC	- Emergency Operation Center
FCC	- Federal Communications Commission
FEMA	- Federal Emergency Management Agency
FRP	- fiber reinforced plastic
GTE	- General Telephone & Electronics Corp.
HEMP	- High Altitude Electromagnetic Pulse
IEEE	- Institute for Electrical and Electronic Engineers
ITS	- Institute for Telecommunication Sciences
LATA	- Local Access Transport Area
M	- one-thousand count
MCI	- MCI Communications Corporation
MeV	- million electron volts
MFJ	- Modification of Final Judgement
MN	- meganewtons
MOV	- metal oxide varistor
MT	- Megaton
MTBF	- Mean Time Between Failures
NCC	- National Coordinating Center

LIST OF ACRONYMS (cont.)

NCS	- National Communications System
NSDD	- National Security Decision Directive
NSEP	- National Security/Emergency Preparedness
NSTAC	- National Security Telecommunications Advisory Committee
ROW	- rights-of-way
TPD	- transient protection device

DEFINITION OF TERMS COMMONLY USED BY INDUSTRY

closure -- A device that surrounds the fiber splices (the number of splices will be determined by the number of fibers contained within the fiber optic cable). The closure protects the splices by closing off exposure to the environment (i.e., air, moisture, dirt, chemicals, etc.)

conduit -- A rigid tube, made of metal, fiberglass, or plastic, whose primary purpose is to protect the fiber optic cable. A conduit can also be constructed by encasing a duct in concrete.

duct -- A rigid tube, usually made of plastic, that is used to support and protect a fiber optic cable installed above or below the Earth's surface. The duct is used primarily to allow lineal movement of the cable (i.e., for cable replacement and for temperature or earthquake stress relief) and provide limited protection from the physical environment.

enclosure -- A structure that surrounds the regenerator electronics and associated hardware, along the fiber optic path placed at, approximately, 25-mile (40-kilometer) intervals. The primary purpose of the enclosure is to control the environment and to protect the enclosed hardware from external stress.

enhancement -- A modification or improvement feature applied to a system that will increase its hardness.

hardness -- The ability of a component, element, or system to withstand nuclear effects or natural disaster.

hardness levels -- The extent to which protection factors have been applied to enhance the capability of a system to withstand stress.

innerduct -- A duct that is placed within a conduit primarily for organization (i.e., to provide separation of adjacent cables within the same conduit).

mode -- A way (path) that light energy is propagated along the optical fiber. The field distribution that is associated with the propagation must satisfy Maxwell's equations.

multimode -- Denotes the capability of an optical fiber to propagation more than one mode of light.

Multitier Specification -- A ranking of hardness levels which provide a progressively higher level of protection.

protection level -- The amount of physical resistance (enhancements) installed to reduce the effects of stress.

single-mode -- Denotes the capability of an optical fiber to propagate a single mode of light.

stress -- The result of an event or situation that modifies the normal environment of a component or physically damages a part of the system.

MULTITIER SPECIFICATION FOR NSEP ENHANCEMENT OF FIBER OPTIC LONG-DISTANCE TELECOMMUNICATION NETWORKS

Volume II: Multitier Specification Background and Technical Support Information

David F. Peach*

Fiber optic telecommunication systems are susceptible to both natural and man-made stress. National Security/Emergency Preparedness (NSEP) is a function of how durable these systems are in light of projected levels of stress. Emergency Preparedness in 1987 is not just a matter of--can we deliver food, water, energy, and other essentials?--but can we deliver the vital information necessary to maintain corporate function of our country? "Communication stamina" is a function of "probability of survival" when faced with stress. This report provides an overview of the enhancements to a fiber optic communication system/installation that will increase durability. These enhancements are grouped, based on their value in protecting the system, such that a Multitier Specification is created that presents multiple levels of hardness. Mitigation of effects due to electromagnetic pulse (EMP) and gamma radiation, and protection from vandalism and weather events are discussed in this report. This study concludes that the probability of survival can be significantly increased with expeditious use of design and installation enhancements. The report is presented in two volumes entitled as follows:

Volume I : The Multitier Specification--An Executive Summary

Volume II: Multitier Specification Background and Technical Support Information

Volume I presents the Multitier Specification in a format that is usable for management review. The attributes of specified physical parameters, and the levels of protection stated in Volume I, are discussed in more detail in Volume II. This study is intended to be a guideline to aid in design and implementation, when the intent is to create a more durable, long-haul, fiber optic telecommunication system.

Key words: electromagnetic pulse (EMP); EMP hardening; fiber optics; fiber optic cable; fiber optic systems; gamma-radiation hardening; high altitude electromagnetic pulse (HEMP); long-distance telecommunication systems; National Security/Emergency Preparedness (NSEP); singlemode fiber optic cable; stress hardening; telecommunications; telecommunication survivability; telecommunication system hardening enhancements

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1. INTRODUCTION

This section provides an introduction to the technical background needed to understand the rationale behind the Multitier Specification. It is submitted by the Institute for Telecommunication Sciences (ITS) to the National Communications System (NCS), Office of Technology and Standards, in partial fulfillment of Reimbursable Order Number 6-10038. The primary output of this study is a Multitier Specification for NSEP-enhancing features required of commercial fiber optic transmission systems using rights-of-way (ROW) owned or controlled by the Federal Government, and included in this report.

1.1 NCS Mission

Executive Order 12472 defines the National Communications System mission (in part) as "The coordination of the planning for and provision of NSEP communications for the Federal Government under all circumstances, including crisis or emergency."

Key responsibilities of the NCS are to: seek development of a national telecommunications infrastructure that is survivable, responsive to NSEP needs of the President and the Federal Government, capable of satisfying priority telecommunications, and consistent with other National policies; serve as a focal point for joint industry-Government NSEP telecommunications planning; and establish a joint industry-Government National Coordinating Center. This study supports the National security telecommunication policy as enunciated in National Security Decision Directive-97 (NSDD-97)... "the national telecommunications infrastructure must possess the functional characteristics of connectivity, redundancy, interoperability, restorability, and hardness necessary to provide a range of telecommunication services to support essential national leadership requirements."

1.2 Purpose of Study

The primary purpose of the work is to prepare a Multitier Specification identifying prudent measures that could be incorporated in the design of commercial intercity fiber optic transmission systems to make them more responsive to NSEP requirements in exchange for right-of-way concessions by the Government. The specification will be structured in such a way that it also can be used as a "report card type" instrument for assessing the degree to which present and future intercity fiber optic systems <u>not</u> using Federally controlled rights-of-way measure up from an NSEP standpoint. The spectrum of situations the fiber optic systems must cope with from an NSEP standpoint include natural disasters (e.g., floods, earthquakes, fire), local acts of sabotage, nuclear attacks [i.e., nuclear radiation effects and electromagnetic pulse (EMP) effects]. The design parameters addressed by the specification will be those that tend to minimize interruptions of service in the face of these hazards by proper attention to features that facilitate quick restoral of operation or bridging around damaged terminals or repeaters.

1.3 Historical Perspective

In 1934, the Communications Act created the Federal Communications Commission. Part of the purpose of the Commission was to regulate telecommunications "in the public interest"--a phrase that apparently has no legal definition that can be cited as a yardstick (Bell, 1985). One of the FCC's missions was, in the words of the 1934 act, "to make available, so far as is possible, to all the people of the United States, a rapid, efficient, nationwide, and worldwide wire and radio communication service with adequate facilities at reasonable charges. AT&T was established as a monopoly to provide this "universal service at a reasonable rate." As a monopoly, AT&T was able to cross subsidize between long-distance and local rates to minimize the cost of less utilized portions of the network. Because the company could rely on its manufacturing expertise provided by Western Electric, it could assure uniform quality in all equipment.

In 1949, the Justice Department filed a major antitrust suit against both AT&T and Western Electric. The accusation dealt with the restraint of trade in the manufacture, distribution, sale, and installation of all forms of telephone apparatus in violation of the Sherman Antitrust Act. The result of this suit was a 1956 out-of-court consent decree which allowed the Bell System to remain intact on condition that it restrict its business to common carrier communication services subject to regulation. Western Electric was barred from manufacturing equipment other than the type used by the Bell System. AT&T, Western Electric, and Bell Laboratories were required to license their patents to all applicants--both domestic and foreign--upon payment of reasonable royalties. During the 1970s the Bell System and its allies pressed Congress for a new telecommunications policy bill that would update the 1934 Communications Act. The company wanted affirmation of the premise of universal service as a natural monopoly and the Bell System as the regulated quasi-utility to fulfill that service. During this period, several competitors (notably MCI) sued the Bell System for unfair anticompetitive practices under the Sherman Antitrust Act.

The advance of technology during the 1960 and 1970 decades made the 1956 consent decree highly constraining to the world's largest company. AT&T recognized the coming of an Information Age brought about by the marriage of computers and telecommunications. Consequently there was much effort to remove the restrictions of this decree to permit competition in the evolution of the information explosion.

In 1980, the FCC handed down a ruling, called the Second Computer Inquiry Decision. It did three things:

- It distinguished between basic transmission services, traditionally provided by common carriers, and enhanced network services such as those incorporating data processing.
- It found that enhanced services and customer-premises equipment would not be regulated as common-carrier offerings, whereas basic services should be so regulated.
- It concluded that AT&T should be allowed to sell equipment and enhanced services, but only through a separate subsidiary.

This Computer II decision opened the way for an explosion of new telecommunications products and services both by new suppliers and AT&T.

In 1974 the Justice Department brought an antitrust suit against AT&T, Western Electric, Bell Telephone Laboratories, and the 22 Bell Operating Companies again under the Sherman Antitrust Act. The Justice Department alleged that AT&T monopolized the long-distance telephone business by exploiting its control of the local telephone companies to restrict competition from other telecommunication systems and carriers by denying interconnection with the local phone service and that AT&T restricted competition from other manufacturers and suppliers of customer-premise equipment. The relief sought was not punishment for past deeds, but a cure that would prevent continued future violations. This suit was settled in 1982 through what is known as the Modification of Final Judgment (of the 1956 Consent Decree). This MFJ brought about the divestiture of the 22 Bell Operating Companies and a major reorganization of the remaining Bell System and the removal of the restrictions of the 1956 Consent Decree. The divestiture took place on January 1, 1984.

One major result of the divestiture is the competitive installation of long-haul, fiber optic, common-carrier systems. The technology for these systems has matured extremely rapidly under the competitive environment.

By April 1985, 12 companies had announced (Galuszka, 1985) plans for long-distance lightwave communication systems in the United States (see Table 1). In many cases, these common carrier or carrier's carrier systems will utilize ROWs of a few main trunk railways. There are more than 7 billion circuit miles of transmission capacity indicated here over a distance of 65,650 route miles. By the year 2000, it is forecast (By F. Dixon, of Electronicast Corporation, Redwood City, CA, in a paper presented at the Conference entitled "Fiber Optics to the Year 2000," held in Monterey, CA, June 16, 1985) that worldwide fiber optic transmission capacity will be about 200 billion circuit miles. All other transmission media combined will provide an additional 50 billion circuit miles. These trends indicate that fiber optic transmission media will be the dominant means of connection nodes of the public switched telephone and data networks in the United States. The opportunity exists to plan for lightwave systems that assure the availability of emergency communications capacity through engineering design and implementation practices.

1.4 Scope and Purpose of Report

The Multitier Specification concentrates on the engineering and installation aspects of optical communication, common-carrier-type systems and recommends those additional practices or alternatives that result in higher probability of survival or restoral in a broad range of NSEP environments. The rating approach is a multitier, rank-ordered specification.

This report is intended to provide background information and references needed to understand the rationale and basis for the NSEP enhancements. The specification is intended to be a living instrument that will grow and improve as feedback from the common carrier industry is obtained and as more complete assessment of the NSEP environments and enhancements is reached. This report is not intended to be comprehensive or definitive, but rather a record of the literature, references, and considerations that were found useful in guiding the work. The work has been based entirely on unclassified literature and information.

Table 1. Planned Lighwave Installations for the United States (after Galuszka, 1985)

LIGHTWAVE PLANS

COMPANY	INVESTMENT	AREAS	CIRCUIT MILES	ROUTE MILES/ DATE
United Telecommunications	$2.0 B	National	1.2 B	23 K/1988
AT&T Communications	1.3 B	National	1.7 B	10 K/1988
Fibertrak (Sante Fe, Southern Pacific, Norfolk Southern)	1.2 B	National	2.4 B	8.1 K/1988
MCI Communications	450 M	National	550 M	8.0 K/1988
GTE Sprint	130 M	National	110 M	4.0 K/1989
Lightnet (CSX and SNET)	500 M	Regional (East of Miss. River)	650 M	4.0 K/1986
LDX Net (Kansas City South Industries)	110 M	Regional (South, Midwest)	165 M	1.7 K/1986
SOUTHERNET (E.F. Hutton et al.)	90 M	Regional (Southeast)	50 M	1.6 K/1986
RCI	90 M	Regional (Northeast, Midwest)	87 M	0.9 K/1986
Microtel (Alltel, E.F. Hutton, Centel, Norfolk Southern)	60 M	Regional (Florida, Georgia)	45 M	1.5 K/1986
Litel Telecommunications (Centel, Alltel, and Pirelli)	57 M	Regional (Midwest)	85 M	1.3 K/1986
Electra Communications	40 M	Texas	72 M	0.55K/1986

(Source: The Hudson Institute)

1.5 Problem Context

Although the nature and level of communication support required to accomplish the NSEP mission varies widely with the nature of the emergency, two broad categories of missions may be defined. They are

1) Time-Critical Missions
   - Continuous communication capability is essential (communications restored "too late" are of little value).
   - Specific user pairs must be linked.

2) Non-Time-Critical Missions
   - Minute-to-minute continuity of communications is not essential (restoral delay is acceptable).
   - An increasing number of specific user pairs must be linked as time evolves after the stress event but the critical nature of each specific call is slowly decreasing as a function of time.

Missions in the first category include those that are primarily military in nature as well as emergencies that arise from natural disaster or man-made events. Those events that are military in nature are best addressed by the development of survivable, mission-specific, dedicated networks. Missions in the second category include nonmilitary government functions as well as military functions, and are best addressed through the gradual enhancement and integration of Federal and commercial common-user networks. It is this latter category of hardness and integration of Federal and commercial common-user networks to which the results of this study are expected to apply. Arbitrary times of restoral have been assumed for various scenarios addressed in this study. For example, a recovery time of the order of 10 minutes following a gamma radiation dose sufficient to disrupt the system due to induced attenuation would meet the requirements of networks to support restoral following a nuclear event. This nuclear event could be the result of an accident or an act of sabotage, and not necessarily a limited nuclear war.

1.6 Organization of Report

The intent of this report will be to provide guidance in designing a durable fiber optic telecommunication system. The guidance will be provided by a "Multitier Specification" that is outlined in the last section of the report. Enhancements that improve the survivability, when the system (or component) is stressed, are discussed and their benefit to making the system more durable is presented. Data made available in this report will aid in predicting the stamina of a particular fiber optic, long-haul path.

Background information is presented in order that the scope of the study is understood. This section defines what components constitute the fiber optic path.

Stresses that affect a fiber optic telecommunication system, or its components, are discussed next. An attempt has been made to define the type of damage that can be expected from each type of stress and whether the damage is gradual (due to deterioration) or catastrophic (causing immediate interruption of service). A presentation of the stress categories, based on whether they are occurrences of nature or caused by humans, is also included. This breakdown is useful for discussion in later portions of this report.

The next section presents a technical discussion concerning the fiber optic system components, their design options, and the design enhancements that provide resistance to stress. This section concentrates on physical parameters of the system.

Environmental enhancements that can be incorporated when installing, or "placing in service", the cable and the regenerator station are discussed next. At this point one must realize that the design and the environment are integral in some cases, and separation is difficult. The discussion of enhancements will reflect these circumstances.

The main objective of this study is to provide protection from stress--countering the effects of stress is the defined problem. "Solutions" to the problems that are of concern to the fiber optic system and components designer, are presented in the next section. An attempt has been made to define the extent of protection that can be provided--since total protection is not always possible as pointed out in this portion of the report. For each major classification of stress, an analysis is provided that defines the level or extent of protection that can be expected for each level of the Multitier Specification.

1.7 NSEP Historical Perspective

(The following excerpts are taken from an IEEE Spectrum article by John Horgan, November 1985)

Ten years ago, before the AT&T installed a new long-distance system, it asked the Department of Defense (DOD) what route it should take. Defense officials looked over their highly classified "laydown" maps, showing the expected targets of a Soviet nuclear strike, and told AT&T which route was most survivable--that is, which was farthest from targets. The company then used that path, folding any extra cost into its rate base.

Today, commercial carriers--MCI and GTE, as well as AT&T Communications--might still ask the Government which routes it considers most survivable, and all other factors being equal, a carrier might use the more survivable route. But no company is likely to pay extra for it. If the Government wants a more expensive route used, the Government must pay for it.

This is just one example of how the relationship between the telecommunications industry and the United States government has changed since the Bell System breakup on January 1, 1984 (divestiture). Change has been particularly profound for those agencies responsible for National Security/Emergency Preparedness (NSEP). These include both military and intelligence groups and civil organizations like the Federal Emergency Management Agency; they are charged with helping the country cope with crises, from floods to nuclear war.

Government and industry have moved to offset the potentially adverse effects of the divestiture. Eventually, the diversity of carriers should make the Nation's total network more robust than ever, and the growth of competition should provide the Government with cheaper, better service.

Divestiture involved a collision between one profound Republican commitment, deregulation, and another, defense. The Administration has sought to increase the "readiness" not only of military command and control systems but of the entire communications infrastructure of the United States as well. In a directive, National Security Telecommunications Policy, (issued on June 13, 1983), the entire United States telecommunications infrastructure, including commercial and private networks as well as Government systems, was declared to be "a crucial element of United States deterrence." This document reflects a shift away from the policy of mutual assured destruction (in which each side assumes that the other will answer a first strike with massive retaliation that will leave both countries completely destroyed) to a concept of flexible response. This concept suggests that nuclear weapons can be used to defeat the enemy in various ways short of an all-out attack. A strategy geared toward mutual assured destruction requires only a minimal, although extremely reliable, command and control system for sensing an attack and launching missiles in response. In contrast, flexible response assumes that a nuclear war may be a prolonged and complex affair; hence the need for extensive, redundant communications that only industry can provide.

In January 1983, the FCC handed down the Computer II ruling. This ruling forced AT&T to form a wholly independent subsidiary, AT&T Information Systems, for selling and servicing equipment such as private branch exchanges and computerized telephones. The AT&T-IS personnel are severely restricted in how they may work with other personnel in AT&T who sell transmission services. (Divestiture constrains the local operating companies in a similar way in their sales of customer premise equipment.) Computer II thus prevents the DOD's primary contractor, AT&T, from packaging, selling, and servicing a complete system of equipment and transmission service from one end of a circuit to the other. (For example: 10 or more vendors--all low bidders--may provide parts of a single link. This leads to administrative nightmares under emergency conditions.)

The FCC did grant the Government some important concessions for NSEP purposes. The Commission agreed that 21 Government communications systems were so critical to NSEP that AT&T could retain control over them from end to end. Most of these systems involve services and equipment from several vendors, but all are managed by AT&T. These systems include

- White House's Echo Fox Radio System (which links the President to his military commanders while he is airborne);

- Defense Department's Minuteman (a combination land-line and mobile radio system that connects key military personnel with the strategic command and control structure even while they are in transit);

- Strategic Air Command's Primary Alerting System (which connects the commander of the Strategic Air Command with bombers and missile silos);

- Automatic Secure Voice Communications Network (which provides DOD personnel with encrypted voice communication);

- Federal Emergency Management Agency's Emergency Broadcast Network (which allows the President to address the country over commercial radio stations during crises);

- Air Force Digital Graphics System, (which distributes weather maps to United States armed forces worldwide); and

- Nuclear Regulatory Commission's Emergency Notification System, (through which operators of nuclear power plants notify the commission of accidents.

As a concession to the needs of national security, Judge Greene's Modification of Final Judgment states that: "The Bell Operating Companies shall provide, through a centralized organization, a single point of contact for coordination of Bell Operating Companies to meet the requirements of national security and emergency preparedness." This ruling resulted in the creation of a special branch of Bell Communications Research Inc. (Bellcore) devoted to helping the Government get fast service from operating companies in NSEP situations. The Bellcore NSEP group is also a single point of contact for other carriers trying to fulfill emergency requests from the Government.

Some of the most important work done to counter the effects of the AT&T breakup on security emerged from the voluntary efforts of industry--in particular, from a group of industry executives called the National Security Telecommunications Advisory Committee (NSTAC). This group was formed under Executive Order 12382 in September 1982. The committee consists of the chief executive officers of 27 of the largest telecommunications companies in the United States. The first problem to be addressed by this committee was the need for a single point of contact representing not only the operating companies but all local and long-distance carriers. The NSTAC created (early in 1984) the National Coordinating Center (NCC) to be located at the Defense Communications Agency headquarters in Arlington, VA. The coordinating center's most critical mission is to provide Government agencies with instant access--24 hours a day, 7 days a week--to industry for emergency communications needs that cannot be filled through normal business procedures. This center has representatives from numerous Government agencies assigned to its offices. The NCC is a private sector extension of the National Communications System. The NCS is an organization of representatives of 22 Government agencies with security and emergency missions. The NCS helps these agencies coordinate their telecommunication policies, standards, and plans. Many of these plans involve the use of commercial communications. The NCC advises the NCS as they devise plans and policies that involve private-sector communications.

1.7.1 NSEP Requirements

According to the NCC procedures manual, the coordinating center is charged with supporting any telecommunication services used:

> "to maintain a state of readiness or to respond to and manage any event or crisis (local, national, or international) which causes or could cause injury or harm to the population, damage to or loss of property, or degrades or threatens the national security emergency preparedness posture of the United States."

A disaster or emergency declared by the President is automatically a national security/emergency preparedness situation. The procedures can also be invoked by various other officials, including Lieutenant General Winston Powers, director of both the NCS and the DCA, as well as at least one official from each Government agency belonging to the National Communications System.

The ultimate Presidential emergency would involve an invocation of war powers. Section 706 of the 1934 Communications Act, in particular, allows the President to commandeer the communications industry during a crisis that he believes threatens the sovereignty of the nation.

1.7.2 NSTAC Concerns

The following are major subjects of discussion in the subgroups of the National Security Telecommunications Advisory Committee:

- The promotion of links between different networks and of standards to make them interoperable;
- The use of materials resistant to electromagnetic pulses;
- The creation of backup power sources for circuits and terminal equipment; and
- The standardization of procedures for restoring networks after a disaster.

Debate may also center on the degree to which solutions should be implemented. For example, should there be an effort to make commercial networks truly survivable, perhaps by burying switches and circuits or using pulse-resistant materials?

Cost is the final determinant. Inevitably conflicts arise between the Government's concern for national security and the commercial carriers' financial considerations. According to the participants, there is much pushing and pulling each way: the Government tries to convince industry that much of what it wants to increase national security would enhance the companies' competitive position; conversely, the companies try to get the Government to pay for programs that they would implement anyway for commercial reasons.

1.7.3 NCS Initiative

One proposal for resolving this cost element is that of bartering. This NCS-sponsored program was developed on the basis of offering interstate right of way for fiber optic common carrier installation in exchange for the carriers' agreements to install the lines in accordance with the Multitier Specification developed here.

1.8 NSEP Context for This Study

This section is an excerpt from a companion report authored by Mr. J. A. Hull, NTIA, Boulder, CO entitled "NSEP fiber optics system background report: Nuclear effects on fiber optic transmission systems," that offers background information to be used in conjunction with the Multitier Specification (Hull, 1987).

1.8.1 NCS Assets and Authorities

The 22 Federal organizations that make up the Member Agencies of NCS have collectively the bulk of the telecommunication resources owned or leased by the Federal Government. These networks and systems support a variety of organization-specific missions in their normal day-to-day use. The context in which these networks and systems become a viable means for satisfying national-level NSEP needs, however, is largely dependent on three factors--the types of services required by the users, the set of networks and systems from which possible approaches to the provision of NSEP services can be fashioned, and the major settings, or scenarios, under which services must by provided. It is primarily within the boundaries offered by these factors that potential NSEP uses for a network, system, or technology must be measured.

By virtue of Executive Order 12472, it is the mission of the NCS to assist the President, the National Security Council, the Director of the Office of Science and Technology Policy, and the Director of the Office of Management and Budget in the execution of their national security emergency preparedness telecommunications functions, and in the coordination of planning for and provisioning of NSEP communications for the Federal Government under all circumstances. The NCS is also charged by the Executive Order to seek to ensure that a national telecommunication infrastructure is developed that satisfies priority telecommunications requirements under all circumstances, using all existing telecommunication resources, regardless of character or ownership. The legal mandate of E.O. 12472, and the policy guidance of National Security Decision Directive-97 compel the NCS to use, improve, and expand the Government's capabilities to assimilate technology in the most fruitful and cost effective manner possible for the purpose of ensuring a flexible, survivable, and enduring national telecommunications capability.

1.8.2 NSEP Services

NSEP telecommunications services are defined as those services that are used to maintain a state of readiness or to respond to and manage any event or crisis--local, national, or international--which causes, or could cause, injury or harm to the population, damage to or loss of property, or that degrade or threaten the National Security Emergency Preparedness Posture of the United States. Two specific categories of telecommunication services are defined: "Emergency NSEP Telecommunication Services" and "Essential Telecommunication Services." The first category includes those that are so important as to be needed as soon as possible, without regard to cost (e.g., support services for Federal Government activities in response to a Presidentially declared disaster or emergency or service requirements critical to the protection of life and property, or to maintain national security under stressed circumstances). The second category includes services that are important and must be provided by the "service-due" date, but do not necessarily require around-the-clock emergency response by a carrier (e.g., services assigned, or eligible for, an NCS/FCC approved restoration priority of one through four, the minimum essential services necessary to carry out military and civilian exercises, and services that are specially provided in support of the Foreign Intelligence Surveillance Act, the President or Vice President, or the conduct of foreign affairs).

1.8.3 NSEP Attributes

Both NSDD-97 and E.O. 12472 specify that the use of all Government, commercial, and private resources must be considered for their potential contributions to NSEP. The ability to include assets of both the public and private sectors is, in fact, seen as an essential element of United States deterrent capability and emergency preparedness. By virtue of the Government's current reliance on commercial systems, it is appropriate that the technologies of those systems be examined for compliance with NSEP requirements. Guidance for performing such analyses is contained in NSDD-97 and E.O. 12472 in the form of policy principles and objectives. Seven system attributes are defined:

- Hardness
- Redundancy
- Restorability
- Interoperability
- Security
- Mobility
- Connectivity

These seven terms reflect the characteristics of communication systems that are desirable for NSEP purposes. These seven attributes in combination reflect the necessary component characteristics of a survivable and endurable communication system. Evaluations of candidate networks, systems, or technologies for supporting NSEP communications, should be based on the degree to which these attributes are present.

1.8.4 NSEP Environments

Four environments of NSEP telecommunications are considered:

- peacetime natural disasters
- crisis management
- limited conventional war
- nuclear war

Each of these presents special concerns to providers of NSEP communication services.

In peacetime natural disasters, communications requirements are characterized by sporadic or localized service disruptions due to the effects of the disaster. This requires restoration of lost connectivity by mending the "holes" in the network so that emergency aid and rescue activities can be supplied to the affected area.

Crisis management situations include international incidents such as the hijacking of the Achille Lauro, domestic incidents such as the accident at Three Mile Island, and third-party military actions that may result in heightened tensions at home or abroad. In these situations, fast, reliable, secure communications are essential for crisis management, averting hostilities, and relaxing tensions.

In limited conventional war, communications are required to support troop and equipment deployments and for battle management. In this situation, communications may be required where no residual capabilities exist. Thus interoperability with commercial systems is required for managing support/sustaining activities.

In nuclear war as considered here, several stages of requirements are suggested to reflect the extent of damage sustained and the nature of the attack. Until the point of exchange, communications needs and the communications environment are considered to be the same as in crisis. After an exchange, however, fixed-plant communications will be damaged or destroyed. In the extreme, the communications infrastructure will be highly fragmented. In this case, regenerative approaches to providing communications must be pursued; the emphasis will be on restoration and use of any and all communications.

1.8.5 Implications for Fiber Optic Systems

In terms of hardness, fiber optic system survivability can be significantly extended by following the recommendations of this study.

In terms of restorability, fiber optic systems offer unique capabilities for automatic restoration when configured in networks (Nesenbergs, 1987).

In terms of security, fiber optic services are inherently well suited to deny access to transmission content by an enemy and are at the present free from the effects of jamming.

In terms of connectivity, present fiber optic, long haul systems are concentrated along railway rights-of-way. The rapid introduction of intraLATA (Local Access Transmission Area) fiber optic systems along with judicious planning of interconnecting links could add significantly to this capability. The concept of this program is to make judicious choices of needed linkages and to utilize interstate highway rights-of-way as means of interconnecting population centers. These rights-of-way provide highly redundant paths between these population centers.

Redundancy is an attribute conveying the duplicity of routes, paths, or even equipment types that may be employed in a network or system. As a result, redundancy measures tend to be highly dependent on network topologies and site-specific installation procedures and more reflective of system rather than component attributes.

Interoperability among the types of systems installed by the competing networks is a subject being actively addressed in the T1X1.2 standards committee (document is in rough draft as of this writing). The objective here is to create an optical cross-connect interface (DS3-level). From an operational perspective, wide variations in network management, transmission record formats, and communications protocols make system interoperability difficult.

The attribute of mobility is not specifically applicable to fiber optic systems. Ubiquity of fiber optic systems may be a more achievable attribute. If, indeed, fiber optic transmission media does to copper and microwave media what solid state components have done to vacuum tubes, then one can expect to see much more NSEP reliance on the terrestrial telecommunications plant.

2. TYPES OF STRESS

2.1 Introduction

A telecommunication system is subject to interruption from numerous causes. Some of these causes are predictable, but most are a result of random events. Many of these events occur as a result of the "forces of nature" and are virtually unpredictable--especially the events of a severe level. The severe events are of most concern to the survivability of a telecommunication system since they will do the most damage. Nature caused events will be discussed later in this report. In addition to the stress caused by nature, there are many events that are caused by humans. Like the events of nature, many of the man-caused events are unpredictable because they are a result of random occurrences (e.g., accidents, construction work, and environmental pollution). These events are easiest to protect against because the magnitude of the stress is predictable; thus measures can be taken to avoid the interruption of operation. These measures will be discussed later in the report. Premeditated man-made damage is also a very real concern (e.g., damage caused by vandalism, sabotage, and nuclear weapons). The magnitude of stress associated with these events is not only unpredictable, but the ingenuity of man comes into play. Protection by design or physical means is impossible because there are no limits on the extent of the stress. Hardening of a system against this type of stress will be dealt with, in concept, later in this report.

2.2 Key elements

This report will assume that a fiber optic telecommunication system is made up of three major functional components: the fiber optic cable, the system regenerator electronics, and the people that may be necessary for continued operation. Each of these vital components can be enhanced to yield a more survivable telecommunication path or network. Obviously, if manual intervention is not necessary for day-to-day operation, the effect on people can be eliminated. However, if restoration of the system is of importance, the effect on human life/health must still be included. For purposes of this report, the assumption will be made that protection of humans is important.

2.3 Controllable Parameters

Physical protection for the key elements of the fiber optic system is necessary if protection from stress is desired. In addition to the physical protection, design parameters that will enhance the durability of components will be included in the discussion. Many of the enhancement ideas are brute-force techniques, however, and implementation is of essence. The implementation may be simple, or may seem so, but may not be easy. Expertise in doing a quality installation, with implementation of enhancements, is a necessity.

The controllable parameters, as shown in Table 2, are a function of the design or of the environment.

2.4 Fiber Optic System Stress Sources

The sources of stress that are a threat to the fiber optic telecommunication system can be classified into two categories:

- naturally occurring events
- man-made events

Table 2. Controllable Parameters

Key Element	Parameter
1. Fiber optic cable	• Component design • Configuration design • Cable environment
2. Fiber optic regenerator	• Electronics design • Enclosure design • Enclosure environment
3. Personnel	• Environment

The source of stress on fiber optic telecommunication systems results from events of nature--such as wind, rain, ice, snow, flood, temperature extremes, sun, lightning, earthquakes, rodents--or from man-made events, such as vandalism, sabotage, construction work, agricultural works, accidents, chemical spills, nuclear explosions. The list of stress initiators increases daily as our culture becomes more active and complex, and the activity related to development of lands becomes more widespread.

Events that emanate from nature are usually not controllable; therefore, mitigation must be through hardening of the system. The logical solution is to design harden the components, thus increasing the system stamina when subjected to stresses of nature. As will be discussed in this report, it is frequently more feasible, economically and technically, to modify the environment surrounding the components of the system. In order that we can devise methods to mitigate the effects of events originating from nature, generic categories of events that cause similar effects (damage) have been created. The common stress categories and stress sources that originate from nature are listed in Table 3 along with the damaging effect that can be expected from each category.

Table 3. Naturally Occurring Stress Types/Effects (CCITT, 1985)

Stress Type	Effects on Fiber Optic System
Temperature	Cable compression in duct by freezing
	Breakage and shrinkage due to temperature change
Winds (sea winds)	Damage to cable sheaths and joints due to vibration
Rain water (hot springs)	Corrosion, water penetration
Snow and ice	Cuts, breaks, sagging, lines down
Moisture	Corrosion, dielectric breakdown
Lightning	Puncture of cable sheath, fusing metallic pairs
Earthquakes	Breaking
Geography, soil	Cuts, personnel falls due to sinking soil
Sun	Fading, degradation
Rodents, birds, insects	Sheath damage, fiber separation

Man-made stress results from either premeditated or accidental events that cause damage. The damage can be either permanent or temporary depending on the stress type. The mitigation options for man-made stress are: to somehow stop the man-made event from happening, to harden the design of the components, or to harden the environment in attempt to build a barrier between the fiber optic components and the stress source. Table 4 lists some of the results of man-made events that cause either short-term or long-term effects on a fiber optic system.

3. SYSTEM DURABILITY ENHANCEMENT

3.1 Fiber Optic Cable Enhancement

The cable construction generally determines the durability of the cable. However, the material makeup of the cable can be shown to have an effect on the functional durability of the cable under certain stress conditions. The characteristics of some materials change state when exposed to certain stress types. If these characteristics are crucial to the function of the optical fiber, a degradation in performance will occur, or in some cases the system will become inoperable.

The object of the Multitier Specification is to identify enhancements that will harden the fiber optic cable installation against various types of stress. Using available parametric data, the level of stress resistance can be predicted. Since the fiber optic technology is relatively new, and only limited in-place (field installed) testing has taken place, some of the parametric data will be somewhat sketchy. The areas where data are incomplete can be used as areas for future testing or topics for further study.

The factors that affect the durability of the fiber optic installation are divided into two categories:

- physical properties of the hardware
- environmental parameters surrounding the hardware

Physical properties can make a system resistant to some types of stress conditions to which the hardware will be subjected. In some cases "brute force" design will be sufficient to protect the hardware, while more subtle design features will be required to provide the required resistance. Design changes as simple as using a different material will, in some cases, add resistance to a stress condition. Shielding the fiber optic hardware from stress is necessary when it is not practical or, in some cases, not possible to

Table 4. Man-made Stress Types/Effects (CCITT, 1985)

Stress Type	Effects on Fiber Optic System
Factory smoke	Corrosion
Cars, trucks	Damage to cable sheaths and joints due to vibration/accidents
Construction work	Cutting or breaking the cable
Communication systems power supply	Damage to cables and hazards to personnel
dc currents	Electrolitic corrosion
ac traction systems	Damage to cables and hazards to personnel, transients
Power lines	Damage to cables and hazards to personnel
Petroleum gas leakage	Damage to cable sheath
Steam and hot water systems	Damage to cable sheath
Vandalism	Sheath damage, cutting
Gamma radiation	Darkening of the fiber/increased loss
Electromagnetic pulse	Damage to cable components and/or fiber

provide stress resistance by changes of design parameters. For example, placing the cable and the regenerator underground provides a great deal of protection from many types of stress conditions.

3.1.1 Physical Properties

Optical fiber types This discussion will be limited to singlemode fiber since the application will be limited to long-haul telecommunication systems. Physical property variations in singlemode fiber are concentrated in the following areas:

- fiber core size
- fiber cladding size
- purity of the fiber material
- dopant used in the fiber material

Core and cladding size generally affect only the functional characteristics and have little effect on durability. The optical fiber lightguide is resistant to most outside effects except gamma radiation.

The purity of the fiber material is a function of the manufacturing process. Pockets of impurities cause imperfections in the glassy structure. These imperfections are referred to as color centers because the light is not absorbed in the same proportion as in the surrounding structure. Color centers can be formed by exposure to ionizing radiation as well as from impurities in the glass.

Whenever light is absorbed, loss of transmitted signal is experienced, requiring a regeneration (reconstruction and retransmission) of the signal. The loss is measured in decibels (dB) per kilometer of cable length. As the loss accumulates, over distance, the system design margin is used up to a point of inoperability (information can no longer be transmitted with an acceptable error rate). The system design margin (excess signal above threshold of inoperability) and the fiber loss accumulation per unit distance plus splice losses determine the regenerator station spacing.

The optical fiber material used for fibers in telecommunication cables is pure silica, to start with, but the glass is doped with impurities to adjust the dispersion for optimized operation at a desired wavelength and to provide a difference in index of refraction between core and cladding. For example, likely be from moisture. When the cable is buried underground there is a major threat from rodents (gophers, rats, squirrels, etc.). This threat requires a very durable sheath.

The sheath acts as part of the strength member, especially if the cable is pulled using a pulling mechanism that is attached to the outer shell of the cable. A metal stranded sheath adds a great deal of tensile strength to the cable as well as protection from abrasion or rodent attacks. When using a metal sheath, a layer of synthetic material is added on either side of the metal layer. This soft material protects against abrasion from the rough surface of the metal layer.

The sheath thickness is a factor due to possible buckling when the cable is coiled or bent while being installed. In most applications the size (diameter) is a consideration--therefore the sheath thickness should be as thin as possible while providing the necessary protection. The size issue is especially important in applications for which fiber optic cable is attractive because of its light weight and small diameter.

<u>Optical fiber splices and splice closures</u> Optical fibers must be spliced when the distance between regenerator stations exceeds the continuous cable length that is practical to use during installation. Continuous cable lengths in excess of 10 km are possible, however not always practical because of the terrain encountered which precludes transporting a large reel of cable along the installation route. When cables have to be spliced, there are two primary goals when making the connection:

1. minimizing the loss effected at the splice
2. making the splice as durable as possible (Georgopoulos, 1982; CCITT, 1985)

In simple terms, the magnitude of loss is a function of the alignment of the two ends of the fiber and length of gap between the ends.

Two common techniques are used to splice singlemode fibers: mechanical splicing and fusion splicing (Georgopoulos, 1982). Mechanical splicing permits easy, permanent splices through use of a jig that holds the two fiber ends together while the joint is filled with epoxy. The epoxy then maintains the alignment of the fibers--even with exposure to vibration or other adverse conditions. The splice alignment jig must allow for positioning of fibers to doping with Ge (germanium) will shift the optimum operating point (zero dispersion) to a higher wavelength, while doping with B (boron) will cause a shift in the opposite direction. It has been determined that doping with P (Phosphorous) has the same effect as doping with Ge, and doping with F (florine) has the same optical effect as with B.

Optical losses in the material occur due to scattering and absorption of the light. As mentioned before, pure silica fibers have the best loss characteristics because there are no color centers to absorb the transmitted light. The process of adding impurities by doping to form the waveguide and to optimize the wavelength operating point increases the losses due to absorption.

Wide bandwidth, singlemode telecommunication fibers typically consist of Ge-doped silica core that may be codoped with F or P to adjust the index of refraction to the desired operating wavelength. The doping reduces the loss characteristics, and these fibers have a somewhat reduced resistance to effects from exposure to gamma radiation. It should also be noted that P doping enhances the manufacturing process by lowering the temperature at which the glass tube collapses to form a boule from which the fiber can be drawn. A more controllable process results from the lower temperature. In addition, the dopants affect the fiber-induced radiation response as a function of temperature. The recovery rate after gamma irradiation is determined by the type and amount of dopants. Thus it becomes clear that the fiber design must be closely controlled to optimize the performance parameters.

<u>Cable configurations</u> The fibers must be protected from the elements and must be surrounded with an environment that is unchanging. Therefore the fibers are suspended in an enclosure referred to as a cable. The cable protects the fibers from physical elements that would cause deterioration and subsequent degradation of performance or operational failure. The primary goal of the cable design is to provide a relatively stress-free environment for the fiber or fibers. This goal can be achieved in several ways as indicated by the numerous design configurations used by different cable manufacturers.

The fiber is commonly placed in a tube or slot to eliminate any physical stress due to lateral or lineal movement. Figure 1 shows the relative sizes of the fiber strand, the tube, and the spacing between the two. The loose tube or slot design allows the fiber to expand or contract independent of the other elements of the cable. For example, when the cable is pulled through a duct it

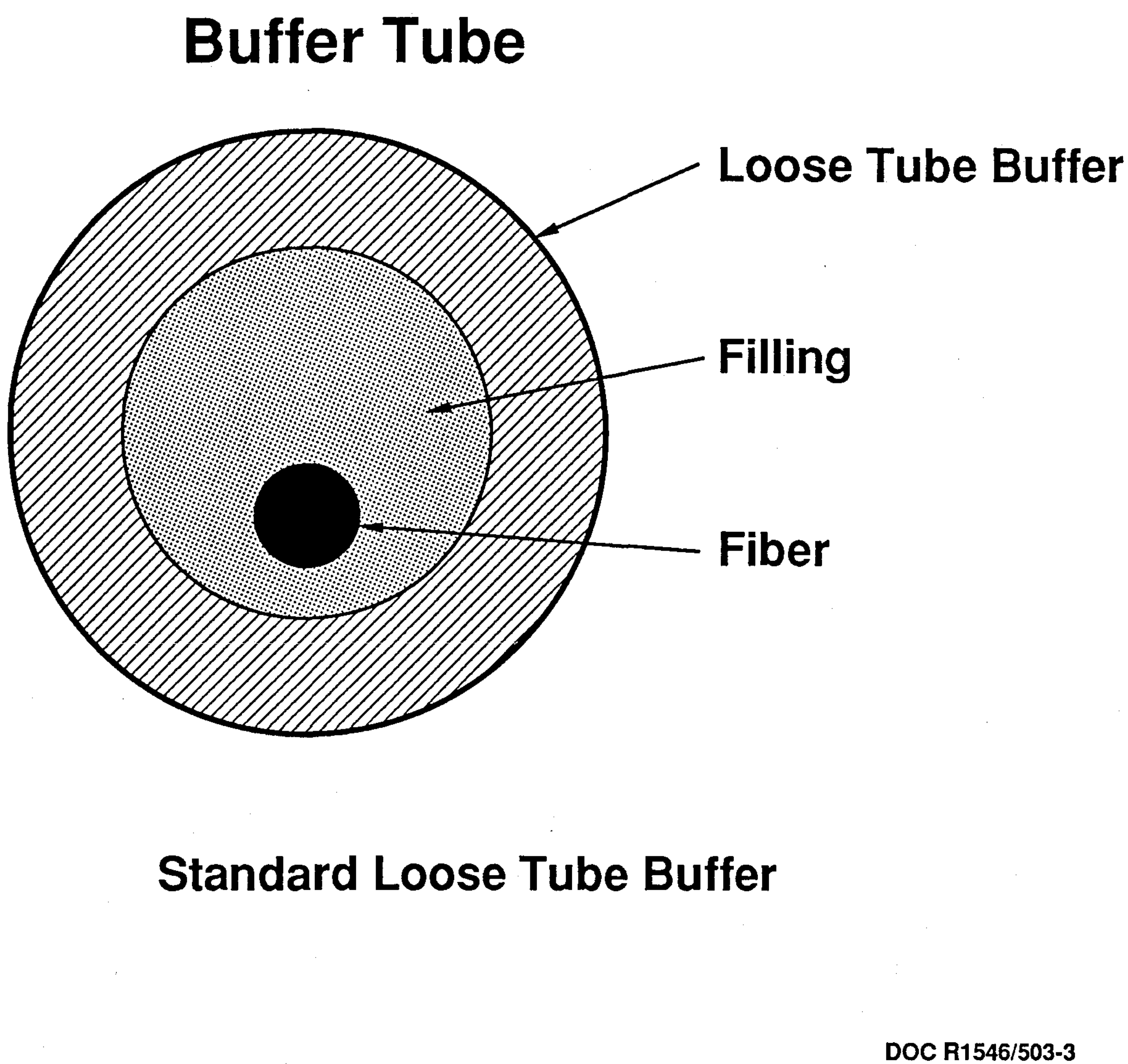


Figure 1. Typical fiber tube configuration.

may stretch--the loose tube design allows this to happen without stress on the fiber because of fiber excess length within the tube. The fiber excess length ranges from 0.1 percent to 0.8 percent. A straight tube will allow about 0.1 percent while a helical tube design will allow up to 0.8 percent of excess fiber length. Figure 2 shows how a straight tube design can accommodate changes in elongation and compression of the cable elements without stress effects on the fiber. The amount of excess fiber length allowable with helical design is greater because the length of the tube is substantially greater as shown in Figure 3.

Figure 4 shows how the channels (tubes) are configured within the cable design. The channels can be either closed tubes or open slots positioned around the central strength member. Open channel (slot) design structure is shown in Figure 5. Strength members are made of metal (steel) or dielectric (e.g., Kevlar) material. In either case, the central strength member is protected by an overcoat to provide a cushion for the channels supporting the fibers.

The open space inside the channel surrounding the fiber is usually filled with a gel material. Two reasons usually are given for using the gel filling: 1) it displaces moisture or chemicals and 2) it forces the fiber to break near the point of stress. In either case the immediate environment around the fiber is preserved.

As an alternate to the tube or slot configuration, some manufacturers use a more closed type of configuration--sometimes referred to as the "tight buffer" design. In this design the fiber has less freedom to float independently of the other cable components. When using this configuration, care must be taken to match the component temperature coefficients of expansion so that the fiber is not stressed when exposed to changes in temperature.

When designing cable with large fiber counts (greater than 18), a version of unit design is commonly used. Figure 6 illustrates a basic unit-type configuration. This configuration will accommodate a number of units--usually a maximum of 18. A second layer of units can be added to increase the capacity of the cable. Depending on the number of fibers required, not all units will be filled with fibers. The unfilled units are replaced with fillers to maintain the symmetry of the cable. Figure 7 shows the use of fillers when there are unfilled units. Of course, the number of filler units will vary depending on the total number of fibers in the cable.

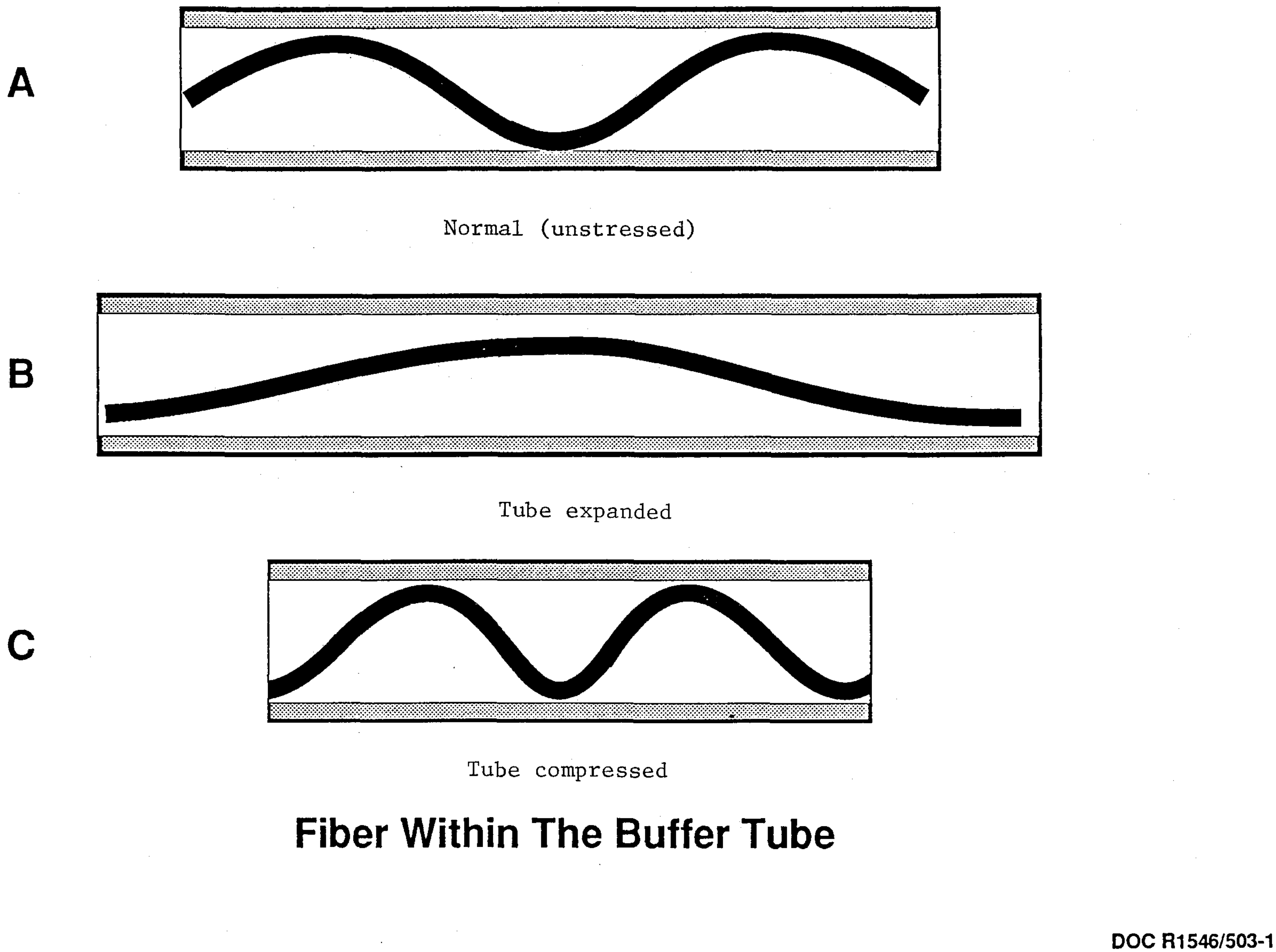


Figure 2. Fiber within a tube during compression and expansion.

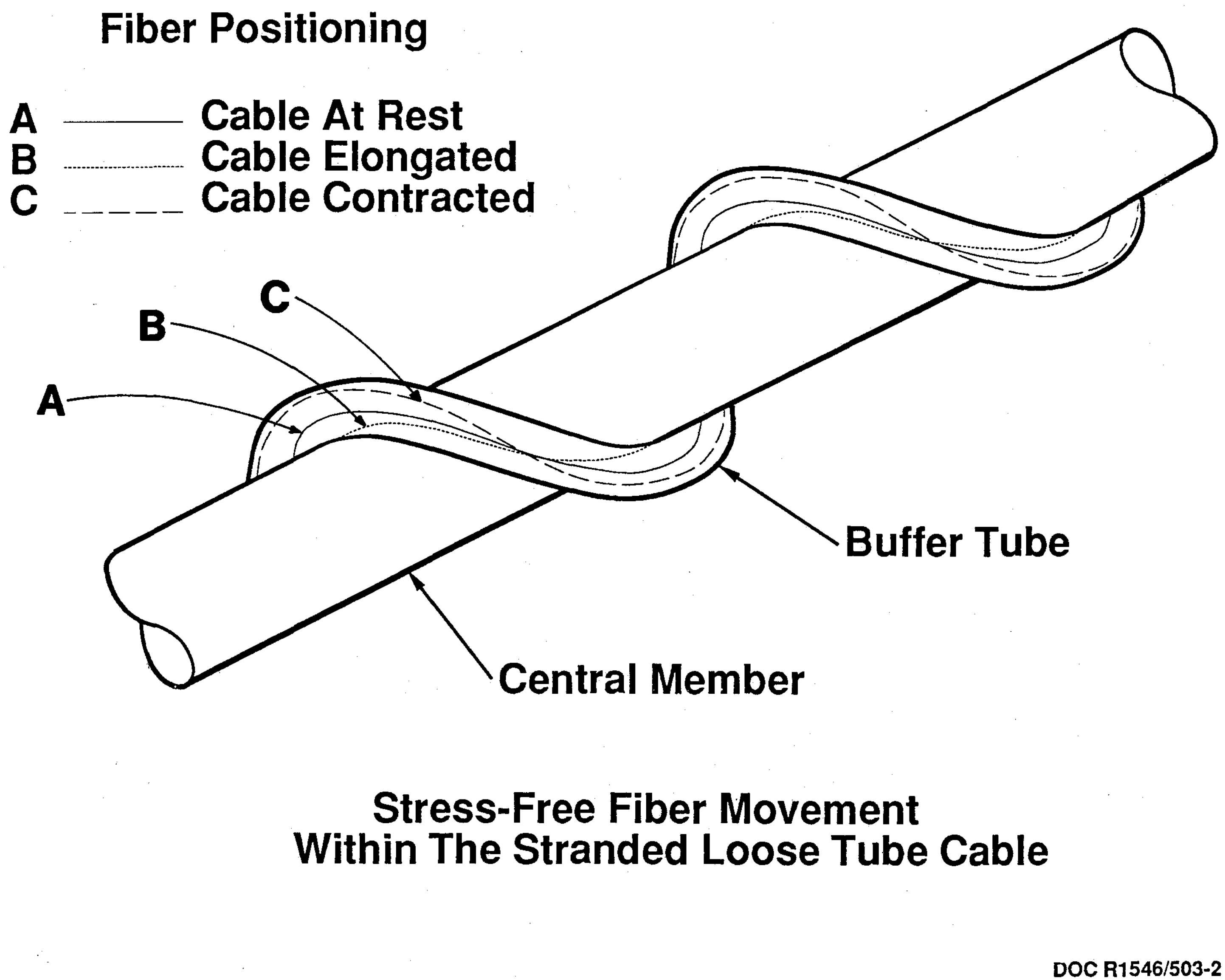
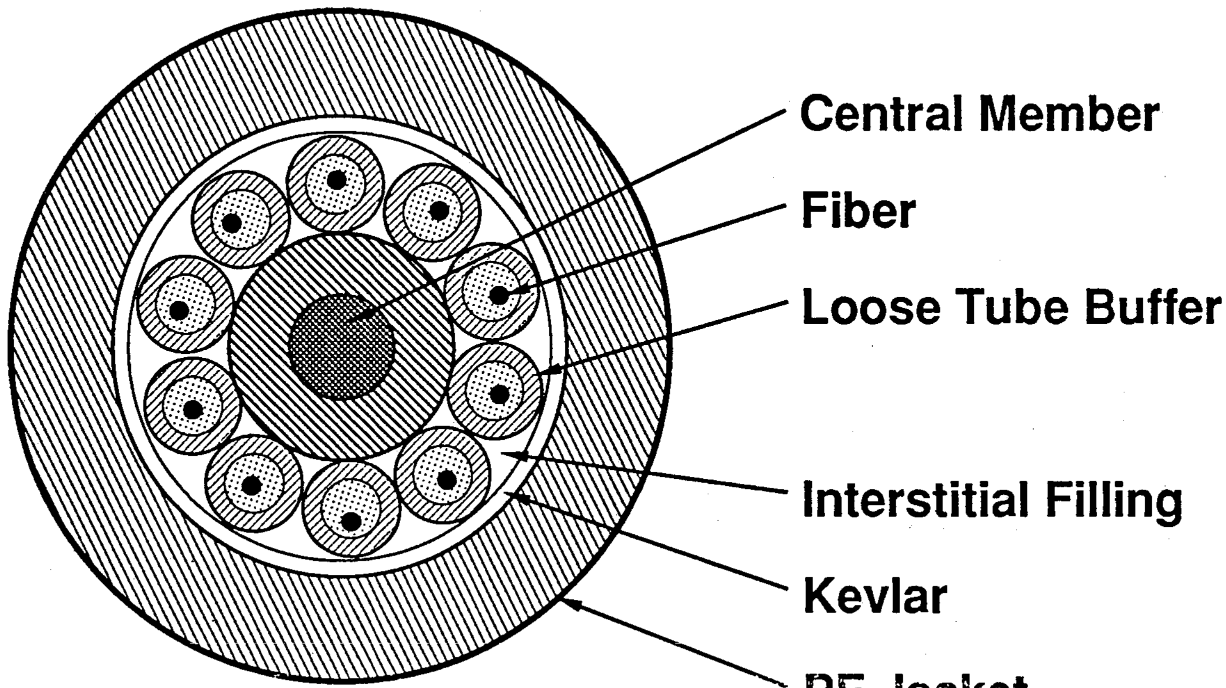


Figure 3. Accommodation of fiber expansion and compression in a helical design.

Stranded Loose Tube Design



Standard Loose Tube Cable
10 Fibers — Single Jacket

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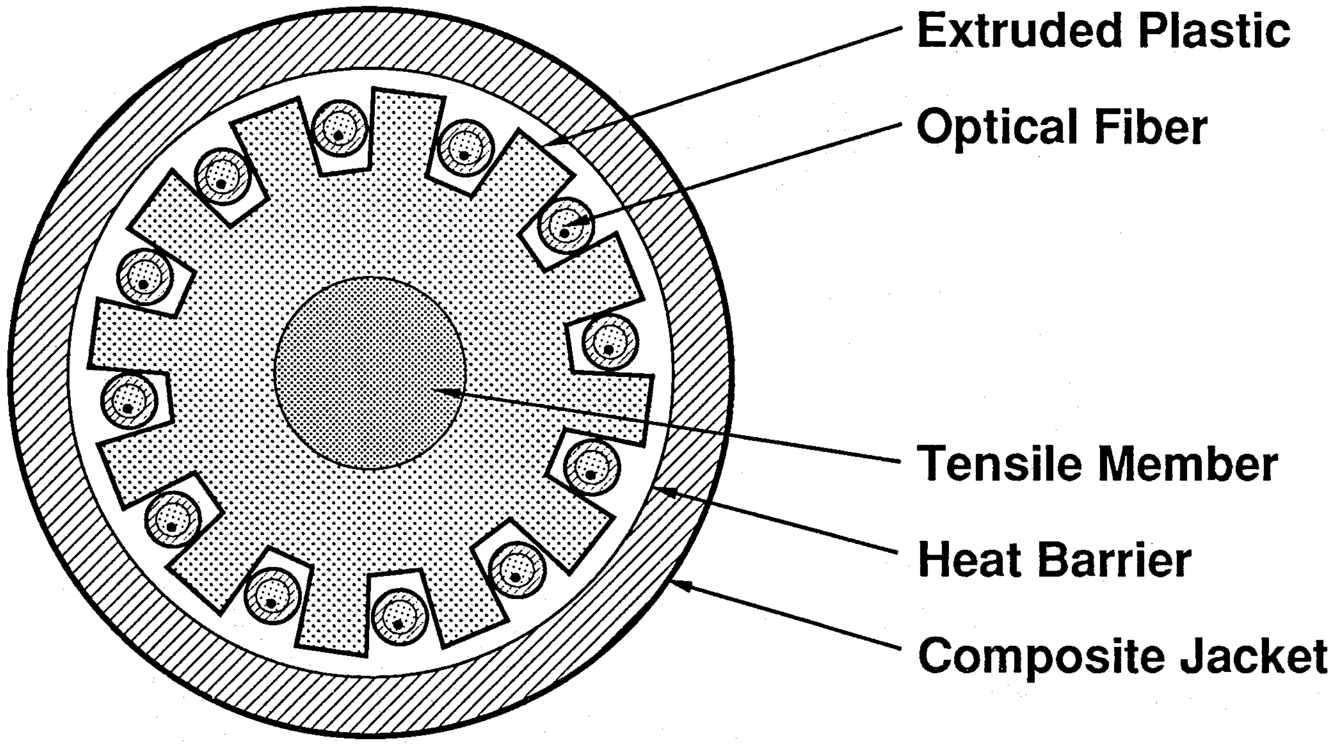
Figure 4. Multiple tubes in cable configuration.



Cross Section of Unit Core Cable

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Figure 5. Cable configuration using open slot design.

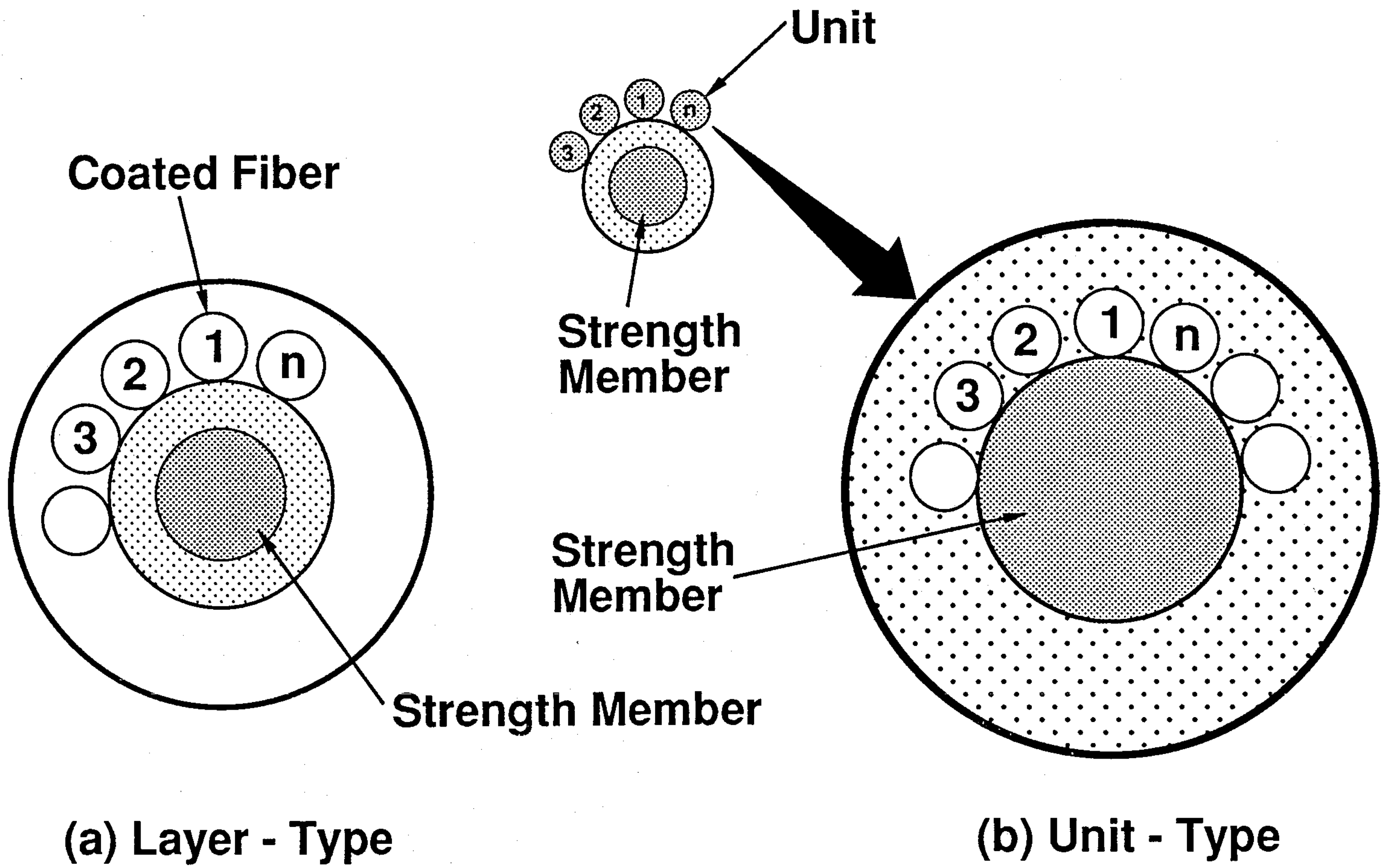

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Figure 6. Cable using "unit design" configuration.

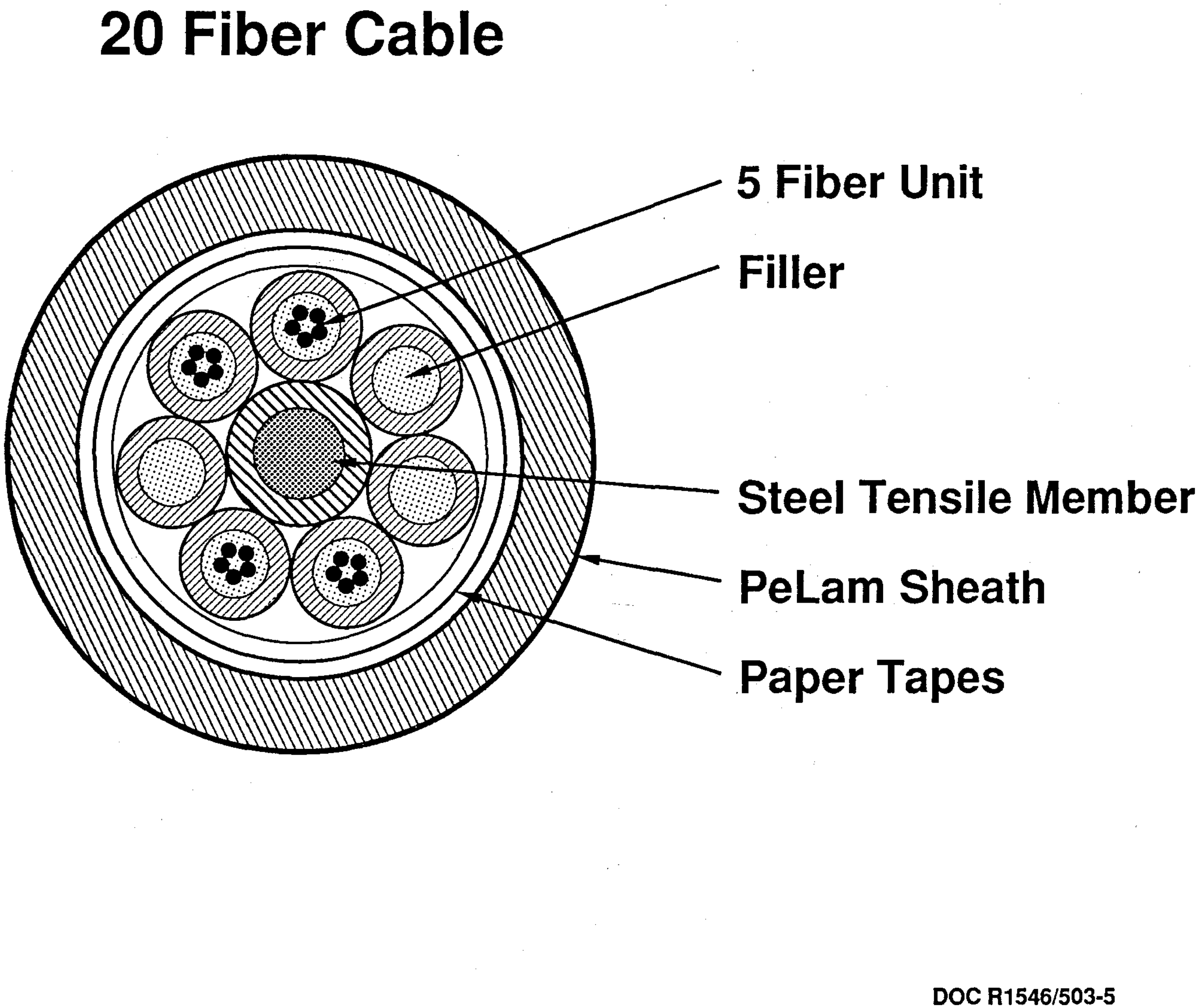

Figure 7. Cable configuration with less than a full complement of fibers.

<u>Central strength member</u> The central element of the cable core generally has two functions:

- to provide mechanical strength in the production stage and eventually in the final cable
- to provide a buffer against environmental temperature changes that cause compression and tension effects due to contraction of plastic coatings (CCITT, 1985)

A central strength element is chosen on the basis of the following parameters (CCITT, 1985):

- tensile modulus
- coefficient of thermal expansion
- compression modulus

Because of the brittle nature, optical fibers are easily broken. Therefore, one or more strength members should be incorporated into a cable structure designed to carry the tensile load associated with installation. The strength member should be designed to minimize the axial and longitudinal compression effects during and after installation as well. Longer term effects, such as those produced by the thermal dynamics of the cable system, should also be considered when designing or specifying the strength member(s).

The backbone of the cable is the central strength member. Optical fibers are very sensitive to mechanical stress and must be protected. Functional parameters of the fiber can be drastically affected by the strain placed on the fiber by the components of the cable. The central strength member provides both longitudinal (axial tension or compression) and transverse (sidewise movement) stability of the structure around the fiber. Bending, torsion, radial pressure, elongation, and axial compression all affect the fiber transmission losses.

The central strength member can be made of either metallic or nonmetallic material. Metallic materials commonly used are steel or stainless steel and aluminum. Nonmetallic strength members are commonly made of fiber reinforced plastic or glass fibers. An analysis of the cable's thermal behavior is important when selecting a material for the central strength member. Expansions and contractions of components of the cable can cause stress of the fibers. Matching the thermal characteristics of the components is a necessity, especially at low temperatures. A buffer layer is used by some manufacturers to allow the layers to slip relative to each other in the event of differences in thermal expansion. Several configurations for implementation of a central strength member are shown in Figures 8 through 10.

An alternative to the central strength member is required when using a configuration such as a fiber ribbon stack. The ribbon stack occupies the center of the cable precluding use of the central strength member. In this case the strength members are distributed in the outer layers of the cable. Figure 11 shows a distributed strength member configuration design when incorporating the ribbon cable stack unit.

Materials that are popular for construction of central strength members because of their Young's moduli are steel wires, plastic monofilaments, multiple-textile fibers, glass fibers, and carbon fibers (Kao, 1982). Some significant features of these materials are summarized in the following list:

1. Steel wires. These have been widely used in conventional cables for armoring and longitudinal reinforcement. Various grades are available with tensile strengths to break, ranging from 540 to nearly 3100 MN (Meganewtons)/m^2. All have the same Young's modulus (19.3 X 10^4 MN/m^2), and the choice is guided by the preference for a high strain and yield compatible with the cable design. The main disadvantage of steel is its high specific gravity, which adds substantially to the cable weight. Futhermore, it cannot be used if a nonmetallic cable structure is required.

2. Plastic monofilaments. These are available commercially in several basic materials. Specially processed polyester filament, which combines a high elasticity modulus (1.6 X 10^4 MN/m^2) with good dimensional stability at elevated temperatures and a smooth cylindrical surface, is available.

3. Textile fibers. Commercial forms normally consist of assemblies of many small-diameter fibers laid up in twisted or parallel configurations. Typical examples in conventional cables are polyamides (nylon) and polyethylene terephthalate (Terylene, Dacron, etc.) with elasticity moduli which may be as high as 1.5 X 10^4 MN/m^2 for the individual fibers. Because of the loose packing of these individual fibers, they are resilient in a transverse direction and are useful as cable fillers and binders as well as providing improved tensile properties in optical fiber cables. An exceptional member in this class that has been widely employed in optical cable is Kevlar, which, coupled with its specific gravity of 1.45, gives this fiber an effective strength-to-weight ratio nearly four times that of steel. Commercial forms of Kevlar suitable for cable reinforcement consist of composites of large numbers of single filaments assembled by twisting, stranding, plaiting, and so on, and/or resin bonding.

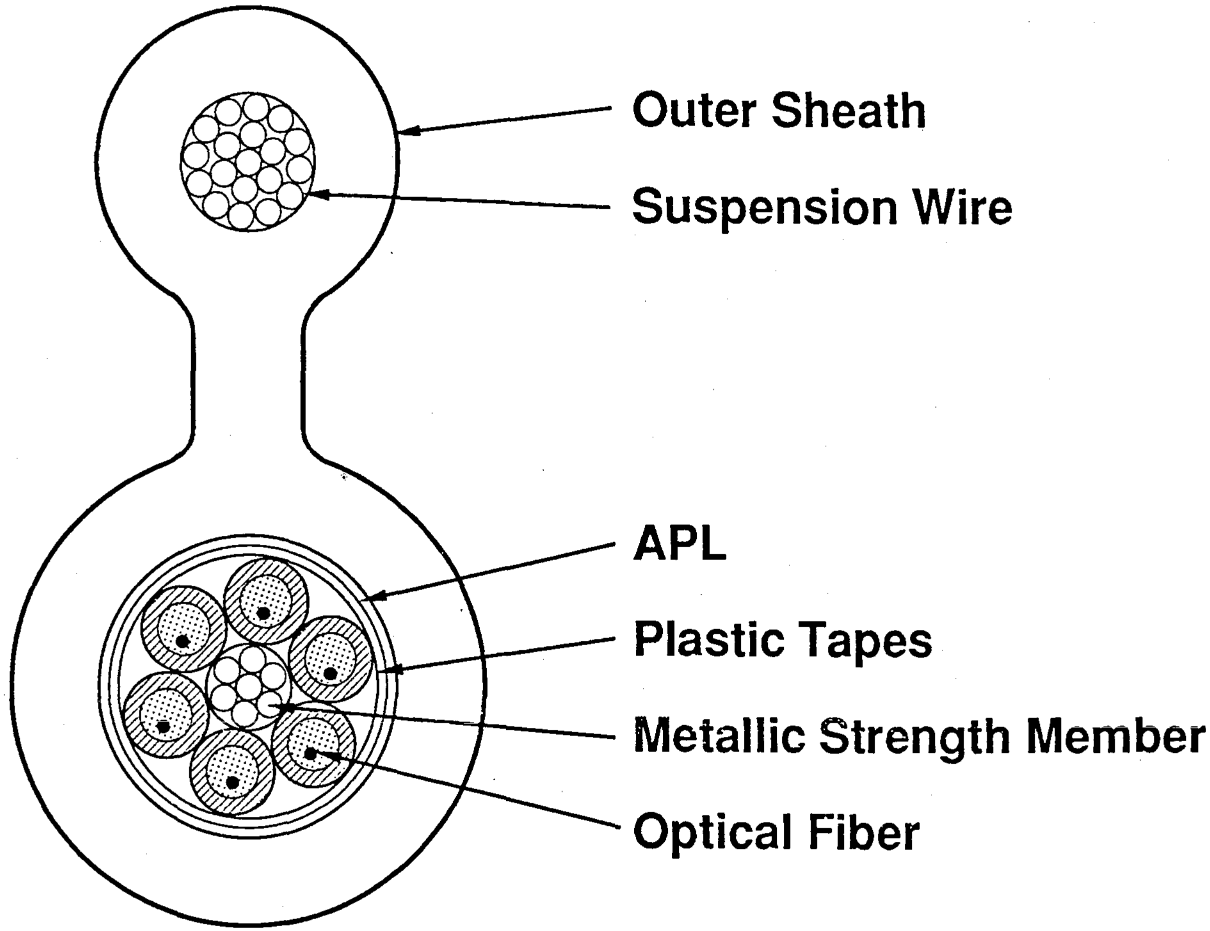

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Figure 8. Central strength member in an aerial cable configuration.

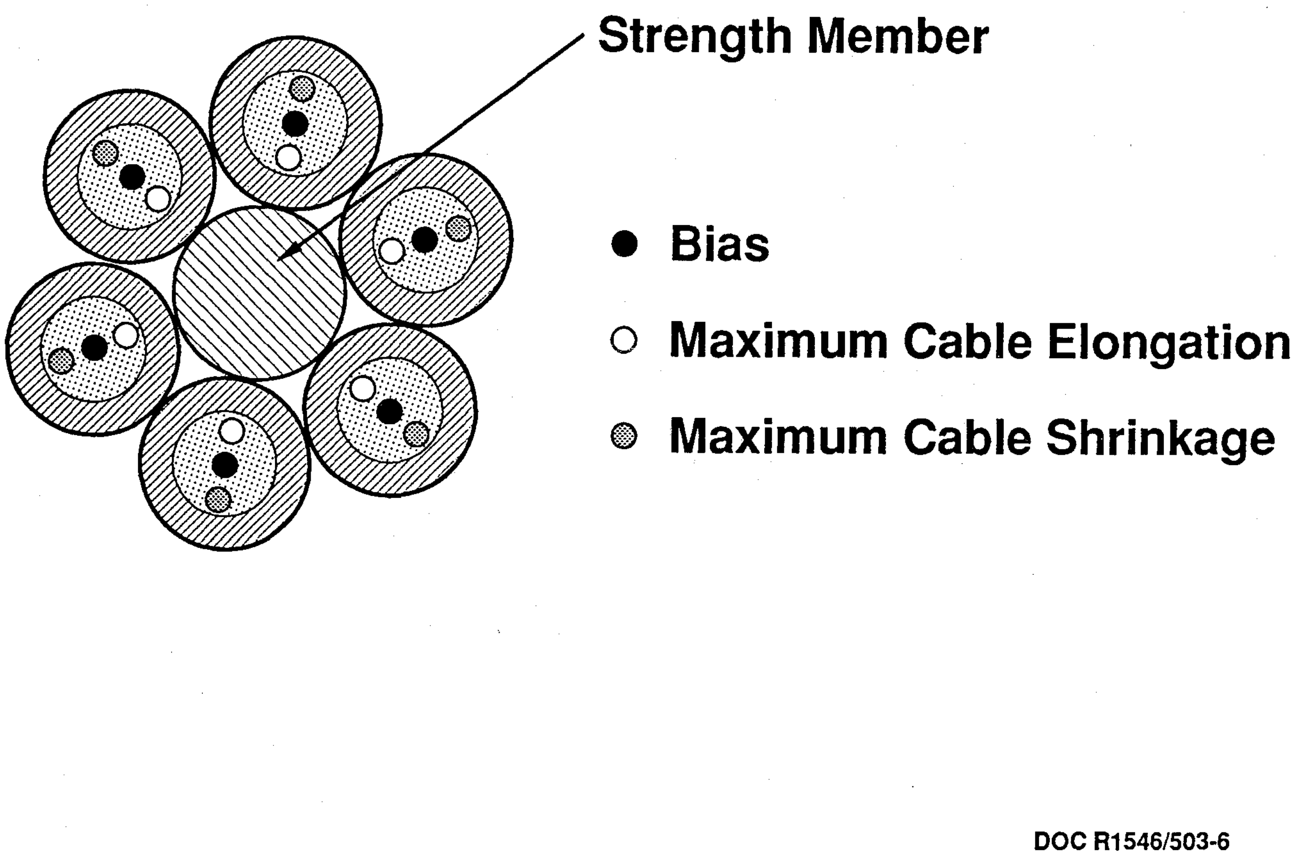

Figure 9. Central strength member with loose tube configuration.

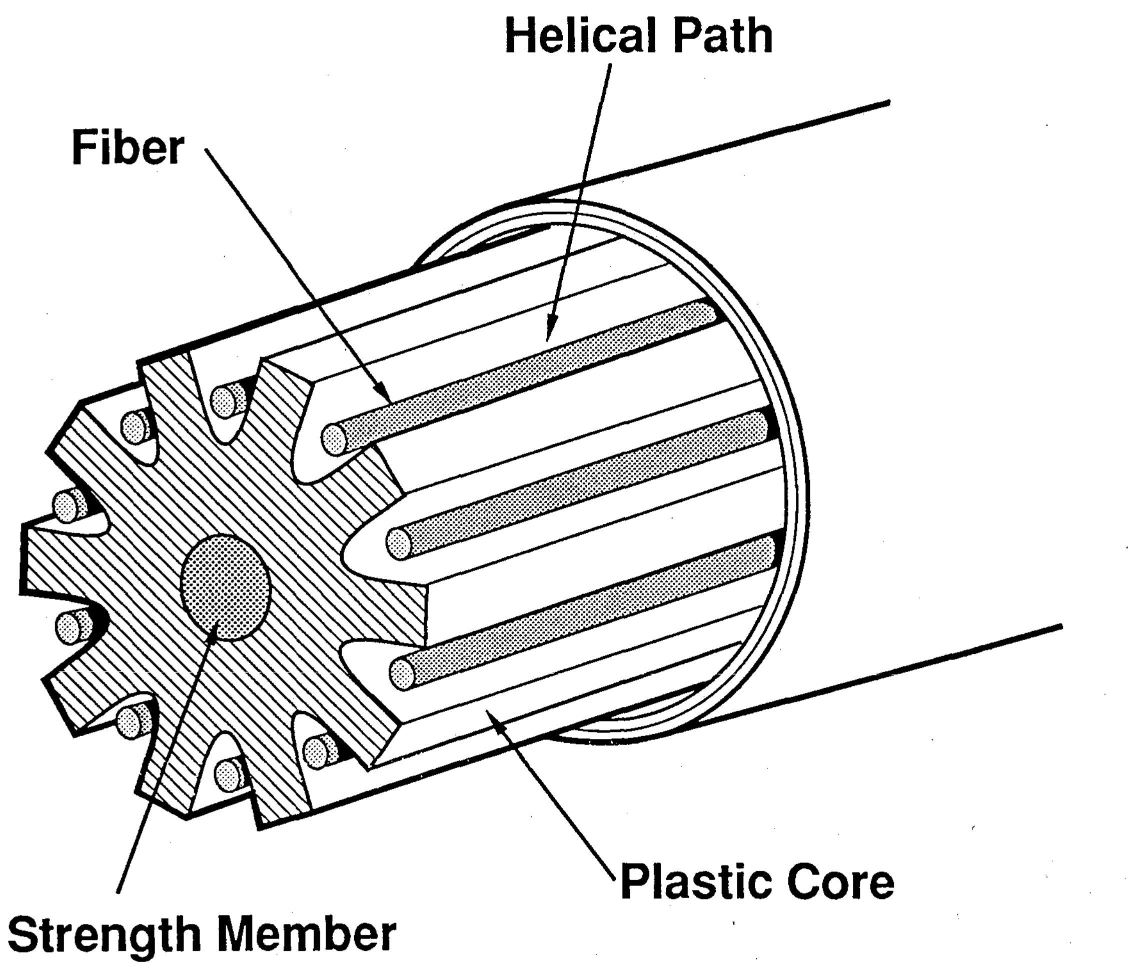

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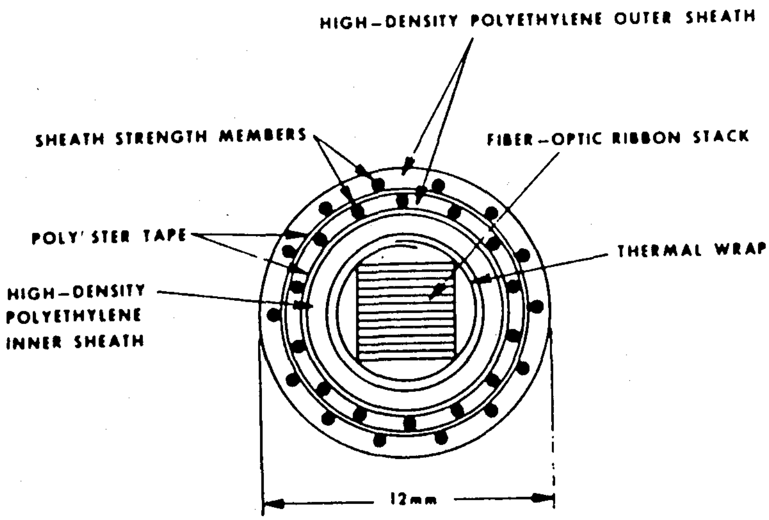
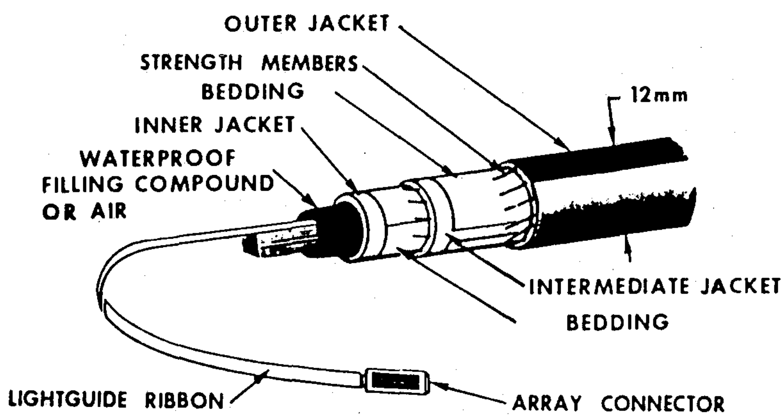
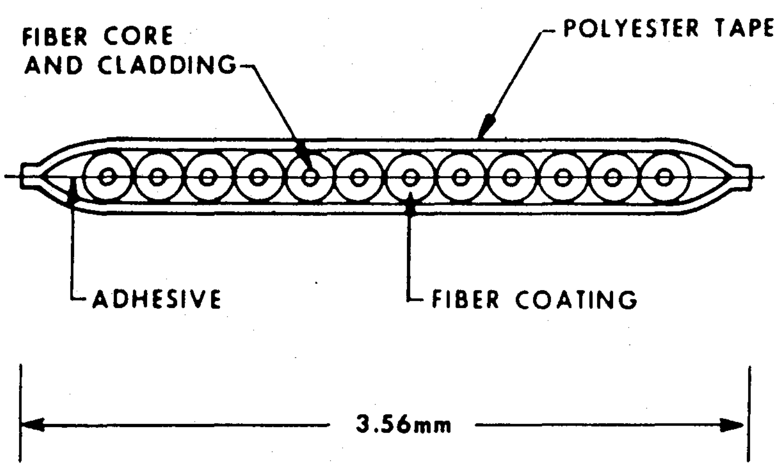
Figure 10. Central strength member integrated with a slotted core design.



a. Crossply cable cross-section



b. Crossply cable



c. Crossection of a ribbon

Figure 11. Ribbon cable stack unit configuration (after CCITT, 1985).

4. Glass fibers. For some applications, the optical fiber waveguides may supply sufficient tensile strength by themselves. Additional nonactive fibers can be used if higher strength is required. The elasticity modulus is high, typically 9 X 10^4 MN/m^2.

5. Carbon fibers. This material has been successfully employed in rigid and semirigid plastic or metal composites and has a modulus of up to 20 X 10^4 MN/m^2 in single filaments.

Relevant properties of these materials, with the exception of carbon fiber, are summarized in Table 5.

While mechanical properties are important, cost is also an important factor in determining the type material used for the central strength member. As can be seen in Table 5, a price must be paid for the advantages of some of the materials. But, depending upon the requirements of a particular installation, the cost may not be the prime determining factor.

Cable sheath The cable sheath protects the cable core from external mechanical damage. The following characteristics should be considered when designing a sheath (CCITT, 1985):

- climatic performance
- airtightness, resistance to moisture penetration
- mechanical stability (bending, torsion, radial pressure, tension, abrasion, etc.)
- chemical resistance
- small diameter, light weight
- resistance to fire
- lightning and electromagnetic pulse (EMP) susceptibility
- gamma radiation shielding performance

Emphasis must be placed on one or more of the attributes depending on the environment in which the cable is to be installed. For example, if the cable is to be installed as an aerial installation, the primary cause for deterioration will probably be from exposure to ultraviolet rays. If the cable is to be installed underground, the primary cause for deterioration would

Table 5. Properties of Strength Member Materials (Kao, 1982)

Materials	Relative Cost	Specific Gravity	Young's Modulus, MN/m^2	Tensile Strength, MN/m^2	Strain at Break, %	Normalized Modulus-to-Weight Ratio	Expansion Coefficient
Steel Wire	Low	7.86	19.3×10^4	$5–30 \times 10^2$	2–25	1.0	1.2×10^{-5}
Polyester monofilament	Low	1.38	$1.4–1.6 \times 10^4$	$7–9 \times 10^2$	6–15	0.3	1.3×10^{-4}†
Nylon yarn	Low	1.14	$0.4–0.8 \times 10^4$	$5–7 \times 10^2$	20–50	0.3	7.2×10^{-5}
Terelyne yarn	Low	1.38	$1.2–1.5 \times 10^4$	$5–7 \times 10^2$	15–30	0.3	1.4×10^{-5}
Kevlar-49 fiber	High	1.45	13×10^4	30×10^2	2	3.5	-1.1×10^{-6}*
Kevlar-29 fiber	High	1.44	6×10^4	30×10^2	4	1.6	-1.1×10^{-6}*
S-glass fiber	High	2.48	9×10^4	30×10^2	3	1.4	1.9×10^{-6}

† Temperature range +5–150°C.
* Temperature range 0–100°C.

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likely be from moisture. When the cable is buried underground there is a major threat from rodents (gophers, rats, squirrels, etc.). This threat requires a very durable sheath.

The sheath acts as part of the strength member, especially if the cable is pulled using a pulling mechanism that is attached to the outer shell of the cable. A metal stranded sheath adds a great deal of tensile strength to the cable as well as protection from abrasion or rodent attacks. When using a metal sheath, a layer of synthetic material is added on either side of the metal layer. This soft material protects against abrasion from the rough surface of the metal layer.

The sheath thickness is a factor due to possible buckling when the cable is coiled or bent while being installed. In most applications the size (diameter) is a consideration--therefore the sheath thickness should be as thin as possible while providing the necessary protection. The size issue is especially important in applications for which fiber optic cable is attractive because of its light weight and small diameter.

<u>Optical fiber splices and splice closures</u> Optical fibers must be spliced when the distance between regenerator stations exceeds the continuous cable length that is practical to use during installation. Continuous cable lengths in excess of 10 km are possible, however not always practical because of the terrain encountered which precludes transporting a large reel of cable along the installation route. When cables have to be spliced, there are two primary goals when making the connection:

1. minimizing the loss effected at the splice
2. making the splice as durable as possible (Georgopoulos, 1982; CCITT, 1985)

In simple terms, the magnitude of loss is a function of the alignment of the two ends of the fiber and length of gap between the ends.

Two common techniques are used to splice singlemode fibers: mechanical splicing and fusion splicing (Georgopoulos, 1982). Mechanical splicing permits easy, permanent splices through use of a jig that holds the two fiber ends together while the joint is filled with epoxy. The epoxy then maintains the alignment of the fibers--even with exposure to vibration or other adverse conditions. The splice alignment jig must allow for positioning of fibers to obtain maximum signal transfer across the splice. This is done with an instrument that can monitor the signal level while aligning the fibers. Fusion splicing is performed in a similar manner using a jig to hold the fibers in accurate alignment while the splice is completed. The splice is completed by a "hot" process that fuses (melts) the two ends together by drawing an electric arc across the gap. The process has been developed to fuse several fibers simultaneously and consequently speeding the splicing process for multifiber cables.

Whether a mechanical or fusion splice is used, the key to the integrity of the splice is the accuracy of alignment while the splice is made. Figure 12 shows the three types of mechanical misalignment of fiber ends during splicing. End finish of the fibers is a very important factor--and can be minimized by careful cutting techniques and fiber end preparation procedures. The losses due to lateral and longitudinal misalignment, illustrated in Figure 12, are referred to as extrinsic losses. The loss due to lateral or axial misalignment (Figure 12a) is given by (Georgopoulos, 1982)

$$dB = 10 \log[1-2L/(\pi D)(1-\delta^2/D^2)^{.5} - (2/\pi)\sin^{-1}(\delta/D)]. \qquad (1)$$

End separation (longitudinal) loss (Figure 12b) is a function of numerical aperture (NA) and gap distance--where the numerical aperture describes the efficiency of light transfer from the transmitting end to the receiving end. The loss due to end separation and numerical aperture variation is given by

$$dB = 10 \log [(D/2)/(D/2+ g \tan\theta_c)] \qquad (2)$$

$$\theta_c = \sin^{-1}(NA/n) \quad \theta \text{ is defined in Figure 12c.} \qquad (3)$$

An angular loss or axial tilt (Figure 12c) is also a function of numerical aperture since gap distance must accompany angular misalignment. From a practical standpoint, the angular misalignment results from bevel due to inaccuracy of end finish.

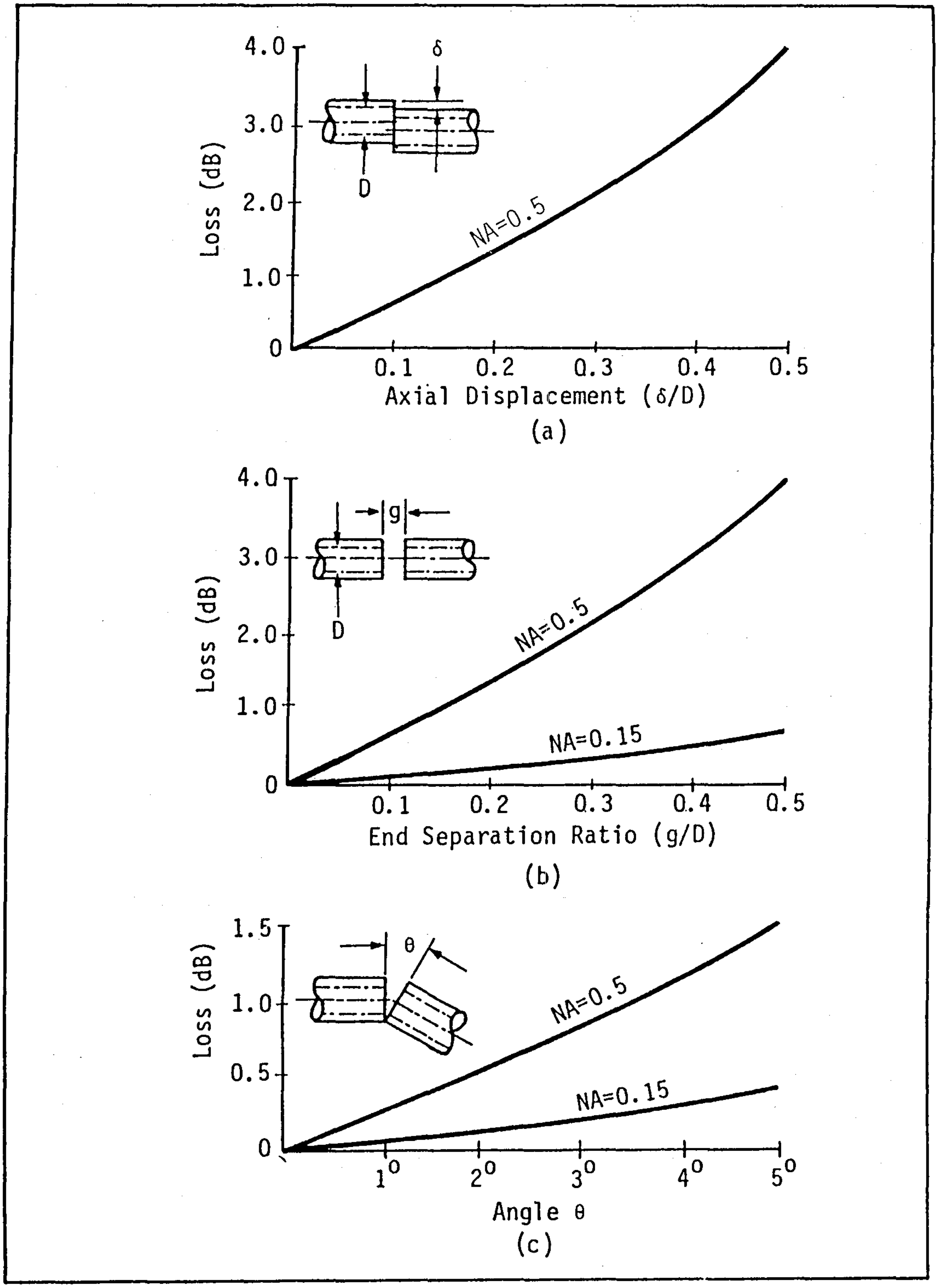


Figure 12. Losses in fiber optic connections.

Joint losses that are a result of the inherent differences of the two fibers being joined are referred to as intrinsic losses. Differences in radius, numerical aperture, and index of refraction are three parameters that contribute to the intrinsic losses. The loss due to differences in diameter of the fiber cores is defined by

$$dB = 20 \log \left\{ \frac{D_r}{D_t} \right\} D_r > D_t \tag{4}$$

and

$$dB = 20 \log \left\{ \frac{NA_r}{NA_t} \right\} NA_r > NA_t , \tag{5}$$

where the subscripts r and t refer to receiving and transmitting ends, respectively. In addition, the differences in ellipticity and concentricity of the fiber cores are contributors to this loss, but are more difficult to quantify (CCITT, 1985).

The Fresnel loss or reflection loss is also considered intrinsic (Georgopoulos, 1982). It occurs due to differences in refractive indices at the fiber-to-fiber interface. For light propagating through the glass-air-glass interface, the loss is given by

$$dB = 20 \log (1-[(n_g-n_a)/(n_g+n_a)]), \tag{6}$$

where n_a is the index of refraction for air and n_g is the index of refraction for glass.

The sensitivity to transverse offset (lateral or angular) is much greater on an absolute scale than longitudinal offset. Figure 13 gives an example of typical levels of loss due to transverse offset (CCITT, 1985) for single mode fibers.

The extrinsic and intrinsic losses are the lumped losses at the splice--total loss of a cable installation should include the distributed loss of the cable as measured or defined by the manufacturer. The total of losses for a span can then be calculated and the link-loss budget can be projected. A

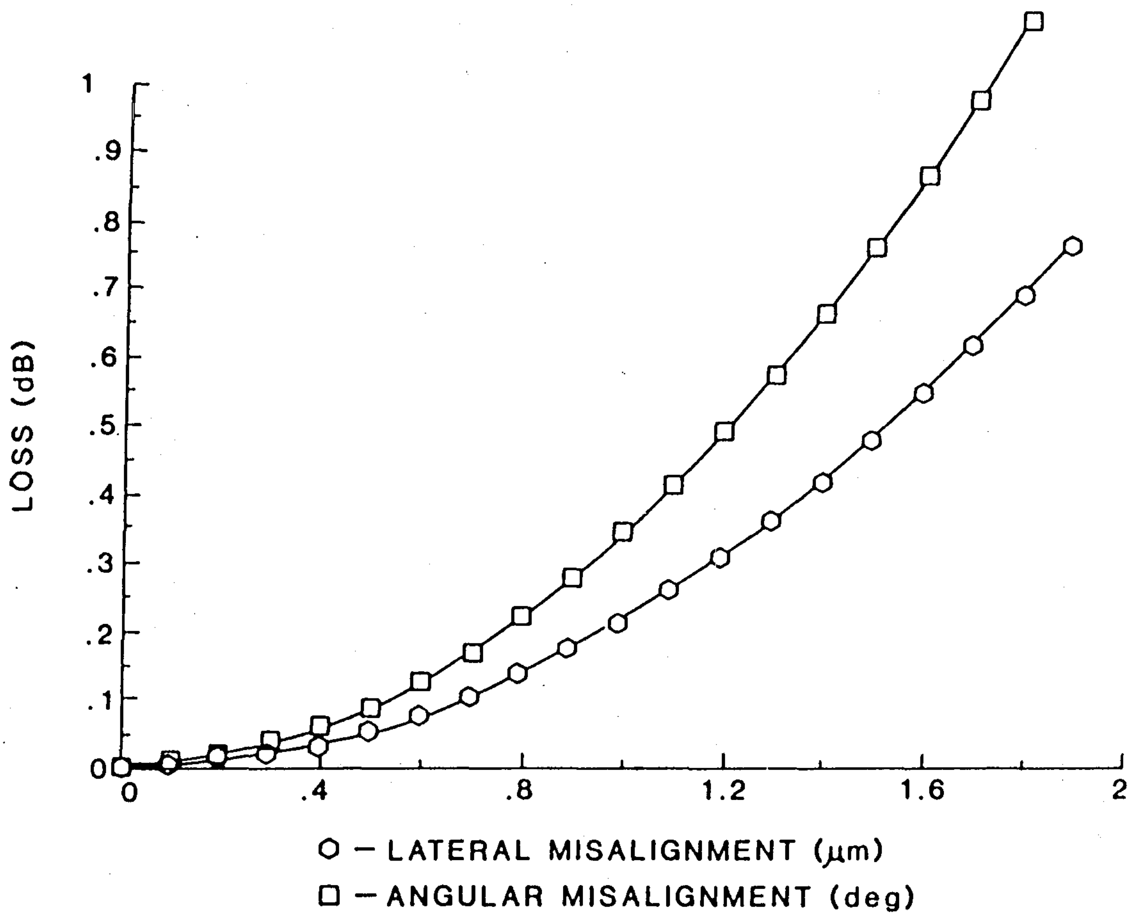


Figure 13. Loss due to misalignment (after CCITT, 1985).

loss design margin in excess of the total losses will be required for sustained operation under limited stress.

Table 6 is a summary of the extrinsic and intrinsic losses that have been discussed. The loss categories represent only the major contributors--there are numerous minor contributors that are not mentioned in this report.

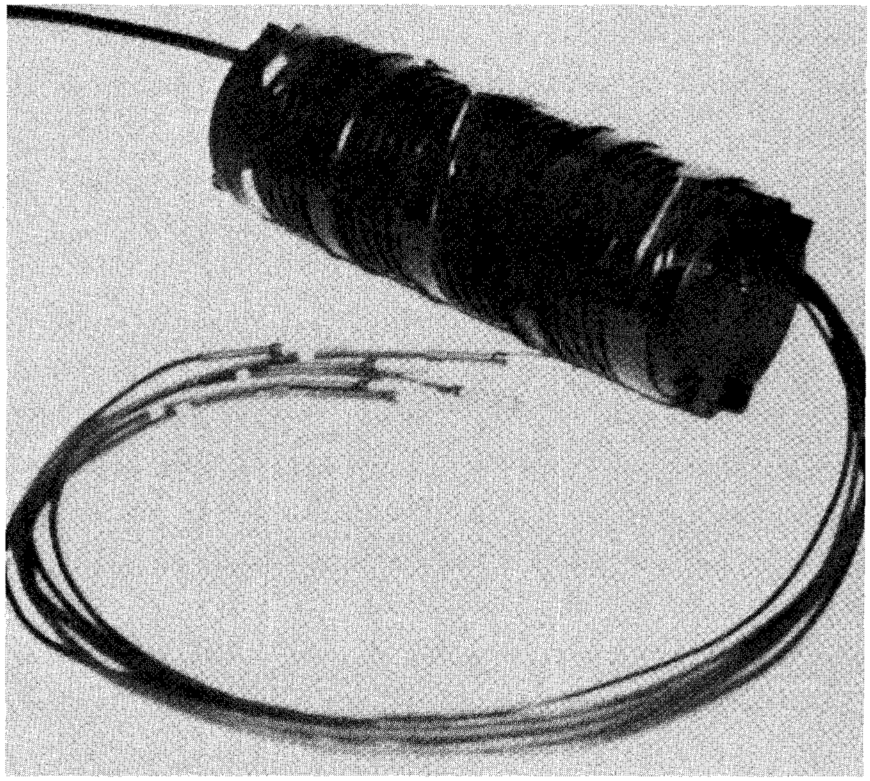
Cable splicing is usually accomplished with a permanent connection rather than a connector because the connector joint is typically more lossy than a well-made permanent joint. The splice, however, is not well protected. A splice closure is used to provide environmental protection for the splices. The finished splices are organized and supported by a splice tray--and the closure then encloses the entire assembly. Splice closures are moisture tight, moisture resistant, and fabricated of durable plastic material that offers protection from external mechanical stress. Figure 14 illustrates a typical splice closure that is used for underground splices. For additional protection, the closure can be filled with a filling compound to block out moisture or chemicals present in the environment around the splice closure.

Table 6. Fiber Optic Splice Loss Factors

Extrinsic splice losses
• lateral offset • longitudinal offset • axial tilt • fiber end quality
Intrinsic splice losses
• differences in core and cladding diameters • ellipticity and concentricity of the fiber ends • Fresnel loss

3.1.2 Cable environmental factors

The types of environmental factors to which the cable will be exposed are determined by the placement methods used to install the cable. The cable location (e.g., above ground or below ground) exposes the cable to different types of stress. The environment can be controlled, to a limited extent, by providing protection for the cable.



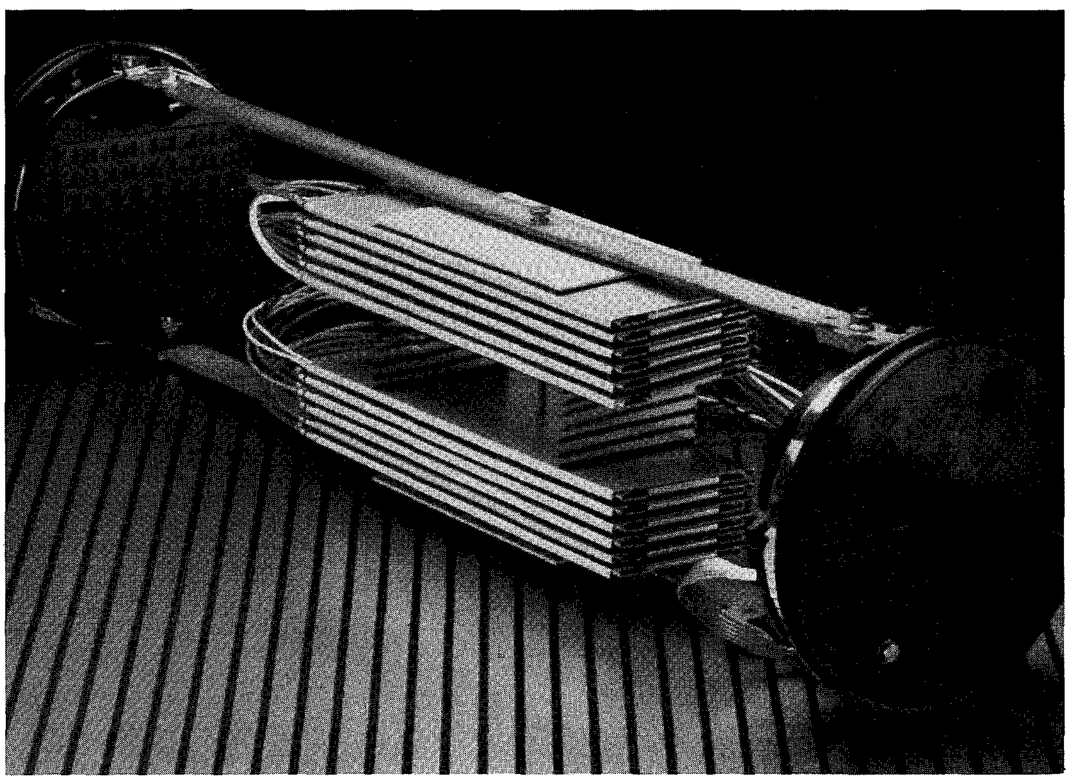


Figure 14. Typical splice closures.

The following discussion will attempt to summarize the environmental factors to which the cable will be exposed when certain types of installation methods are used. By defining the specific types of stress, the method of protection required to counter that stress can be designed, developed, and implemented.

Aerial installation of cable The most basic, and in some ways the most primitive, method of supporting fiber optic cable is by suspension from poles from point-to-point of service. This method of installation consists of using poles dedicated to the fiber optic service or parasiting the fiber optic cable on a pole route constructed for another use. The cable can be attached directly to the pole or attached to an existing cable carrying another type of service along the route.

When the cable is attached directly to the pole, a nonmetallic messenger is sometimes used to support the cable from pole to pole. Some designs include the messenger as part of the cable assembly as a central strength member, a distributed strength member, or as a parallel attached suspension component. Figure 15 illustrates an assembly that incorporates a suspension wire as part of the manufactured unit. While Figure 15 shows the suspension element as a metallic component, this element can be a nonmetallic component if so desired.

When the cable is lashed to another element, care must be taken to avoid stressing the cable by overtensioning or creating stress due to mismatches in thermal characteristics. For example, frequently fiber optic cables are supported by wrapping around the phase or neutral wire of high voltage power lines. This method of support is possible only if an all-dielectric cable is used (e.g., cable design that is devoid of metallic components).

The mechanical stress on an optical fiber is usually less when performing aerial cable installations than when installing underground (CCITT, 1985). The following factors must be considered to maintain a stress free environment for the cable installation.

1. Physical suspension of the cable (pole route)

   - Poles must be of sufficient height, mass, and strength to properly support the cable.

   - Poles that have deteriorated with time due to natural elements must be replaced as their strength falls below that sufficient to provide proper support.

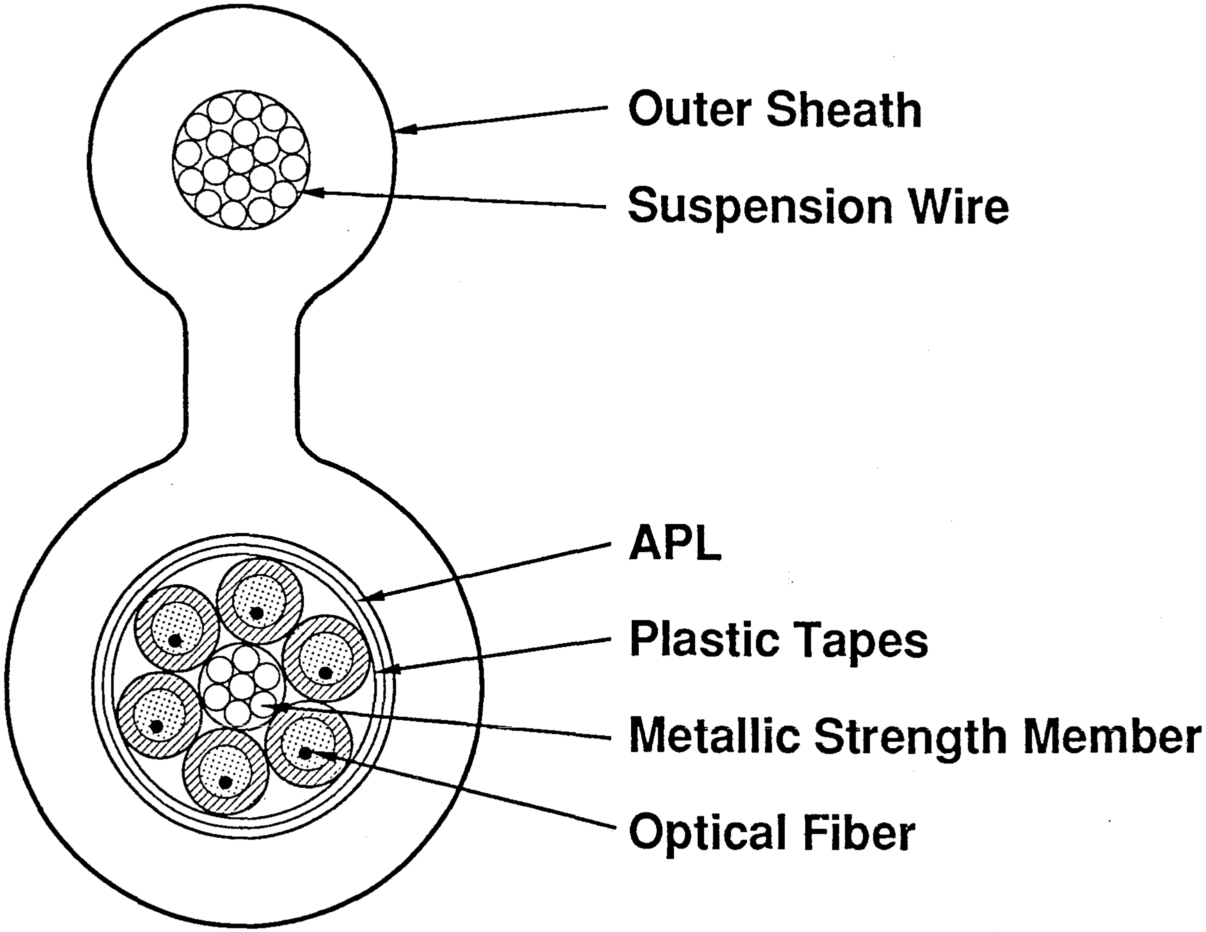


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Figure 15. Cable with a metallic suspension element.

- If there is a good probability that other cables will be placed on the same pole route, the fiber optic cable should be placed as high as possible to avoid damage from subsequent installation.

- Pole span lengths should be selected such that the cable tension limits are not exceeded. An example of the guidelines necessary for this analysis is given in Tables 7 and 8 (AT&T, 1982). As illustrated in Table 8, temperature plays a role in determining the tension.

- Each pole should be properly stayed and all guy wires properly anchored to prevent movements that could cause damage to the cable or the mounting hardware.

2. Stress due to wind, ice, and temperature variation

   - In an effort to reduce these effects on fiber optic cable, many of the same techniques used for conventional cables can be used.

     The design of the mechanical system should include enough margin to prevent damage during typical storm conditions. Use of the line and how critical continuous service is, will determine the design margin as illustrated in Table 9 (AT&T, 1982). A least risk design favors lashing the cable to a pretensioned messenger. The messenger can be metallic or nonmetallic as specified in the application.

   - Fiber optic cables are usually smaller and lighter than their copper counterparts and the problems associated with wind, ice, and temperature will be fewer. Proper analysis during design is necessary to avoid overstressing the cable. Severity of storms and especially the effects of ice vary across the Nation as shown in Figure 16 (AT&T, 1982). The design based on pole loading must be performed with these data in mind.

3. Protection from rodents

   - The most effective deterrent to rodent damage is fabrication using a tough material. Use of an armored cable is most effective; however, some plastic materials are also effective.

   - The use of a cable with sufficient diameter to exceed the incisor span of the rodent's mouth is also an option that has been shown to be effective in tests (see Section 4.2).

Buried cable Placing cable underground has become the preferred method of installation for the following reasons:

Table 7. Strength of Galvanized Suspension Strand (after AT&T, 1982)

Size (M=1000)	Breaking Strength (Lb)	Diameter (In.)	Weight (Lb/Ft)
2.2M	2400	3/16	0.077
6.0M	6000	5/16	0.225
6.6M	6650	1/4	0.121
10.0M	11500	3/8	0.270
16.0M	18000	7/16	0.390
25.0M	25000	1/2	0.510

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Table 8. Stringing Tension Guidelines for Suspension Strand (after AT&T, 1982)

Strand M=1000	Span Length (Ft)	Stringing Tension (Lb) at Temperature (°F)					
		0°	20°	40°	60°	80°	100°
6M	Up to 250	1550	1400	1250	1100	900	825
	250-450	1475	1350	1225	1100	1000	900
	Over 450	1375	1275	1175	1100	1025	950
6.6M	Up to 250	900	800	700	600	500	425
	250-450	850	750	675	600	525	475
	Over 450	775	700	650	600	550	525
10M	Up to 400	2675	2475	2275	2100	1900	1725
	Over 500	2600	2425	2250	2100	1925	1800
16M	Any	4425	4150	3875	3600	3325	3075
25M	Any	9125	8800	8400	8000	7625	7250

Table 9. Storm Loading Stress Design Guidelines (after AT&T, 1982)

Class of Line	Description*	Design Stress for Transverse Storm Loading (% of Max. Strength)	
		At Installation	At Replacement
AA	More than 180 toll circuits or 1800 exchange pairs, Priority I defense circuits.	25	37.5
JB	Both communication circuits and power circuits of NESC Grade B construction.	25	37.5
A	100-180 toll circuits or 1000-1800 exchange pairs, Priority II defense circuits.	40	60
JC	Both communication circuits and power circuits of NESC Grade C construction.	50†	75
B	Fewer than 100 toll circuits or 400-1000 exhange pairs, Priority III defense circuits.	60	90
C	25-400 exchange pairs only.	70	105
R	Fewer than 25 exchange pairs, one 6M or lesser strand, two multiple line wires, or one crossarm of open wire.	80	120

* One toll circuit is equivalent to 10 exchange pairs. For broadband circuits, 4 kHz is equivalent to one toll circuit, e.g., one 50 kHz circuit equals 12-1/2 toll circuits.

† 37.5 at railroad crossings.

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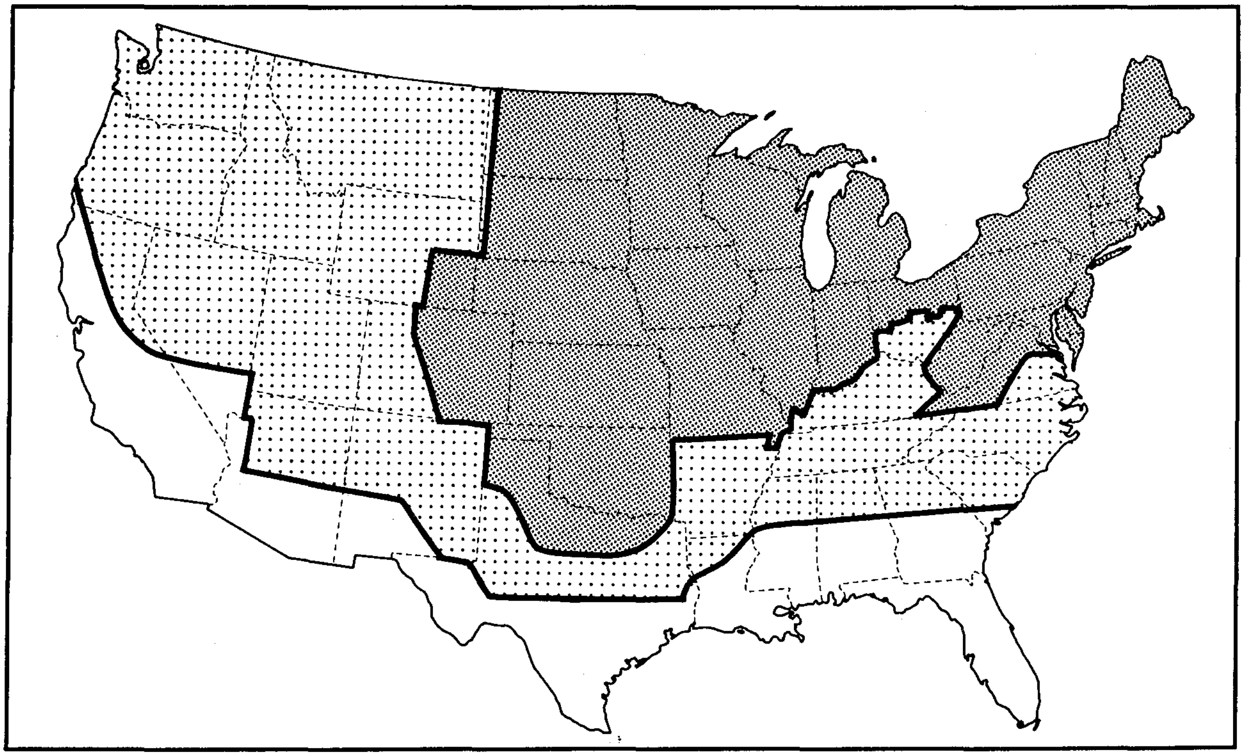

POLE LINE DESIGN LOADS

	STORM LOADING AREA	RADIAL THICKNESS* OF ICE COATING ON CONDUCTORS AND MESSENGERS (IN.)	TRANSVERSE WIND PRESSURE (LB/FT² OF PROJECTED AREA)	MINIMUM TEMPERATURE (°F)
▩	HEAVY	1/2	4	0
⬚	MEDIUM	1/4	4	15
☐	LIGHT	NONE	9	30

*WHEN COMPUTING TRANSVERSE WIND LOADING, IGNORE ICE COATING ON POLES AND TOWERS.

Figure 16. Ice loading data (after AT&T, 1985).

1. Aesthetics--Retaining the beauty of the land has become a priority along the routes of installation. The solution has been simply to place the cable underground by using trenching or by direct burial utilizing a specially designed plow. If the route of installation is properly restored after placing the cable underground, the only indication of the cable presence will be an occasional marker that is necessary to identify the location if maintenance is required. If locating the cable is a concern, a plastic tape containing a metallic compound can be placed in the ground (usually a few inches above the cable) at the same time the cable is laid. Commonly used instruments for locating copper cable can then be used to determine the location of the fiber optic cable.

2. Physical protection--Placing the cable underground separates the cable from most natural and man-made elements that may disrupt telecommunication service. The earth around the cable acts as a buffer from all surface activity such as wind, rain, snow, ice, and cold temperatures. Violent activity such as floods and earthquakes may still be a problem due to movement of the earth that results in exposure of the cable.

   Man-caused activity can still be a concern; however, the risk will be reduced by concealing the cable. Vandalism has been a continuing concern for companies with surface installed (aerial) cable. Damage from gun shots, slashing, or severing has been virtually eliminated by placing the cable underground.

There are several methods of placing the cable underground. The most common methods are listed in Table 10 with an example of where each method is used.

When installing cables underground, consideration must be given to mechanical requirements of the installation method--relating to the mechanical limitations of the cable design. Specified parameters such as minimum bending diameter, crushing force, tensile load, and fiber strain limits must not be exceeded. The cable design may include an armor sheath to minimize the risk of damage from backfill, land movements, diggings, rodents, termites, and other earth-moving operations.

Table 10. Cable Burial Methods

Placement Methods	Application
1. Plowing in--either with or without a duct or conduit	- Long-haul installation, routes with very few obstructions, and continuous rights-of-way
2. Trenching--with machine or manual methods	- Long- or short-haul installations through urban areas where numerous obstructions will be encountered
3. Placing in existing conduit--channel used for existing telecommunication cable or duct	- Usually short-haul installations through urban areas where telecommunication service exists using copper or coax distribution facilities
4. Horizontal boring--using high-pressure air blast or drill bit. The bare cable or duct is placed in the resultant channel	- Used for placement under highways, rivers, ditches, swamps, bridges, viaducts, and other obstacles where commonly used methods are not feasible.

The durability of the underground cable installation can be enhanced by various methods and techniques that prevent or lessen the risk of damage. A number of excellent ideas, listed below, are being used by telecommunication companies to accomplish these objectives.

- Bury the cable deeper than normal to reduce the risk of cable damage in areas of digging for purposes of agricultural cultivation, postholes, agricultural irrigation ditches, landscape sprinkler trenches, and laying of other utility services.
- Share a common trench with other services, especially when a rigid conduit or trough is utilized.
- Place cable in a rigid duct.
- Lay an additional duct parallel with an installed cable for use in adding additional facility--preventing dig up and damage during installation of the second cable.
- Condition the backfill around the cable by tamping or packing to prevent damage during mass backfilling. Eliminating any sharp rocks from the backfill will reduce the damage during backfill.

- Use underground jointing enclosures for ease of access for maintenance and protection from surface elements.

- Consider the effects of strain that may be imposed on the cable when using a vibrating plow--e.g., vibration, curvature of cable guides and feed system, and tension or compression.

- Consider protective storing of cable reels at work sites along installation routes. Fiber optic cable can be damaged by natural surface elements or vandalism.

The possibility of using one method of installation for an entire route is low, therefore improvising by using the best method for each portion of the route is important. A balance between cost of installation and plant protection objectives must be achieved. Whether the balance swings one way or the other depends upon the type of service being carried, the requirements of the customer, and the harshness of the environment along the cable route.

<u>Conduit protection methods</u> Conduits are used when installing fiber optic cable for a number of reasons. An exhaustive list of all types of conduits and their uses is not possible or necessary to fulfill the objectives of this report. The majority of applications for conduit can be grouped into two categories. A discussion of the more common applications of conduit in each category is included below as an introduction to the art of applying conduit technology.

1. Protection of the installed cable

   - From corrosion--exposure to chemicals or other naturally occurring substances that may accelerate deterioration of the cable components.

   - From vandalism--particularly where the cable is above ground, a protective conduit is necessary to inhibit slashing, severing or crushing the cable.

   - From rodents--additional protection from rodents such as gophers or rats can be provided by placing the cable in a conduit. A number of tests have been run to determine the most vulnerable materials as shown in Table 11 (AT&T, 1970). A metal sheath appears to be the most effective protection from rodents--therefore use of an all-dielectric cable design may not be feasible in areas of high rodent activity.

   - From moisture--several materials are available that provide adequate blockage of moisture. The optical fiber is not significantly affected if contacted by water, accept that the lifetime of the fiber may be reduced due to micro-cracks that form on the surface of the

Table 11. Material Resistance to Gopher Damage (after AT&T, 1970)

Summary of Materials Tested	
Materials Found To Resist Gopher Damage	**Materials Vulnerable To Gopher Damage**
Sheathing Materials	Polyethylene-jacket and insulation
Glass reinforced epoxy tubing (0.125" wall)	Polyethylene-petroleum jelly blend
Armor Materials in Cables	High-density polyethylene with tert-butylsulfenyl dimethyl-dithiocarbamate repellent
0.010" low carbon steel 0.005" stainless steel 0.006" tin plated steel 0.010" copper 0.010 brass 0.002" Cu/0.002" Fe/0.002" Cu laminate	Polyethylene insulated copper conductors Polypropylene Polycarbonate
Insulated Wires	Poly (vinyl chloride), insulation and jacketing
0.005" x 0.625" spiral bronze tape armor 0.006: x 0.500" low carbon steel tape armor 0.005" x 0.500" stainless steel tape armor 0.002: Cu/0.002" Fe/0.002" Cu laminate tape armor*	Aluminum-shield, polyethylene insulated conductors Aluminum adhesively bonded to PVC jacket Asphalt flooding compound Coal tar flooded jute Lead-sheath

*When used with solid core construction

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glass resulting in failure due to other stress such as bending or twisting of the cable (CCITT, 1985).

- From landworks--digging with large scale equipment such as large backhoes, bulldozers, and trenching equipment is virtually impossible unless a concrete conduit is used to protect the cable installation. However, the risk from small scale landworks (e.g., agricultural cultivation, posthole digging, irrigation or drainage ditching, etc.) can be effectively reduced as a threat by placing the cable in a flexible or rigid conduit or duct.

- From underwater environments--submarine crossings require special protection from not only the constant exposure to water, but stress due to crushing forces at the bottom of the sea, while other subaqueous installed cable may be exposed only to the stress due to water. Conduits have been designed for use in these environments; however, since the fiber optic cable is very light in weight, the outer sheath is made more resistant to high moisture environments without creating a cable with excessive weight. The conduit is not necessary in some cases.

- From natural or man-caused damage on bridges and other supporting structures--wear and tear from natural elements and damage from vandalism can be a threat to a telecommunications system if the cable is not protected. Simple, but very durable, conduits are used to protect the cable in these cases--common galvanized pipe or a fiberglass tube are frequently used for this purpose.

- From stress when crossing under highways or railroads--steel pipe is commonly used to protect the cable from stress due to compaction or vibration. Other rigid conduits that are cost competitive could also be used for protecting the cable in these situations.

- From other harsh environments--an inert gas filled conduit system can be used to totally exclude any foreign liquid, gas, or solid from contacting the cable. Although costly, this method of protection can be an insurance policy for protection in a high exposure area.

2. Expansion of capacity

- As new technology is developed, and the user desires to upgrade an existing system by replacing the cable, the old cable can be removed from the duct or conduit and the new cable pulled into the conduit. This operation can be accomplished at a significantly lower cost than installing a second cable.

- If added capacity is desired that would require an additional cable, preplanning for this requirement can be accomplished by installing an oversized conduit that will accommodate multiple cables or installing a duct parallel to the first cable that can then be used, when the requirement arises, to pull a second cable along the same route. In either case, the second cable can be installed at minimal cost and with a small amount of hassle.

The use of conduits during fiber optic cable installation is not a requirement, but their use can be of benefit in protecting the cable from stress as illustrated in the above discussion. Other uses, such as for expansion purposes, are a function of the creativity of the system designers.

Installation on obstacles such as bridges, viaducts, trestles, culverts, and access boxes The fiber optic cable is usually supported within a conduit when crossing bridge structures. A cable is a relatively small and delicate component and difficult to grasp without damaging the cable or the cable sheath. The cable is relatively free of stress when supported inside a conduit.

For above-ground installations, the conduit is attached to the structure in a manner acceptable to the owner of the structure or the governing authority. Galvanized iron pipe is commonly used as a conduit--usually a standard 2 inch (5 centimeter) diameter pipe is adequate for most installations requiring a single cable. A fiberglass tube is used by some installers as a substitute for the iron pipe. In either case the conduit is supported from the bridge by suitable brackets, which will usually be clamped to wooden or steel bridge girders. The conduit should be placed through the bridge end-walls by core drilling the structure. Welding to bridge members or drilling for attachment is usually discouraged because of the risk of weakening the structure. Expansion joints are usually necessary to compensate for stress due to expansion and contraction during temperature changes. It is important that the conduit be sealed to prevent water accumulation which, when frozen, could cause crush pressure on the cable. Lateral pressure can cause excessive losses that could cause the system to become inoperable. The accumulation of water can be eliminated by creating a sump pit at the entry and exit of the conduit section that will allow the water to drain into the ground at each end thus preventing water accumulation. Using an inner liner (innerduct) inside the conduit is another solution. The inner liner should extend beyond the end of the conduit. All innerducts and conduits should be sealed, after the cables are pulled in place (e.g., with liquid polyurethane compound). Appropriately spaced weep holes should be drilled along the horizontal section of the conduit to allow drain off of condensed water inside the steel pipe.

An alternative to attaching to the structure is available. The technology required to place the cable underground, when confronted by an obstacle such as a bridge over a natural waterway, another highway, or some other type of crossing, is now available. A channel is horizontally drilled several feet under the obstacle with a rig designed for this purpose. The cable is placed inside a conduit which is first inserted in the channel drilled by the horizontal drilling machine. This technique removes the cable from any exposure to natural or man-made surface elements. In addition, when crossing a waterway such as a large river, the cable is not subject to damage from anchors, dredging, erosion, or bottom scouring.

Installation across obstacles such as natural waterways, ditches, highways, and railroads Most minor crossings can be accomplished by placing the cable under the obstacle. A galvanized pipe (4 inch) can be placed below the obstacle by using either a pushing or jacking method. The push pit and the pull pit must be dug at a distance from the obstacle that is appropriate for the application and is acceptable to the right-of-way owner. Since a 4-inch conduit is used, more than one cable can be placed in the conduit. Innerducts can be placed in the conduit to protect the fiber optic cables. Three innerducts can usually be placed in a 4-inch conduit; thus it would be possible to pull three cables in the conduit (or if the requirement is for only one cable in the beginning, cables can be added later when the requirement exists).

Methods for placing cable under major waterways and large obstacles are discussed in the section of this report that deals with placement and use of conduit. The installation process includes drilling a channel under an obstacle such as a large waterway or multilane highway rather than placing a conduit under the obstacle using the pushing or jacking method. The horizontal drill method of placement is not labor intensive but does require an initial set up charge that can make a short distance placement costly as compared to other methods of placement. However the horizontal drill method may be the only solution when the placement path includes passing through rock, underground debris, or other impediments.

Cable splice protection Sections of cable must be joined because finite lengths of cable are a necessity due to the limitations on transporting and handling. Even though the manufacturer can produce continuous cable lengths in excess of 10 km, the shear bulk of the cable precludes carrying the reel of cable along, especially while plowing-in cable over rough terrain. The splicing technology has reduced the loss at a joint to 0.2 dB or less; thus the splice is not a major contributor to erosion of the design loss budget. For example, when the loss per kilometer of cable is typically 0.2 to 0.5 dB per kilometer, a splice loss of 0.2 dB is not significant. For the sake of expediency and convenience, shorter lengths of cable may be used, with the requirement for additional splices.

The splice can be a weak point in the installation if the splice is not well protected. Technology for performing the splice, organizing the fiber, supporting the fibers after being spliced, and sealing the splice from outside soft (liquid) effects is proven. The splice closure, which protects the splice and supports hardware, performs this function. However, the splice is vulnerable to damage if not protected from external effects that may crush, puncture, or in some other way damage the closure. Protection can be provided in a number of ways--based on cost (lowest), based on convenience, or based on a standardized procedure set by the installing company.

A brief discussion of commonly used techniques for protecting splice closures is provided below. The intent of this discussion is not to recommend one method over another, but rather to describe the parameters of each method of installation.

- Splice closure burial without protection--A simple technique for underground placement of the splice that involves laying the excess cable and splice in a pit (dug to the nominal depth of cable burial) and then covering with sand. The sand provides a protecting buffer for the cable and splice while the pit is backfilled. The splice location is usually suitably marked to facilitate relocation--using physical surface markers or electronic markers at the discretion of the installing company.

- Splice closure burial with protecting splice box--A vault that is constructed of concrete or a dielectric material is frequently used to house the splice and the splice closure. This vault is not necessarily watertight, but the splice will usually be protected with a watertight closure anyway. The splice closure will provide physical protection for the splice and will provide easy access to the splice if necessary for maintenance in the future. A splice closure does not provide any significant protection against stress. In fact, the exposure to EMP and gamma radiation will usually be reduced because the soil cover will typically be less in the vicinity of the splice.

Security The major threat to a fiber optic system is physical damage to the cable or the regenerator electronics. A fiber optic system is very delicate and can be disabled very easily if exposed to a hostile element. Deterrents to damage are possible--depending on the type of threat. The threats from the people element can be premeditated or spontaneous depending on the motivation. A discussion of the major areas of threat to security follows:

- Sabotage--This threat element derives from premeditated malicious destruction of property done with the intent to disrupt and/or cause harm. Positive protection of the system is not possible, especially if sabotage is the motive for the damage. The threat from sabotage will be directed at the components of the system which offer exposure with convenience--inconvenience being a deterrent. Therefore any type of barrier between the saboteur and the fiber optic hardware will offer significant protection. For example, the use of cipher locks on the regenerator enclosure is known to be a deterrent. Placing of the system components underground will also be a deterrent, especially if the location is not marked with visible means. The use of electronic markers to locate the underground cable, splice boxes and other enclosures is a way of reducing the threat from sabotage.

- Vandalism--The threat from vandalism can be minimized by placing the system components out of sight or out of reach. Placing the cable and regenerator enclosures underground will virtually eliminate damage from vandalism. Gun shots from rifles or shotguns, the most common type of vandalism, can be virtually eliminated with placement of the systems underground. Of course, easy access to facilities is also a temptation for vandals to do damage, thus a durable locking mechanism is a necessity to prevent entering.

- Tapping--intercepting of the signal being sent on the fiber optic cable would be of interest to certain individuals or organizations for political or monetary gain. The optical signal is very difficult to intercept because, unlike a wire, the fiber does not emit any external field or effect. The light can be extracted by physically cutting into the fiber such that transmission can be intercepted or the fiber can be wrapped around a mandrel, with less than the critical radius, causing light to leak from the cladding where it can be sensed. The later technique is used for monitoring during splicing or for sensing for intrusion (security alarm application) of a fiber optic system. The greatest harm would come from the damage caused in the attempt to tap the signal. In fact a cable or fiber could be severed during the process and a link would become inoperable--not the original intent of the act.

The effort required to prevent any breach of security is enormous and probably impossible. However, physically securing the facilities and placing the system components out of sight (underground) are effective methods to secure the facility from all three types of security concerns discussed above.

3.1.3 Stress Sensitivities

Degradation/deterioration The useful life of a cable will be decreased by gradual deterioration of the cable components and consequently the fiber by exposure to environmental parameters. As described in (7), a degradation of a fiber/cable parameter, P, is sometimes known, as a function of time t, under a certain environmental condition, x. Then the "lifetime" limited by the particular cause can be determined by the time required before the parameter, P, degrades to the acceptable limit (Abe, 1986):

$$(dP/dt)_x \times (\text{lifetime}) = (\text{limit of } \Delta P). \qquad (7)$$

A common approach to the problems of this type is an accelerated aging test. An approach to this problem is described by Abe (1986). Each performance parameter can be related to the environmental parameters that cause degradation of that parameter using the techniques described by Abe (1986).

Performance parameters, P, that are of interest include attenuation, strength, and integrity. As the system requirement becomes more stringent, parameters such as bandwidth, dispersion, modal velocity, bit error rate, etc., become a concern.

Environmental parameters will cause an effect on the performance parameters. The relative magnitude of effect has been characterized for some of the environmental parameters, but not for others as illustrated in Tables 12 and 13. The environmental parameters are divided into two categories, X and Y, to designate those with well characterized effects and those with less well known effects as shown in Tables 12 and 13.

The cable as a component is commonly protected by a duct or conduit, which lessens the effect of the environment and effectively lengthens the lifetime of the cable. Protection from outside effects that are naturally occurring or from man-caused sources, is upgraded with the additional protection.

A lifetime goal of 20 years is typical in the fiber optic cable industry, according to available specifications. However, the "functional obsolescence" lifetime is probably somewhat shorter than 20 years. For example, the early fiber optic, long-haul systems have lasted only about 5 years. As the technology matures, the useful lifetime will probably increase. Upgrading will take place by replacing the regenerator electronics without a replacement of the cable.

Table 12. Well Characterized Reliability Parameters (Abe, 1986)

P	X	Y
Attenuation	Hydrogen Radiation	Micro/macro bends Temperature
Strength	Stress Moisture Water Chemical environment	Mechanical effects
Cable integrity		Mechanical effects Lightning, etc.

Table 13. Less Characterized Reliability Parameters (Abe, 1986)

P	X	Y
Attenuation	Stress and hydrogen Radiation and hydrogen	
Dispersion	Hydrogen	Temperature
Fiber integrity	Water	
Cable integrity		Vibration Dancing, etc.

<u>Naturally occurring events</u> Naturally occurring events that may affect a fiber optic telecommunication system are made up of stresses caused primarily by random deviations (e.g., wind, rain, ice, snow, cold weather, floods, earthquakes, mudslides, avalanches, tidal waves, dust storms, snowstorms) of nature's cycle. These events are generally not created, controlled, or in any way caused by man-made activity. The effects, however, can be influenced (lessened) by precautions that are taken by those designing, maintaining, or planning structures in the path of these random occurrences.

Obviously any structure that projects above the surface of the Earth is subject to stress from natural elements. Protection from these effects involves common-sense design and ingenuity to mitigate the stress in a cost effective manner. For purposes of this report, the following categories of natural events will be considered. An attempt to show mitigation of effects for each of these stress categories will be discussed later.

- Wind--Stress due to movement of air will result from a number of sources. Normal sources for wind are a result of atmospheric disturbances accompanying a weather pattern. Man-made sources of wind are a result of blast fronts that emanate from a detonation of conventional explosives or fission/fusion processes.

  Winds that are a result of atmospheric disturbance can be of a constant velocity, variable velocity, or of swirling nature depending on the type of disturbance or severity of the storm. Damage from wind is a result of the force impact, but can be compounded because of the rapid change in force vectors. The damage results not only from the change in force vector direction, but from the magnitude change.

  The resultant wind from a detonation such as a nuclear explosion has characteristics different from natural events. A wave front impinges on the target from the direction of the source followed by a sudden reversal of the air current. The blast wave produces sudden outward displacements of air and large peak dynamic (wind) pressures. Table 14 shows the relationship between peak overpressure, peak dynamic pressure, and maximum wind speed (Glasstone and Dolan, 1977; Pittock et al., 1986).

- Moisture--A Fiber optic cable will not malfunction due to exposure to water, but deterioration of cable components will be hastened by the chemical reaction. If the fiber (cladding) is exposed to moisture, the silica material will develop microcracks (private conversation with representative of AT&T, Bell Laboratories) that will cause the

Table 14. Blast Parameter Relationships

Peak Overpressure	Peak Dynamic Pressure	Max Wind Velocity
100 psi	120.0 psi	630 m/s (1400 mph)
10 psi	2.2 psi	130 m/s (290 mph)
2 psi	0.1 psi	30 m/s (70 mph)

fiber to fail under stress (e.g., bending, compression, tension, torsion, vibration). The tensile strength of the fiber is reduced and the time to static failure is also reduced with exposure to moisture (CCITT, 1985). Subcritical microcracks, which normally occur during the manufacturing process, may be propagated in the presence of water or other reactants (Kao, 1982).

In certain locations, the cable will be exposed to naturally occurring hot springs. The temperature can be in excess of 125 °F (52 °C). Water penetration will be enhanced due to the elevated temperature, increasing the threat of moisture entering a cable sheath, cable splice closure, or another component of the fiber optic transmission system. In addition, corrosion may be accelerated because of the elevated temperature (CCITT, 1985).

- Snow and Ice--Fiber optic cables that are hung above ground are most susceptible to damage from ice or snow. The most common type of damage to exposed cable results in cuts, breaks, sagging, and stressed mounting hardware (CCITT, 1985). A properly designed installation should not be affected except in cases of extreme build-up of ice during an infrequent weather condition. If maintenance down time cannot be tolerated (e.g., a fiber optic path carrying time-critical information that cannot be delayed), another type of installation must be used--such as underground burial. Burial of the cable [e.g., 36 inches (0.9 meters) or more] will provide an installation that is not affected by even extreme weather conditions with ice and snow. However, the moisture that results from melting of the ice and snow is a concern that is discussed in another section. In addition, extreme cold temperatures that sometimes accompany ice and snow will present added stress.

- Temperature--A fiber optic cable will not normally be affected by nature's extreme temperatures--either hot or cold. However, if the cable components are not balanced (by design) to eliminate expansion/contraction effects, breakage or other physical damage can occur due to temperature change (CCITT, 1985). The most damaging effect can result from freezing water inside a rigid duct and around the cable. Lateral pressure on the cable, from the freezing process, will cause an increase in transmission loss resulting in an inoperable system (private conversation with a representative of Litel, Inc.). Gel filled cables can suffer sheath damage over their lifetime. This damage can arise from several causes including installation, lightning, and dig up. If the cable is buried in saturated soil there exists the potential for water ingress and possible fiber damage, especially if the water freezes (McKay et al., 1986).

- Lightning--Damage to a fiber optic cable from a lightning strike will vary depending on the type of cable and the environmental conditions surrounding the cable. A cable that is constructed with metal components is obviously more susceptible to damage than a cable that does not use metallic materials. Discharge currents from lightning will be attracted to conductors such as a cable sheath or a metallic strength member of a fiber optic cable. Two types of damage are common to a lightning strike:

1. Currents flowing in the metallic component of the cable will seek a path to ground at any point along the cable. The exchange of current between the cable and ground will be through leakage current and, if the voltage buildup is sufficient, by an arc. Leakage current will usually be of a level that will not cause damage to the cable; however, the arc will cause a puncture of the metallic sheath as well as the dielectric sheath that provides the external protection for the cable. The puncture will allow ingress of foreign matter such as moisture and chemicals that will initiate corrosion and reduction in cable lifetime.

2. If the cable design utilizes two metallic components (e.g., metallic central strength member and a metallic sheath), a difference of potential between the two components may exist causing an arc. The arc can cause a puncture or a fusing of the metallic parts. The denting or crushing of the shield/armor of a cable from exposure to lightning discharge has been observed--the rationale is that the arc created steam that propagated and caused physical damage to the cable. This phenomena has been termed the "steam hammer" effect (Fischer, 1986). In all of these cases, the lifetime of the cable will have been reduced or the cable could have been rendered inoperable.

Energy from lightning strokes will be coupled to telecommunication system components from radiated fields and by direct strokes to cables or electronics installed on the surface of the Earth or underground. The radiated field is on the order of 10 V/m or less and has a half-time duration of 40 μs with a rise time of a few microseconds (NCS, 1978). The risk of damage from lightning radiated fields is rather low. However, MIL-STD-461A and associated specifications defines levels of nonsusceptibility to interference as 1 V/m (NCS, 1978). A reduction of the radiated field energy by a factor of 10 would be necessary to ensure that the system (e.g., fiber optic regenerator) will run without risk of error. Damage due to direct strokes of lightning to cables or other components of the transmission system or to personnel is of much greater concern. The median value of crest currents is 16 kiloamps and the maximum is 220 kiloamps. The average fall time is 400 μs, while the rise time (1 to 99 percent) is 100 to 2,000 μs (NCS, 1978). A great deal of protection is required to protect the telecommunication system from damage due to injected current from lightning strokes. Typical protection includes a fast acting current shunt that will activate when the current pulse impinges upon the electronics module. Shunting the current to ground will prevent the transient from entering the functional parts of the transmission system--resulting in possible transmission errors.

Gamma radiation Single mode optical fibers used for long-haul telecommunications have been found to be sensitive to gamma radiation. A darkening effect is observed that results in less efficient transmission of light through the fiber causing an increase in perceived loss. This increase in loss will obviously erode the design margin (built-in budget for loss over and above that allowed for maintained operation) to the point of errored operation or inoperability.

The sources of gamma radiation are numerous; they range from natural occurring background levels to enormous levels that could result from fallout of a nuclear detonation on the Earth's surface. Lesser levels of radiation can result from high altitude nuclear detonations or accidental release of radiation from sources such as a nuclear power plant. Background levels of radiation are not thought to be a threat because the levels are projected to be below a maximum level of 500 mrads/yr (including deposits of naturally occurring radiating substances like Uranium) with an average level of about 130 mrads/yr (Shah, 1975; Haber, 1987).

Fiber optic cable durability enhancements First the cable, as a component, will be analyzed separate from the remainder of the system. There are four primary variables for consideration when attempting to improve the durability of the fiber optic cable. For this discussion, the cable will be assumed to be installed in an operating environment. Each of the variables is subject to design considerations. A short description of the four areas is provided below in an attempt to clarify the basis for discussion.

- Optical fiber--The glass fiber used in a fiber optic cable is a rather delicate component. A fiber or bundle of fibers is not physically tough when subjected to mechanical stress. The physical size is similar to that of a 3-pound rated monofilament fishing line. Obviously, if the fiber is not protected, it could be easily damaged. The components surrounding the fibers provide a very durable environment for the fibers, shielding them from most mechanical stress. Because the fiber is shielded by the surrounding cable components, the need to design a more physically stress resistant fiber is minimal. The only real physical protection for the fiber is the primary coating that is applied immediately after drawing the fiber. The coating prevents surface cracks that can reduce the strength of the fiber when subjected to tensile stress or bending stress (CCITT, 1985). Another design consideration, related to gamma radiation resistance, is a function of the glass molecular makeup. Resistance of the fiber to gamma radiation can be enhanced by using special glass formulations.

- Cable configuration--The physical arrangement of cable components are not critical to the function of the fiber optic communication link, but the protection provided for the fiber is determined by the configuration of components. Several different configurations provide acceptable protection for the fibers. Each manufacturer has developed unique configuration designs and each has its preference. The configuration design is usually driven by the intended application and the number of fibers to be supported by the design. Simply stated, the cable is a physical support system for the optical fibers--preventing or reducing tensile, compression and lateral stress, and blocking any contact with chemicals to which the cable may be exposed.

- Cable sheath--The sheath is that part of the cable that provides a continuous layer or layers of material around the physical support structure for the fiber. A typical sheath consists of at least one layer of metal (solid or wire overlay) and at least one layer of nonmetallic sheath material. An analysis of several nonmetallic sheath materials is included as Table 15 (CCITT, 1985).

- Cable environment--The cable environment can be thought of as a fourth level of protection for the functional component of the cable--the optical fiber. The preceding three levels are: 1. the fiber coating, 2. the fiber structural support (configuration), and 3. the cable sheath. Each level of protection provides stress resistance at a greater distance from the fiber. The amount of protection that can be provided by the environment is limited only by the economics of the installation. However, it is not possible to protect from <u>all</u> types and degrees of stress, even if money was not a factor. Total protection against events of nature may be possible (possibly not practical), but the ingenuity of man will make it impossible to thwart all types and degrees of man-made stress. Thus we must think in terms of "levels of protection" and rather than in terms of "total protection."

  The environment of the cable is a function of the installation design, utilizing ingenuity and common-sense ideas to reduce the effect of man-made and natural stress. "Brute force" techniques are applicable for physical protection, but in developing resistance against stress such as gamma radiation, knowledge of the stress source is a necessity. Further discussion of this topic will follow later in this report.

  Stress mitigation through environmental design requires the least technological finesse; the benefits are generally understood and implementation is straightforward.

A summary of the most common types of stress to which a cable will be subjected is included as Table 16. The primary effect from each stress type is

Table 15. Comparison of Several Nonmetallic Sheath Materials and Structure for Optical Fiber Cables (after CCITT, 1985)

Characteristics		Sheath Material						
		LPDE	HPDE	LAP	PVC	PUR	PA-12	Lead
Mechanical Characteristics	Tension	▲	▲	●	▲	▲	●	●
	Bend	●	●	●	●	●	●	▲
	Torsion	●	●	●	●	●	●	●
	Radial pressure*	▲	▲	●	▲	▲	●	●
	Abrasion*	▲	●	▲/●**	▲	●	●	▲
Climatical Characteristics	Climatic performance	●	●	●	▲	●	●	●
	Moisture barrier	x	x	●	x	x	x	●
	Chemical resistance	●	●	●	▲	●	●	●
	Hydrocarbon resistance	x	●	▲/x**	▲	▲	●	●
Physical Characteristics	Thermal expansion*	▲	▲	●	▲	●	●	●
	Small diameter light weight	●	●	●	●	●	●	x
	Fire retardancy	x	x	x	●	x	x	●

* Especially important for optical fiber cables
** Depending on choice of outer sheath material

● Good ▲ Average x Poor

LDPE: Low Density Polyethylene
HDPE: High Density Polyethylene
LAP : Laminated Aluminum Polyethylene
PVD : Poly Vinyl Chloride
PUR : Polyurethane
PA : Polyamide

Table 16. Fiber Optic Cable Stress Sensitivities

	Stress	Effect	Solution Areas		
			Fiber	Cable Config.	Environment
Natural Events	Moisture/Chemicals/Corrosive Mat'l	Degradation	-	X	X
Natural Events	Ice/Snow/Wind/Floods/Sun	Degrad/Inop	-	X	X
Natural Events	Soil Separation/Shifting	Inop	-	X	X
Natural Events	Rodents/Birds/Insects	Inop	-	X	X
Natural Events	Temperature (Hot or Cold)	Degrad/Inop	X	X	X
Natural Events	Lightning	Degrad/Inop	-	X	X
Man-made Events	Electromagnetic pulse	Degrad/Inop	-	X	X
Man-made Events	Gamma Radiation	Degrad/Inop	X	-	X
Man-made Events	Vandalism	Inop	-	-	X
Man-made Events	Sabotage	Inop	-	-	X
Man-made Events	Accidents	Inop	-	X	X
Man-made Events	Construction/Agriculture Work	Inop	-	-	X
Man-made Events	Power System Failure	Inop	-	-	-

noted along with an indication of the most likely area of mitigation. The areas that are not noted as "solution areas" may yield some benefit, but are not a primary source of benefit.

3.2 Fiber Optic Regenerator Station Enhancement

3.2.1 Stress Sensitivities

Naturally occurring events A very durable structure is required to survive violent storms and other weather conditions. Events of nature that occur only once in 2, 10, 25, 50, 100, and 250 years can cause extreme stress on an above-ground structure. Placement of the fiber optic telecommunication system components underground ensures that the system is not exposed to these violent events. The magnitude of the extreme events is discussed and presented in Section 4 of this report.

Man-made events Protection against man-caused events can be provided either through design enhancements or physical features that increase resistance to stress. Brute-force techniques can be used to protect against vandalism, accidents, or sabotage--but a bit of finesse is required to protect against nonviolent stress such as EMP or gamma radiation. Solutions to the problems presented by this stress are presented in Section 4 of this report. A brief discussion of the common enhancements that can be used to increase durability is presented below.

3.2.2 Regenerator Station Stress Protection

Three general areas of enhancement will be discussed for improving the durability of the regenerator facility:

- The regenerator electronics
- The regenerator enclosure
- The regenerator enclosure environment

Each of these areas of enhancement is subject to design sensitivities that will increase the durability. A short discussion of each area is provided to define the bounds of the area being analyzed.

- The regenerator electronics--Regeneration of the telecommunications signal is necessary to retime the digital data, identify and correct errors, and overcome loss by retransmitting the digital optical signal. The electronics, as defined for this discussion, includes any digital or analog electronics, the optoelectronics for transmitting and receiving, and the associated power supplies used for powering the electronics. The devices used to fabricate the regeneration circuitry are off-the-shelf, commercial grade devices that have not been stress hardened. In the design of the circuitry, the assumption is made that frequently used design guidelines for reduction of transient effects are incorporated. Reduction of effects from transients originating from the "ground system" or the "power supply system" is the goal when incorporating transient reduction concepts. The assumption is that transients are not coupled directly into the circuitry; however, this could happen if the intensity of the impinging field is large, e.g., the field of electromagnetic pulse (EMP) resulting from a nuclear detonation.

  The threat from gamma radiation is real, also, since it is known that gamma radiation will affect the operation of the solid state devices. Radiation hardened replacement devices are available for some of the device types, but are very expensive. The lack of replacement devices for all devices used, e.g., optoelectronic devices, and the extreme cost may preclude use of this solution for protection from gamma radiation. The analysis provided in Table 17 illustrates which stress sensitivities can be mitigated by design enhancements to the regeneration electronics.

- The regenerator enclosure--The regenerator enclosure is vital to the operation of the telecommunication system because it provides a secure place to house the regenerator electronics. In the past "secure" has meant protection from weather and from exposure to passersby who may be tempted to damage the rather delicate electronics. One hundred percent protection was not the goal, and the owner of the station expected some down time from severe weather events and possibly occasional acts of mischief or vandalism.

  Today several things are different regarding the extent of protection expected from the enclosure. A brief description of these differences follows.

1. With the use of fiber optic transmission, and the large amount of data carried on a single fiber, the cost of any down time is prohibitive. Therefore, the goal is zero down time and when down time does occur, the design must lend itself to a quick fix of the problem.

2. Because of the zero down time requirement, the structure must be a great deal more durable--allowing no penetration of effects from outside weather conditions. Withstanding of 50 and 100-year storms is essential because it is during these conditions when telecommunication is most important.

Table 17. Fiber Optic Regenerator Stress Sensitivities

	Stress	Effect	Solution: Electronics	Solution: Enclosure	Solution: Environment
Natural Events	Moisture/Chemicals/Corrosive Mat'l	Inop	-	X	X
	Ice/Snow/Wind/Floods/Sun	Inop	-	X	X
	Soil Separation/Shifting	Inop	-	X	X
	Rodents/Birds/Insects	Inop	-	X	-
	Temperature (Hot or Cold)	Degrad/Inop	X	X	X
	Lightning	Inop	X	X	-
Man-made Events	Electromagnetic pulse	Inop	X	X	X
	Gamma Radiation	Inop	X	X	X
	Vandalism	Inop	-	X	X
	Sabotage	Inop	-	X	X
	Accidents	Inop	-	X	X
	Construction/Agriculture Work	-	-	-	-
	Power System Failure	Inop	-	-	-

3. Another dimension has been added to the vandalism threat--the possibility of man-made stress from sabotage. Again the durability and strength of the enclosure must be increased. Local protection against this threat may not be possible and must be countered by rerouting traffic via another path when a path becomes inoperable due to sabotage.

4. Damage due to accidents along rights-of-way is a current threat. Since most of the fiber optic cable is laid along railroad rights-of-way, the greatest threat is from train derailments. Obviously, damage can occur from excavation during the accident, but the fire that can result from the derailment may be an even greater threat. In addition, chemical spills from these accidents may also cause damage and can cause long-term deterioration for some installations.

   It is obvious that the enclosure is a critical component in the fiber optic system. Fortunately the technology required to produce a more durable enclosure is developing. The enclosures of a few years ago were rather flimsy--capable of being penetrated by a 4x4 truck, for example. The designs used today are usually of prefabricated concrete construction with a rebar matrix in the concrete. The strength is much greater than an on-site fabricated wood-frame type building. The single-unit type construction prevents entry of residue (e.g., water, dust, dirt, snow, etc.) from weather conditions occurring along the path. The rebar matrix included in the construction will not only add strength but provides a metallic shield around the electronics resulting in some shielding from lightning and EMP. In addition, the concrete structure will provide a limited shield from gamma radiation, depending on the structure thickness.

   Protection from lightning and EMP can be significantly improved by effecting a "meaningful" ground at the enclosure site. A meaningful ground is effected with adequate surface contact with the soil. Developed guidelines for grounding should be used when designing and installing a grounding system. Military Handbook 419 provides guidelines for proven grounding techniques (DOD, 1982).

- Regenerator environment--If the enclosure is installed on the surface of the Earth, very little can be done to modify the environment surrounding the enclosure. However placement of the enclosure in less visible locations or in locations that are naturally protected, e.g., protected by trees or other natural formations, is a benefit.

  The most effective environmental enhancement has been to place the enclosure underground. Most benefits are obvious for protection against natural elements of weather. The greatest benefit is realized when the enclosure is placed below the surface such that there are at least 36 inches (0.9 meters) of soil covering the enclosure. When using this type of placement, the protection from events of nature is multiplied, the risk of damage from vandalism is virtually eliminated, the risk from sabotage is decreased significantly, and significant protection is provided against gamma radiation.

The shield effectiveness of earth (soil) becomes a subject of analysis. The reduction in gamma ray flux (i.e., power) is of interest for this analysis--in particular, one can start with the half-thickness value. Simply stated, this is the thickness of material that reduces the flux level to one-half the original level. The half-value thickness varies with the energy of the gamma photons as illustrated in Table 18. Actual energy levels for industrial radiographic sources are included in Table 19. To illustrate the thickness of materials necessary to equal the shielding effectiveness of 36 inches (0.9 meters) of sand, Table 20 has been included. It should be noted that at an energy of 6 MeV (million electron volts) the required amounts of material necessary for reduction to half-value is more than double that for 1 MeV.

Table 21 shows the absorption factor for various thicknesses of commonly used shielding material. The absorption factor is derived from:

$F = F_o e^{-\mu x}$, where x is the thickness in cm and F is the gamma radiation flux. The absorption is then:

$$\frac{F_o}{F} = e^{\mu x}. \tag{8}$$

The attenuation (dB) has been calculated for some of the data points to illustrate the variation with gamma particle energy level. Attenuation in decibels is derived as follows:

$$dB = 10 \log \frac{F_o}{F} \tag{9}$$

The assumption has been made that the density of dry and loose soil is about 70-80 percent of the density of sand, thus the reduction in shielding effectiveness. This approximation is consistent with data provided by DCPA (1976)--estimates of shielding factors for fallout shelter design.

3.3 Personnel Protection

3.3.1 Stress Protection

The primary method of protection for personnel that are necessary for the operation or maintenance of the telecommunication system is to provide a protective environment. Design changes are obviously not an option. Protection from the natural elements and events of nature can be effected by providing a work area that is physically durable. Buildings such as those used

Table 18. Half-Value Thickness vs. Energy for Gamma Radiation (AEC, 1960)

Material Type	Half-Value Thickness (cm) @1 MeV	@3 MeV	@6 MeV
Lead	.87 cm	1.37 cm	1.48 cm
Steel	1.51 cm	2.51 cm	2.96 cm
Concrete	4.5 cm	7.89 cm	10.73 cm
Sand	4.95 cm	8.4 cm	11.81 cm
Water	9.82 cm	17.5 cm	25.02 cm

Table 19. Half-Value Thickness and Tenth-Value Thicknesses for Industrial Radiographic Sources (AIHA, 1982)

Radio		Half-Value Thickness (cm)		Tenth-Value Thickness (cm)	
Isotope	Energy (MeV)	Lead	Concrete	Lead	Concrete
Ra-226	0.047-2.4	1.7	6.9	5.5	23.4
Co-60	1.17, 1.33	1.2	6.2	4.1	20.6
Cs-137	0.662	0.65	4.8	2.2	15.8
Ir-192	0.136, 1.065	0.6	4.3	2.0	14.7

Table 20. Material Thicknesses of Various Materials that Provide the Same Shield Effect as 36 in of Sand

Material	1 MeV	6 MeV
Lead	6.3 in	9.9 in
Steel	10.9 in	21.4 in
Sand	36.0 in	85.9 in
Water	71.4 in	181.9 in

Table 21. Absorption Factors (DCPA, 1976)

		Absorption Factor $\left(\frac{F_o}{F}\right)$ $F = F_o e^{-\mu x}$	
Material Type	@ 1 MeV	@ 3 MeV	@ 6 MeV
12" Concrete	73.7	11.6	6.1
12" Sand	71.5	12.4	6.0
12" Clay	52.7	11.5	5.4
12" Earth, Dry and Loose	38.9	8.6	4.6
24" Concrete	5437	136	37.0
24" Sand	5115 (37.1dB)	153 (21.9dB)	35.9 (15.6dB)
24" Earth, Dry and Loose	1510 (31.8dB)	75 (18.7dB)	22.1 (13.3dB)
36" Sand	362,000 (55.6dB)	1883 (32.7dB)	214 (32.7dB)
36" Earth, Dry and Loose	58,000 (47.6dB)	1568 (28.1dB)	224 (20.0dB)
48" Sand	25,800,000 (74.1dB)	23313 (43.7dB)	1281 (31.1dB)
48" Earth, Dry and Loose	2,300,000 (63.5dB)	5542 (37.4dB)	461 (26.6dB)

$$dB = 10 \log \left(\frac{F_o}{F}\right)$$

for regenerator enclosures would be adequate; however, other designs may provide a more comfortable work space.

Protection from the results of a nuclear detonation can only be obtained by providing an underground facility. Placing the work space underground will reduce or eliminate the effects of blast from the detonation, heat from the blast, and gamma radiation that will result from the nuclear fallout. Table 22 analyzes the stress sensitivities of people and attempts to suggest what variables can effect a solution to the need for personnel protection.

Table 22. Personnel Stress Sensitivities

		Solution	
Stress	Effect	Technology	Environment
Natural Events/Disasters	Slow Down	X	X
Lightning/EMP	Disable	X	-
Gamma Radiation	Disable	-	X

3.3.2 Safe Radiation Levels

The human body is probably the most sensitive component in the system if personal intervention is necessary for operation. Table 23 shows the level of injury that occurs for incrementally higher levels of radiation. Figure 17 illustrates the short and long term effects of radiation--defining the safe levels, the recovery times, and the levels of radiation that will result in death.

If short-term functioning of the individual is important, e.g., for operational function or maintenance, the safe level as taken from Table 23 is 50 roentgens (50 rads) or less. For purposes of this study one roentgen will be assumed to equal one rad. Levels above 50 roentgens, will cause sickness that will hamper the person's effectiveness in performing his/her jobs; therefore it is important that the radiation level is reduced through shielding to a point that is safe for personnel.

The shield factors for personnel protection have been included in shield effectiveness data presented in Section 4 of this report. The analysis shows that the shield requirement for personnel and fiber optic components (e.g., the optical fibers) is very similar--the safe radiation levels are 50-100 rads for

Table 23. Summary of Relationship Between Exposure and Level of Radiation Sickness* (after FEMA, 1980)

Exposure Range	Type of Injury	Probable Mortality Rate Within 6 Months of Exposure
0 - 50R **	No observable signs or Symptoms	None
50 - 200R	Level I Sickness	Less than 5 percent
200 - 450R	Level II Sickness	Less than 50 percent
450 - 600R	Level III Sickness	More than 50 percent
More than 600R	Levels IV & V Sickness	100 percent

*Adapted from National Council on Radiological Protection and Measurements, Radiological Factor Affecting Decision-Making in a Nuclear Attack, Report No. 42, November 1974.

** Roentgens

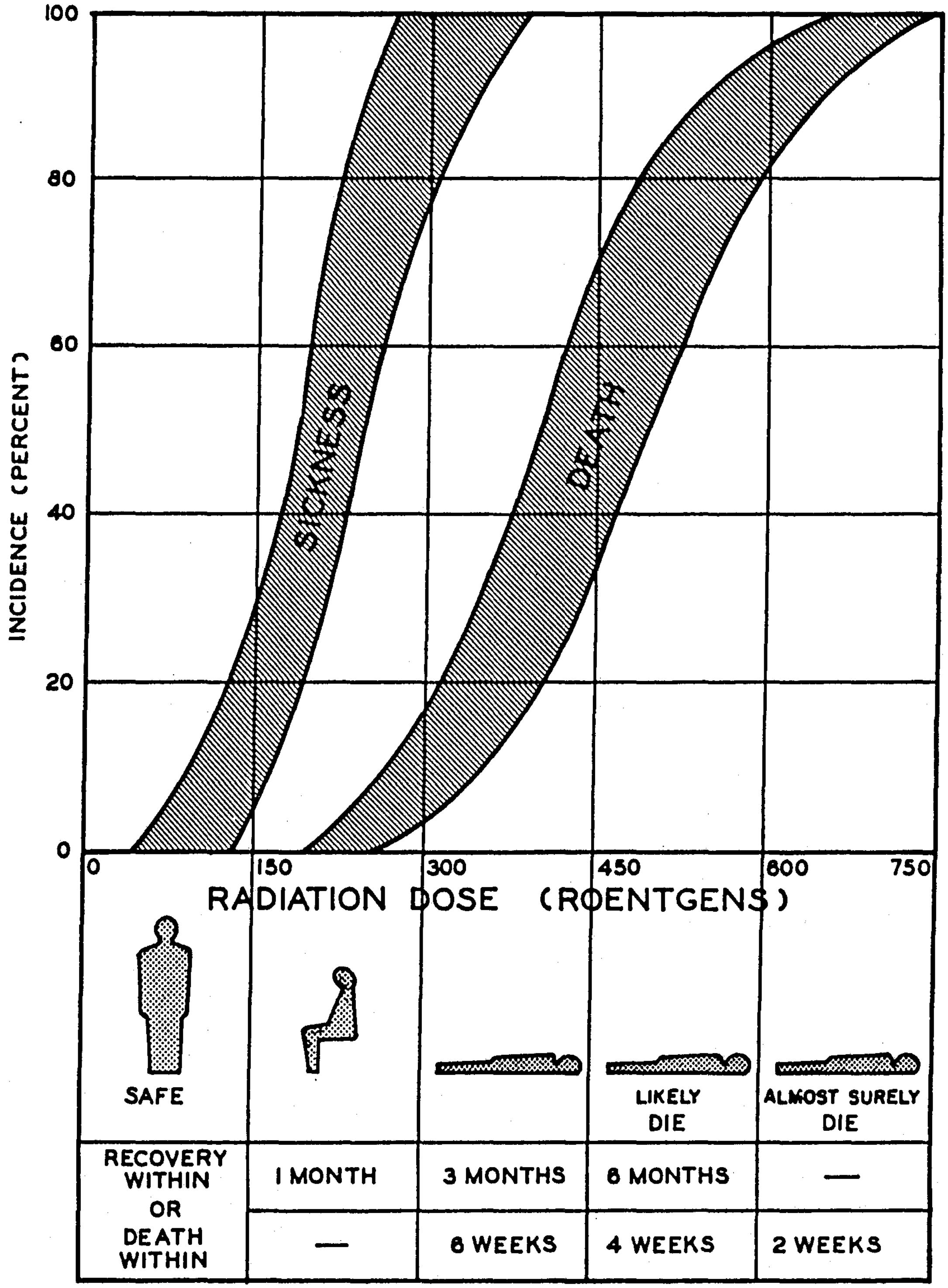

Figure 17. Summary of effects of radiation exposure (after FEMA, 1985).

both. The upper levels of the Multitier Specification provide full protection for personnel as shown in the Section 4 analysis.

4. SOLUTIONS

4.1 Background

Solutions are found through design enhancement and/or environment enhancement--frequently a combination of both is the most effective solution. Design enhancements must be selectively implemented. A particular design attribute may be adequate to eliminate or reduce a targeted stress, but may not provide any stress relief for another stress condition. Figure 18 illustrates the application of design enhancement and the limits on expected results.

Tables 24 through 26 list the enhancements, for the cable and the regenerator, that are judged to be the most effective for stress reduction. Each table lists enhancements in the order of importance for providing short-term benefits. While long-term benefits are important, they are much more difficult to assess and maintain. A comprehensive plan for maintenance of the enhancements is under study. A limited plan for monitoring the integrity of the enhancements is contained in the Federal Emergency Management Agency (FEMA) Civil Preparedness Guide that is specifically directed at EMP enhancements (FEMA, 1986). The ideas and procedures set forth in this guide could be used as a basis for monitoring the integrity of other enhancements.

Design enhancements are obviously an important part of the total enhancement program, but these features are very difficult to develop and, in most cases, very slow to be implemented. The cost penalty is often great and not all manufacturers are able to incorporate the changes in their manufacturing process. Thus enhancement through design changes of components (e.g., cable configuration, fiber, cable sheath, regenerator optoelectronics, regenerator enclosure) is a very slow process. Manufacturers of components can be enticed to incorporate changes by illustrating the benefits, but cannot be required to comply.

On the other hand, implementation of environmental enhancements is much easier to effect because, in most cases, the installing company accrues "benefits of economy" from the enhancements. Installing companies are willing to incorporate enhancements if they can reduce their maintenance cost or reduce the system down time.

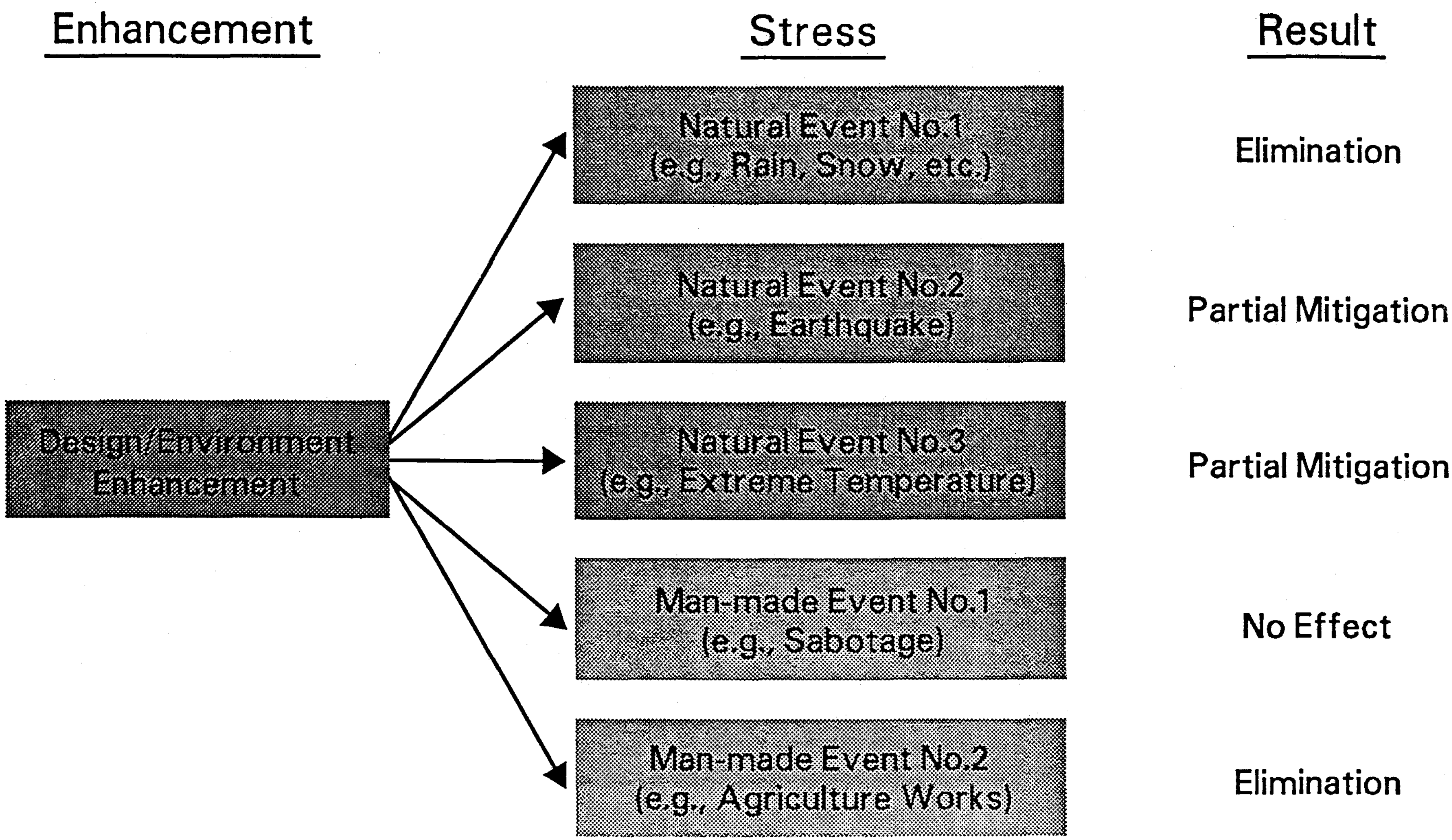

Figure 18. Solutions through design/environment enhancement.

Table 24. Cable Design Features/Enhancements

	Enhancement (Short-Term Benefit)	Primary Benefit	Negatives
1.	Eliminate Metallic Central Strength Member	Lightning/EMP Protection	Mechanical Stress
2.	All Dielectric Cable Design	Lightning/EMP Protection	Cost Rodents
3.	Low Resistance Sheath	Lightning/EMP Protection	Cost
4.	Stainless Steel Sheath	Rodent Protection	Cost
5.	Loose Tube or Slot Design	Tensile and Compression Stress Protection	-
6.	Chemical Resistant Sheath	Chemical/Corrosion Protection	-
7.	Silica Fiber Material (phosphorus free) or with equivalent design characteristics	Gamma Radiation Loss Reduction	Cost

Table 25. Cable Environmental Protection Enhancements

	Enhancement	Primary Benefits	Negatives
1.	Underground >36 in - Open space plow-in or trench	Protection from all natural events including wind, rain, ice, snow, flood, temperature extremes, vandalism, sabotage, and gamma radiation	Earthquake/Ground Shifts Rodents
2.	Underground >36 in - Includes obstructions such as bridges, viaducts, highway crossings, rocky areas, etc.	Same as above	Cost Ground Shifts Rodents
4.	Place cable in rigid conduit	Physical protection from natural and man-made stress	Cost
5.	Place cable in existing duct or pipe	Physical protection from natural and man-made stress	-
3.	Underground >36 in - splice enclosures	Same as above	Cost
6.	Meaningful ground for metallic components, e.g., central strength member and metallic sheath	Lightning & EMP protection	-
7.	Install slack pits, e.g., at 250 m intervals (creates slack cable for ground separation)	Earthquake protection	Cost
8.	Surround cable with concrete	Construction and accidental damage prevention	Cost
9.	Place marker tape above cable location, mark splice boxes	Construction and accidental damage prevention	Cost Vandalism

Table 26. Regenerator Protection Enhancements

Enhancement	Primary Benefit	Negatives
Design		
1. Transient Circuit Design Techniques	Lightning/EMP	-
2. Grounding Techniques - Optoelectronics	Lightning/EMP	-
3. Grounding System - Enclosure	Lightning/EMP	-
4. Blast Resistant Design	Nuclear blast to 2 psi Gun shots Vandalism Weathering	-
5. Underground Installation	Minimizes all stress	Cost
6. Electromagnetic Shielding	Lightning/EMP	Cost

Table 27 lists the most beneficial enhancements that can be installed now. The benefits for each have been discussed previously. If these enhancements would be incorporated in all installations of fiber optic systems, the durability of the United States' telecommunication network would be significantly improved. The cost of installation is low and the technology and knowledge required is readily available.

Table 27. Summary (Most Beneficial Enhancements)

1.	Underground Installation of Cable and Regenerator [> 36 in (0.9 m) everywhere]
2.	Grounding, Bonding, and Shielding (Electronics, Power System, Building) • MIL-HDBK-419, (1982) • FEMA EMP PROTECTION GUIDE, CPG 2-17, (1986) • AT&T Telecommunication Electrical Protection Manual, (1985)
3.	Eliminate Cable Metallic Strength Member
4.	Rodent-Proof Cable Design
5.	Chemical-Resistant Cable Sheath
6.	Radiation-Resistant Fiber

4.2 General Optical Fiber Cable Characteristics

4.2.1 Absence of Latent Residual Stress

The residual stress on fibers during or after installation should not degrade the mechanical stability or transmission performance as long as specified construction practices are followed.

4.2.2 Absence of Hydrogen Gas

The integrity of the cable configuration should be such that, during normal shipping, storage, or installation, the concentration of hydrogen will be so small as to cause no degradation of mechanical parameters or affect the transmission performance.

4.2.3 Localization of Fiber Breaks due to Construction Dig ups or Earthquake Activity

The goal will be to replace the shortest possible segment of cable if damage or a break should occur. The cable design should be such that the fiber will break within 5 m of the stress point. A short segment of cable (about 25 m) will suffice for rejoining the cable.

4.2.4 Chemical Resistance

The cable design should include two design attributes that will increase its chemical resistance:

1. blocking gel or filler material that will not allow entry of water or chemicals along the axis of the cable

2. a single or multilayer sheath that will block lateral entry of water or chemicals

4.2.5 Absence of Metallic Central Strength Element

EMP simulation tests completed under contract by National Communications System (NCS) suggest that arcing will occur between current carrying conductors within a cable (NCS, 1985b). The possibility exists that arcing could occur from the metallic central strength member and the outer sheath, if the sheath is metallic, or to the ground if the cable does not have a metallic sheath. If the arc occurred near or through the optical fiber, damage could occur resulting in an interruption of service. A direct hit from lightning is likely to vaporize some parts of components, and possibly the central strength element, resulting in exploding the cable assembly.

Nonmetallic materials such as plastic, aramide fiber, and fiber-reinforced plastic (FRP) are being used by manufacturers to replace the metallic component (CCITT, 1985). This alternate design must include an analysis to ensure that residual stress within the configuration does not affect the mechanical stability or the transmission performance. The mechanical behavior of candidates for use as a central strength member vary when subjected to tensile stress as shown in Figure 19 (CCITT, 1985).

4.2.6 Insensitivity to Temperature Extremes

The cable must be insensitive to temperature extremes during storage, installation, and operation. A risk of damage during installation is of

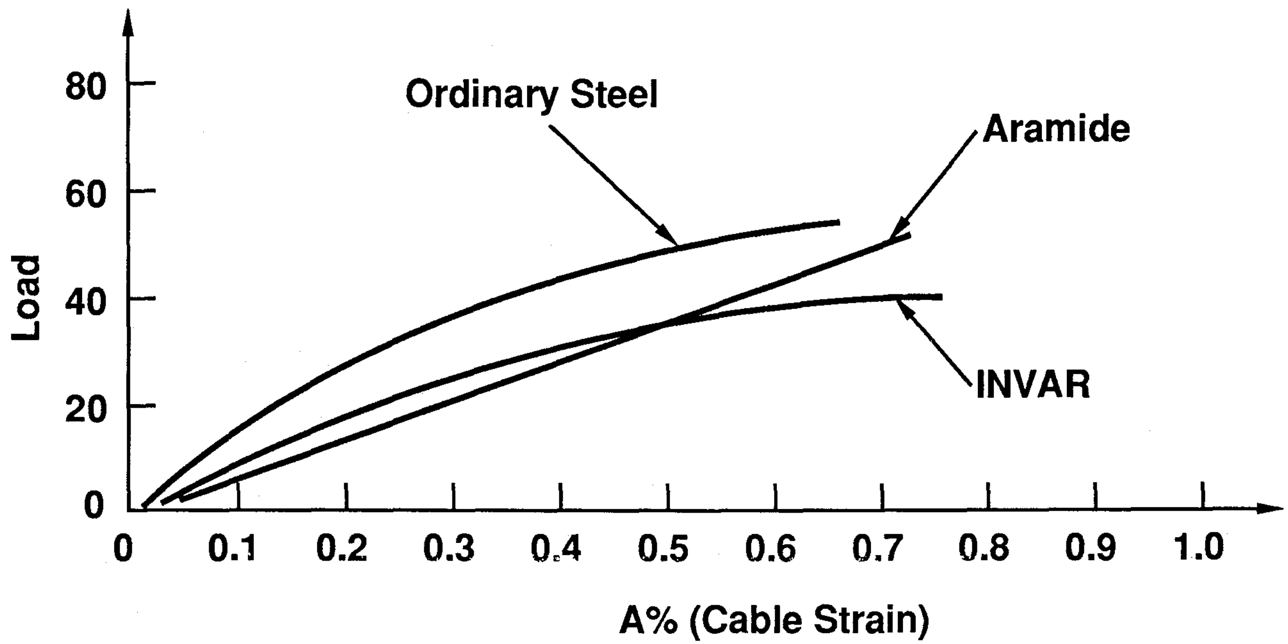

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Figure 19. Mechanical behavior of central strength member materials.

primary concern; thus the safe temperature range must be determined and specified. During storage and operation the concern is that the mechanical stability and transmission performance be maintained.

Typical temperature ranges for storage, installation, and operation are listed in Table 28.

Table 28. Safe Temperature Ranges

	°F	°C
Storage Temperature Range	-40 to +160	-40 to +71
Installation Temperature Range	-20 to +140	-40 to +60
Operating Temperature Range	-40 to +160	-40 to +71

Temperature extremes across the United States will exceed the limits stated above at some time during the lifetime of the cable. Figures 20 through 25 show the contours for minimum and maximum temperature extremes for 2-, 50-, and 100-year "return periods" across the continental United States. For installations that traverse the areas where temperatures exceed the "safe temperature" (See Table 28), the cable must be protected to avoid interruption of service. Table 29 lists the extreme temperatures for the entire United States.

Table 29. Temperature Extremes

	Minimum / Maximum	
Return Periods	°F	°C
2 year	-40 / +112	-40 / +44
50 year	-64 / +124	-53 / +51
100 year	-64 / +124	-53 / +51

On the surface of the Earth, the temperatures listed in Table 29 are even more extreme due to physical effects at the Earth's surface. Table 30 gives an estimate of the actual surface temperature for a selected high and low

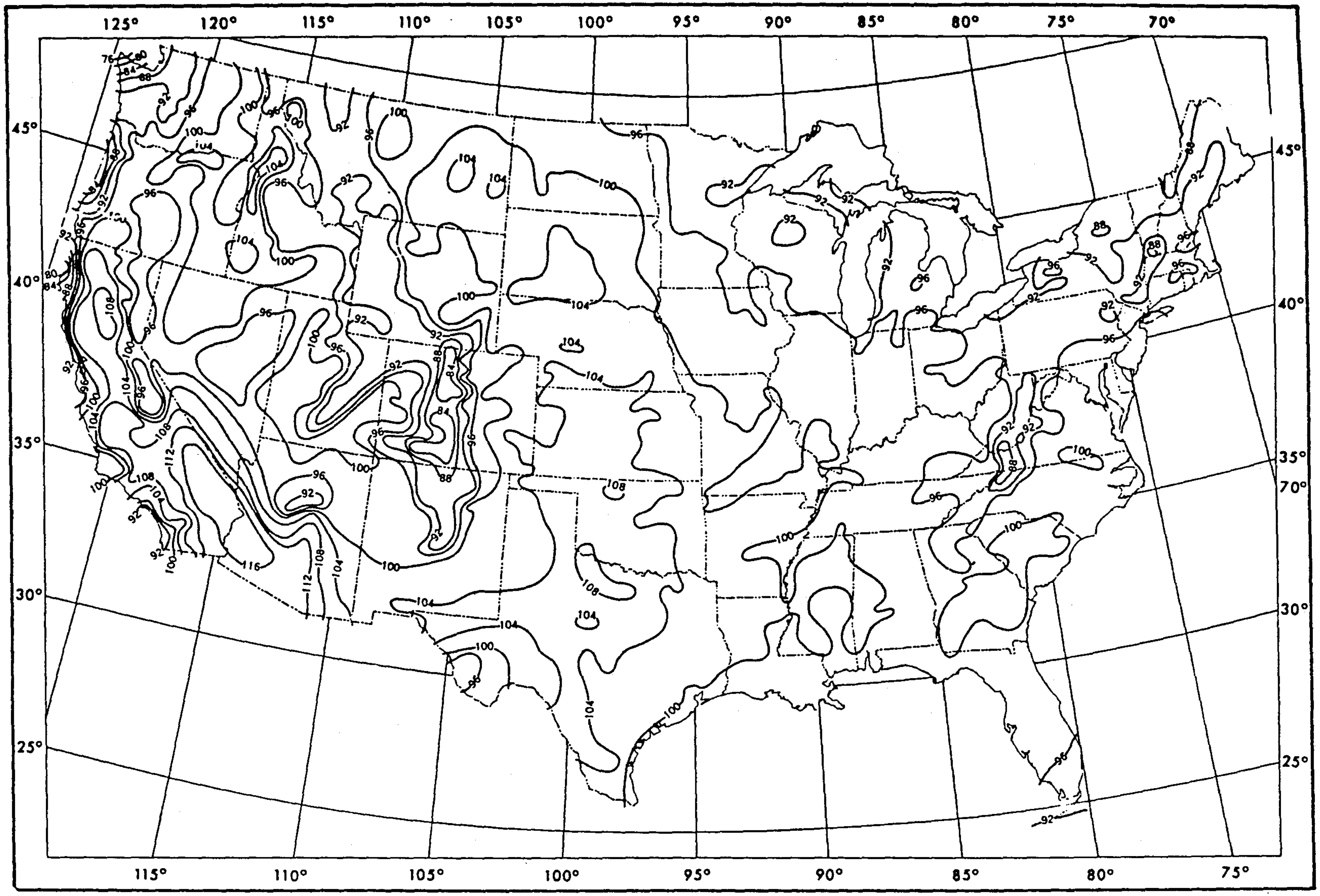

Figure 20. Extreme annual maximum temperature for the .5 probability level (2-year return period).

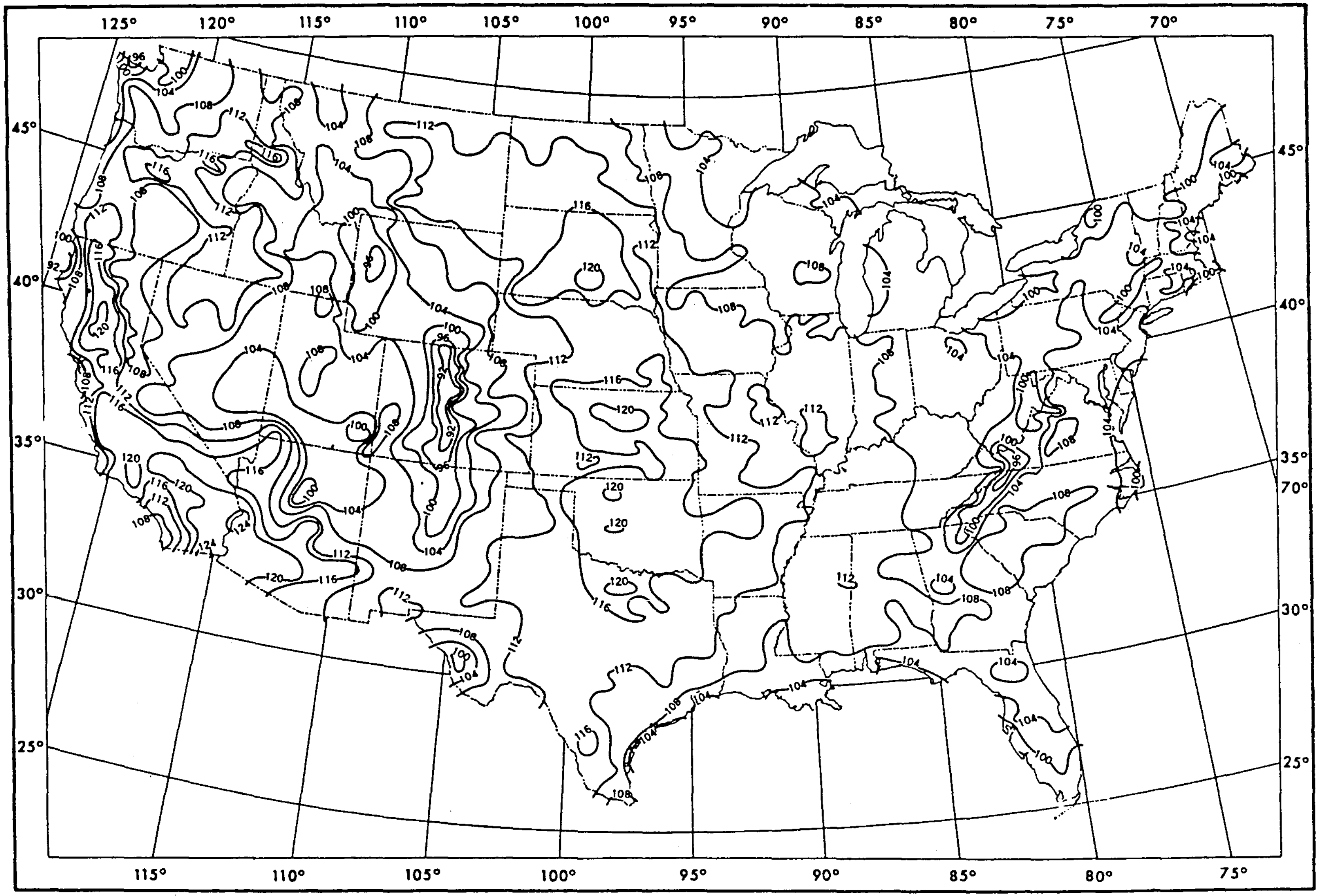

Figure 21. Extreme annual maximum temperature for the .98 probability level (50-year return period).

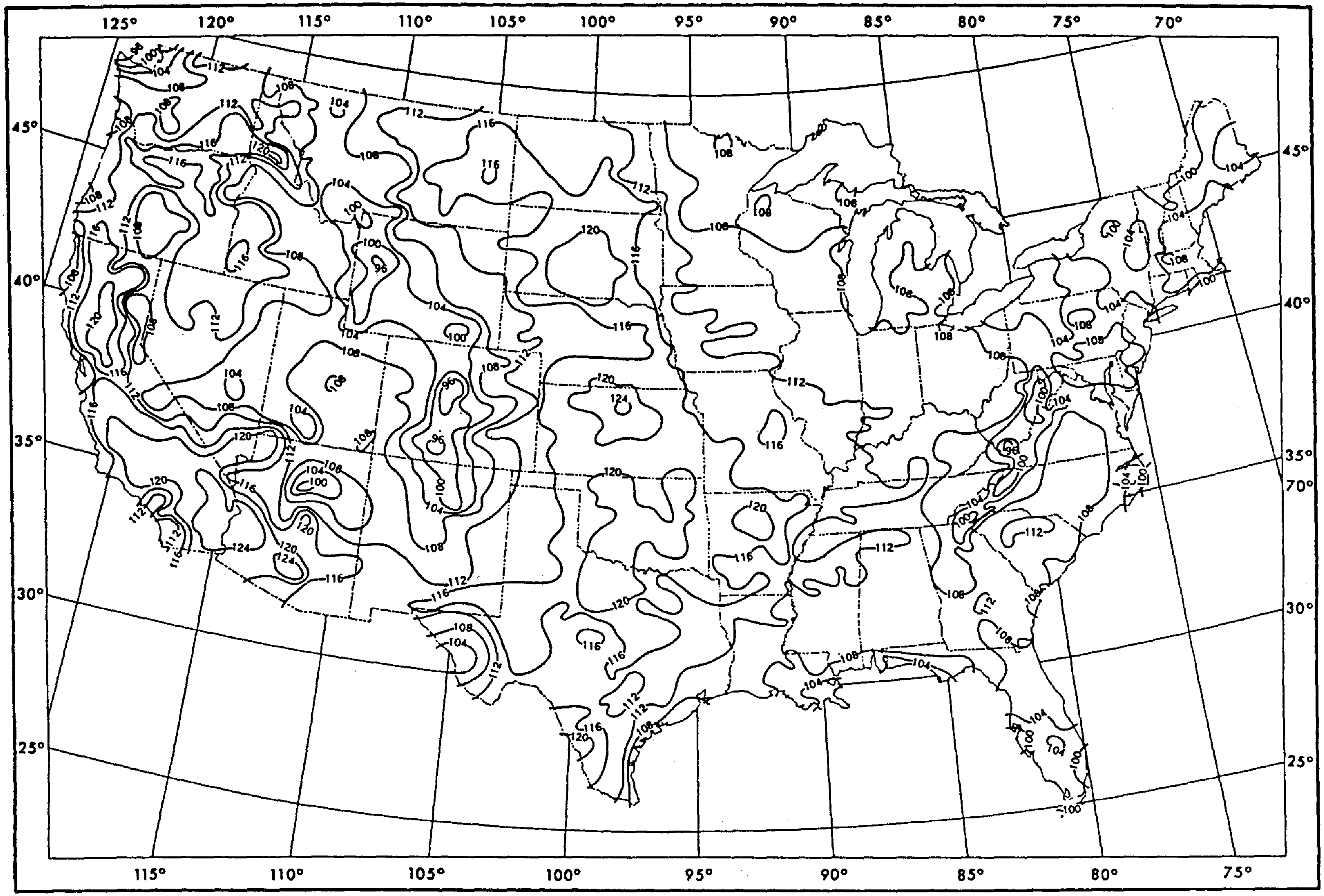

Figure 22. Extreme annual maximum temperature for the .99 probability level (100-year return period).

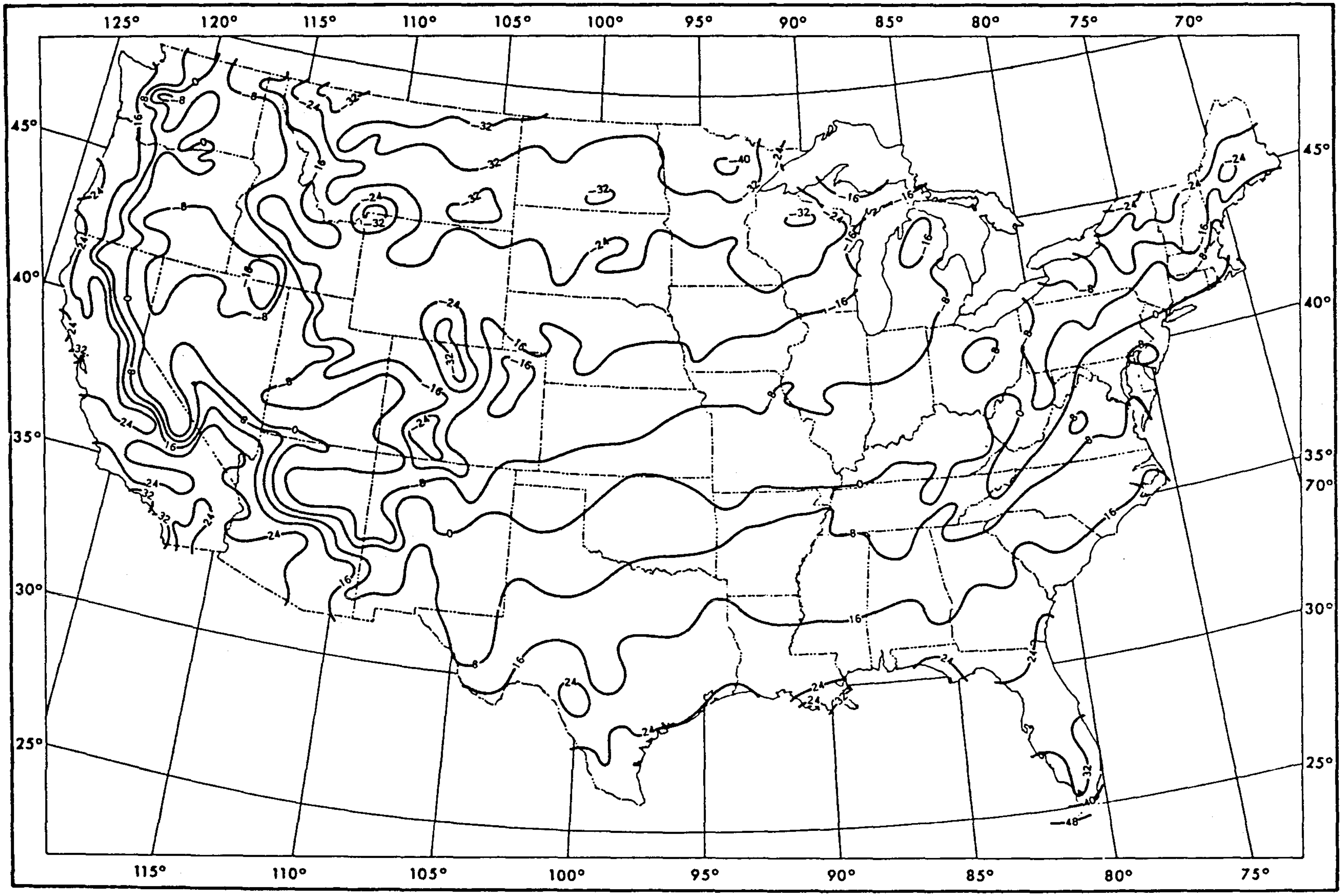

Figure 23. Extreme annual minimum temperature for the .5 probability level (2-year return period).

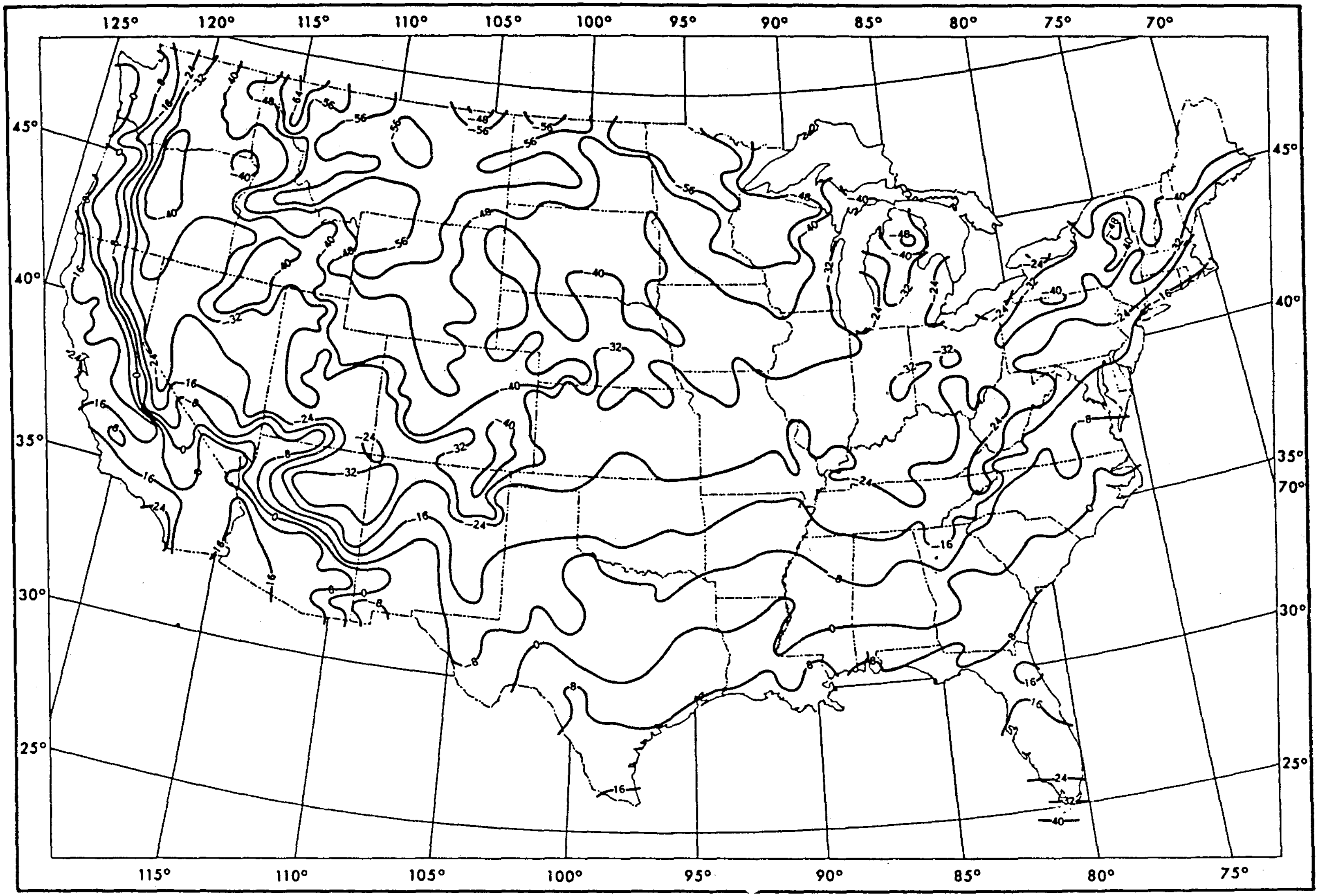

Figure 24. Extreme annual minimum temperature for the .98 probability level (50-year return period).

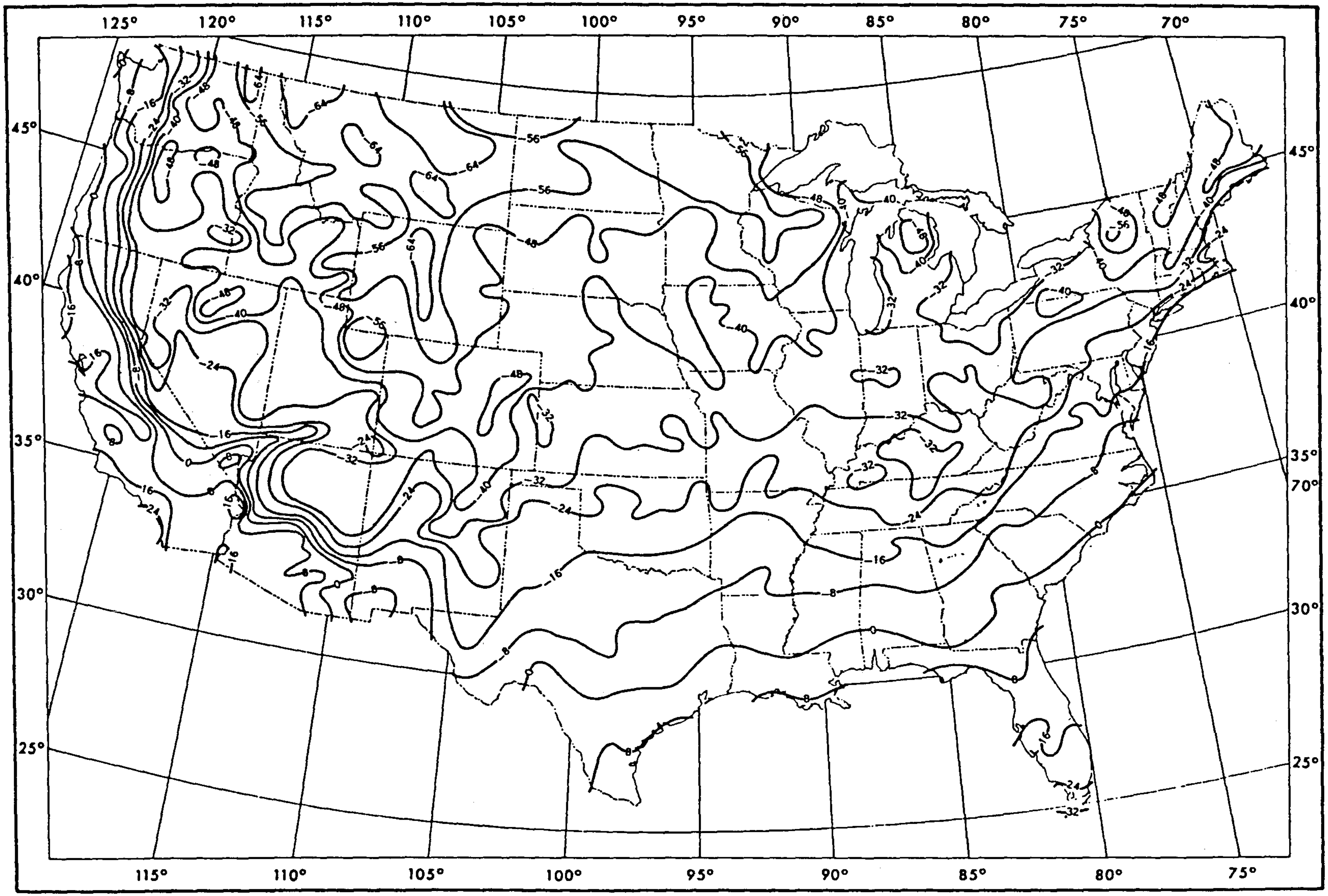

Figure 25. Extreme annual minimum temperature for the .99 probability level (100-year return period).

temperature (results of data compiled by Colorado State University climatologists).

Table 30. Surface Temperature Variations

	°F	°C
Surface air temperature	-40 to +120	-40 to +49
Surface (Earth) temperature	-44 to +150	-42 to +66

Placing the cable, or any other component, on the surface of the Earth is not recommended. The temperature extremes are "worst case" for the surface air as shown above. A black fiber optic cable placed on the surface of the Earth, and exposed to direct sunlight, may experience temperatures even higher than noted in Table 30.

A solution to these problems is placement of the components underground. The exposure to events of nature that occur on the surface of the Earth is significantly reduced, and the temperature effects will be tempered to a great extent. Table 31 illustrates the moderation of temperature extremes as a function of depth below the surface. These values are sampled from data compiled by Colorado State University climatologists.

4.2.7 Metal-free Cable

Metal-free (nonmetallic) cable has the advantage not only of lightness, but also of immunity to lightning, electric corrosion, electromagnetic interference, and electric hazard to personnel. In addition, the cable will not pick up energy from electromagnetic pulse (EMP).

The metal will not provide a moisture barrier; thus the outer sheath must block all chemicals and moisture. Or if the conditions are severe, a gas filled conduit can be used to protect the cable.

Table 31. Temperature Moderation Effect vs. Depth Underground

	Temperature Range	
Component Depth	°F	°C
Surface Level	-40 to 120	-40 to 49
2 Feet Below Surface	35 to 70	2 to 21
3 Feet Below Surface	38 to 68	3 to 20
4 Feet Below Surface	41 to 66	5 to 19

4.2.8 Rodent Resistant Sheath

Rodents such as gophers, squirrels, and rats are a threat to a fiber optic cable. Although squirrels are capable of chewing and damaging cable, they do not frequently cause an interruption. Only installations that are above ground are subject to squirrel damage. These installations are also subject to damage by numerous other natural events and these installations expect interruptions of service. Thus the concentration should be on gophers--primarily an underground problem.

The threat can best be understood by data that show the biting force for each of the rodent types. Table 32 lists the mean and maximum force recorded in tests performed at the Wildlife Research Center, Denver, CO (Cogelia et al., 1976). The data show that the rodents will attack with rapid bites with rates up to 6 per second with an average of 1.5 bites per second.

Table 32. Biting Force of Common Rodents (Cogelia et al., 1976)

	Biting Pressure (lbs/in^2)	
Rodent Type	Mean	Maximum
Gray Squirrel	22,245	25,385
Pocket Gopher	18,300	24,000
Norway Rat	7,115	11,642

The incisors (teeth) of the rodents are extremely hard--a measured Shore D Hardness of 93-95 for all three rodent types is noted by Cogelia et al. (1976). The method of measuring material hardness using the Shore D durometer is described in the American Society for Testing and materials (ASTM, 1975).

Common sense dictates that the protection material must be of at least an equivalent hardness or greater. It should be noted also that a rodent must chew on something in order that the incisor length is controlled. Typical growth rate of the incisor can be up to 12 inches per year as reported by Connelly and Cogelia, 1970. Obviously there is an incentive to keep chewing on something hard--even if it is not food.

The solution lies in three areas:

1. covering the cable with a material hard enough to sustain the gopher chewing

2. making the diameter large--exceeding the opening of the rodents incisors (Connelly and Cogelia, 1970)

3. making the cable material distasteful.

Table 33 lists the Shore D Hardness values for several metals and plastic materials commonly used for cable sheath or as innerduct material (Cogelia et al., 1976; unpublished data from AT&T Bell Laboratories, Norcross, GA). Only the stainless steel and tin-plate materials listed have a hardness value equivalent to the hardness of the rodent incisor. In addition, a toughness index is used by Cogelia et al. (1976), to recommend the most likely candidate for use as a cable sheath. For example, Type 304 stainless steel has much higher Toughness Index than Type 430 stainless steel; therefore it is likely a better candidate--unless another parameter precludes its use.

Hardness alone is not sufficient to resist the gnawing of the rodents--a toughness index, as defined by Cogelia et al. (1976), is also important to control the deformation of the shield material. Figure 26 illustrates that at a toughness index of 16.5, or greater, the survival rate of cable sheath is near 100 percent. If the hardness and toughness is of a sufficient value, as defined by Table 33 and Figure 26, the rodent threat can be eliminated.

The second parameter that can effect the level of rodent threat is the outside diameter of the protective cable sheath. An outside diameter of about 2.1 inches or greater is reported by Connelly and Cogelia (1970) to be safe from the Plains Gopher's bite. Since a fiber optic cable is not likely to be that large, this solution can be implemented by placing the cable inside a rigid duct of this diameter or larger. The duct material must be hard enough to repel the rodent incisor, in addition to having a sufficient diameter.

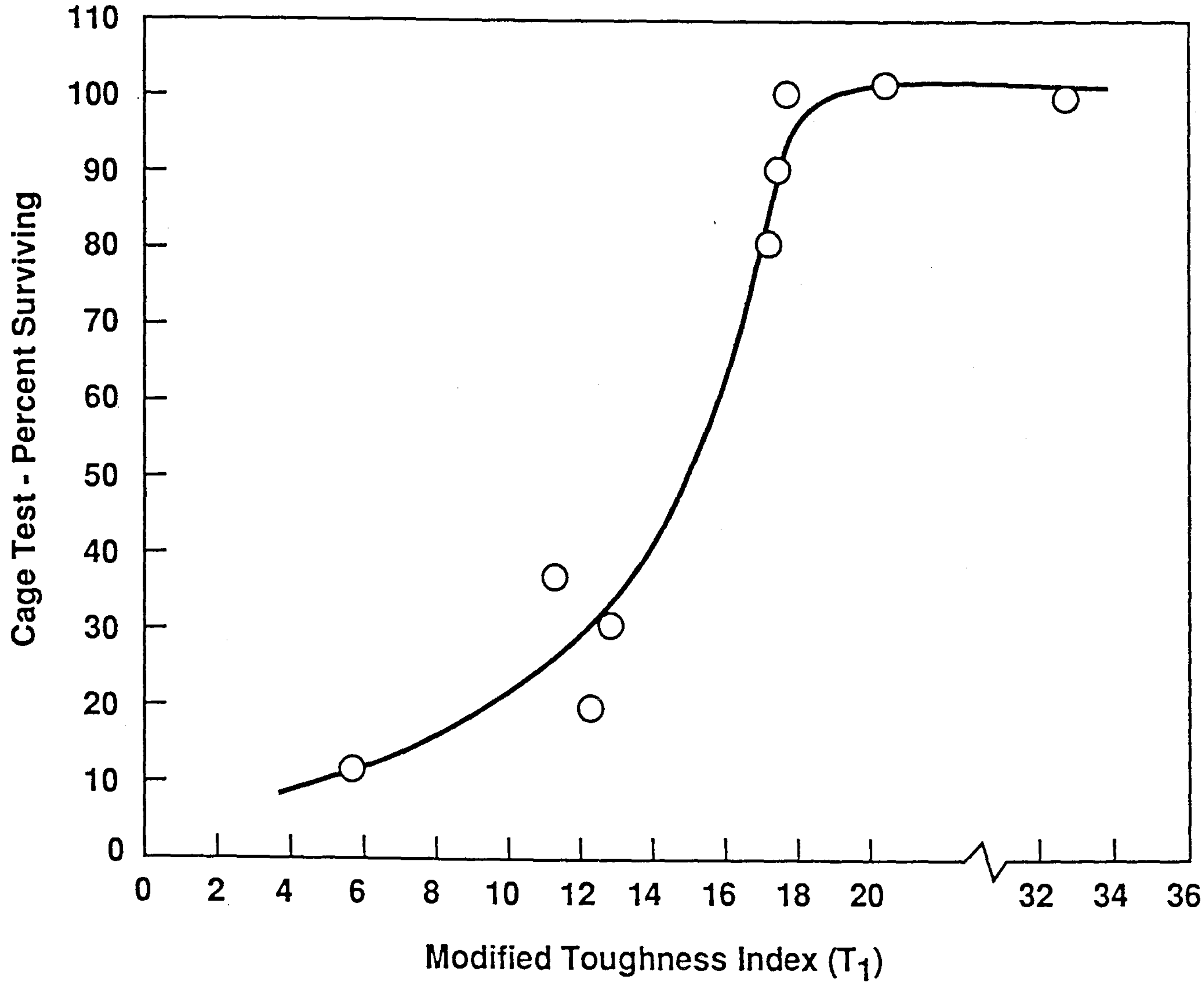

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Figure 26. Determination of optimum toughness index (Cogelia et al., 1976).

Table 33. Shore D Hardness Values for Sheath Materials (Cogelia et al., 1976)

Shield Material	Shore D Hardness	
	Rodent Incisor	Sheath Material
CDA 220: Bronze-1/4 hard	93-95	94
Terneplate(Lead-Tin plated steel)	93-95	94-95
Stainless Steel: Type 440	93-95	95
Stainless Steel: Type 304	93-95	95
Galvanized Steel	93-95	95-98
Annealed Copper	93-95	79
Polyethylene(low density)	93-95	45-49
Polyethylene(high density)	93-95	58-60
644 PVC	93-95	48-50

4.3 General Regenerator Electronics and Opto-electronics Characteristics

Realizing that the cost to implement design changes that would significantly increase the stress resistance of the electronics would be extremely high, for purposes of this report, enhancements to the electronics will not be considered. Ingenuity beyond our vision, at present, could change this perspective, however.

4.3.1 Electromagnetic Interference Design Practices

The assumption is made that circuit design practices that will suppress transients and other electromagnetic interference will be incorporated by the manufacturer. A list of design enhancements are included--however this is not an exhaustive list. Much of the design technique must be tailored to the specific application using learned (frequently by trial-and-error) skills for optimizing the transfer function of the system being designed.

- Shielding--Components shall be housed in chassis, drawers, or other enclosures that provide a continuous metallic, conductive shield with a minimum of apertures. Enclosures that meet EMI, EMC, and TEMPEST specification are acceptable.

  Except where access is required, the component (system) housing structure (enclosure) must be metal and must have continuous joined conductive seams. Attachment methods described in MIL-HDBK-419 (DOD, 1982) are adequate. Bonding requirements of MIL-STD-188-124A (DOD, 1984) apply.

  Housing apertures greater than 2.5 cm in the largest dimension must use honeycomb, perforated panel, or wire mesh as the application permits. No uncovered single aperture shall be larger than 2.5 cm in the largest dimension, and the apertures shall total less than one-half of the surface area on which they exist. The guidelines presented by Harry Diamond Laboratories, describing the protection necessary for Defense Switched Networks (Miletta et al., 1982) apply.

- Isolation--Techniques for isolating the dc and ac ground systems are described by Miletta et al., 1982. These guidelines illustrate the implementation of the grounding systems commonly used for telecommunication systems and other isolation techniques as follows:

  1. Power system dc and ac ground network separation

  2. Signal and control cable buffering using isolation transformers and opto-isolators for balanced signal paths. Unbalanced signal paths require no special isolation precautions.

  3. Spacing of apertures (shield ingress/egress openings) to ensure ground shield integrity.

4.3.2 Transient Suppression Design Practices

- Transient suppression--Transients shall be suppressed by Transient Protection Devices (TPDs) at the enclosure power, signal, and control cable entries. Three stages of protection can be implemented:

  Stage 1 at the ac primary power input to the regenerator enclosure,

  Stage 2 at the ac power input to the equipment within the regenerator enclosure, and

  Stage 3 at the dc power supply lines that furnish dc power to the regenerator electronics and the optoelectronics.

  All phases of the power input should be protected as shown in Figure 27. The number of metal oxide varistor (MOV) devices, required and installed, depends on whether power system is delta or wye or a variation as illustrated.

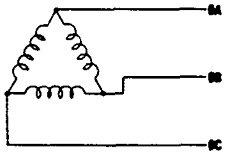
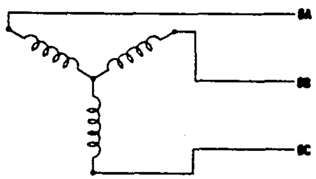
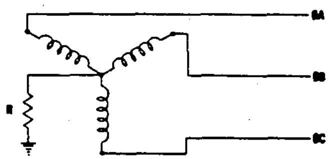
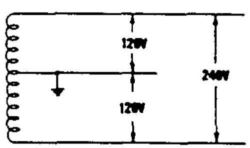
Configuration	Nominal system voltage (V)	Phase-to-phase voltage (V)	Phase-to-neutral voltage (V)	Phase-to-ground voltage (V)	Phase-to-ground MOV
Ungrounded delta 	240	240		Varies with system capacitance	V250HE250 or V250PA40C (3 each)
	480	480		Varies with system capacitance	V480HE450 or V480PA40A (3 each)
Ungrounded or resistance grounded wye  	480	480		Varies with system capacitance	V480HE450 or V480PA40A (3 each)
Single-phase grounded neutral 	120/240	240	120	120	V130HE150 or V130PA20A

Figure 27. MOV protector selection for various power-source configurations (after FEMA, 1986).

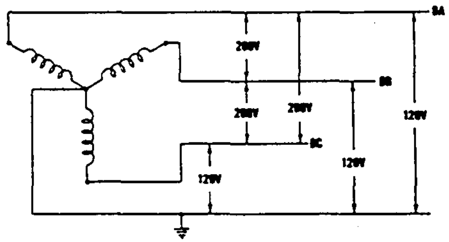
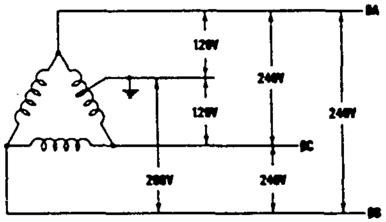
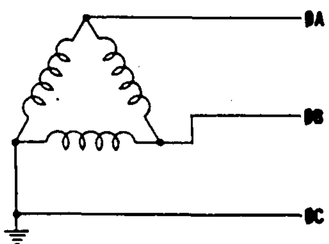
Configuration	Nominal system voltage (V)	Phase-to-phase voltage (V)	Phase-to-neutral voltage (V)	Phase-to-ground voltage (V)	Phase-to-ground MOV
Grounded wye	120/208	208	120	120	V130HE150 or V130PA20A (3 each)
	277/480	480	277	277	V275HE250 or V275PA40A (3 each)
Center-tapped delta	240, center tapped	240		Phase A - 120	V130HE150 or V130PA20A
				Phase B - 208	V250HE250 or V250PA40C
				Phase C - 120	V130HE150 or V130PA20A
Corner-grounded delta	240	240		Phase A - 240	V250HE250 or V250PA40C
				Phase B - 240	V250HE250 or V250PA40C
				Phase C - 0	V250HE250 or V250PA40C
	480	480		Phase A - 480	V480HE450 or V480PA40A
				Phase B - 480	V480HE450 or V480PA40A
				Phase C - 0	V480HE450 or V480PA40A

Figure 27. (cont.) MOV protector selection for various power-source configurations (after FEMA, 1986).

Stage 1 and 2 protection (ac) can be effected with use of MOVs. The varistor response time to transients is < 1 nanosecond (FEMA, 1986). These devices will recover--with the recovery time dependent on the heat dissipation available and the rise in temperature that has occurred within the varistor during the conducting of the transient. When exposed to high-frequency transients, the varistor impedance changes from a high quasi-static value to a low-dynamic conducting value, resulting in a shunting effect and a reflection point for incident transients and reducing transient peaks to 1.5 to 4 times the peak rated operational voltage. For low duty cycles, the lifetime of the MOV is indefinite. Based on experience of FEMA EMP protection engineers, the specifications for the three stages of protection have been developed.

Specification for MOVs used for Stage 1 (power line entrance to the regenerator enclosure) protection are:

1. minimum transient energy dissipation of 150 joules
2. rating of ac working voltage
3. clamping voltage of 2 x ac working voltage at rated current
4. maximum current carrying capacity of 20,000 amps

Stage 2 protection (ac) can be effected with use of MOVs. Specifications for Stage 2 devices should be:

1. minimum transient energy dissipation of 20 joules
2. rating of 1.5 x ac working voltage
3. clamping voltage of 2 x ac working voltage at rated current
4. maximum current capacity of 5,000 amps

Stage 3 protection can be effected with commonly available MOVs--devices typically used by appliance manufacturers to prevent transient damage. These devices have leads that should be cut as short as possible when installed to minimize the inductance of the transient shunt path. Specifications for a Stage 3 device are:

1. minimum transient energy dissipation of 5 joules
2. rating of 1.5 x ac working voltage or less
3. clamping voltage of 2 x ac working voltage at rated current
4. maximum current capacity of 100 amps

Figure 28 illustrates typical MOV devices that are used for Stages 1 through 3 protection. The devices used for Stages 1 and 2 are leadless to reduce the inductance of the shunt path. If jumpers are required for installation, a solid metal strap must be used--preferably made of pure copper.

Transient suppression practices are not specifically required for signal and control cables when they are shielded by a cable shield, conduit, or a tray. Fiber optic cables are treated similar to other cables, except that the signal-carrying component does not require any protection. The fiber optic cable shield (if metallic) grounding practice is described in a later section dedicated to "grounding."

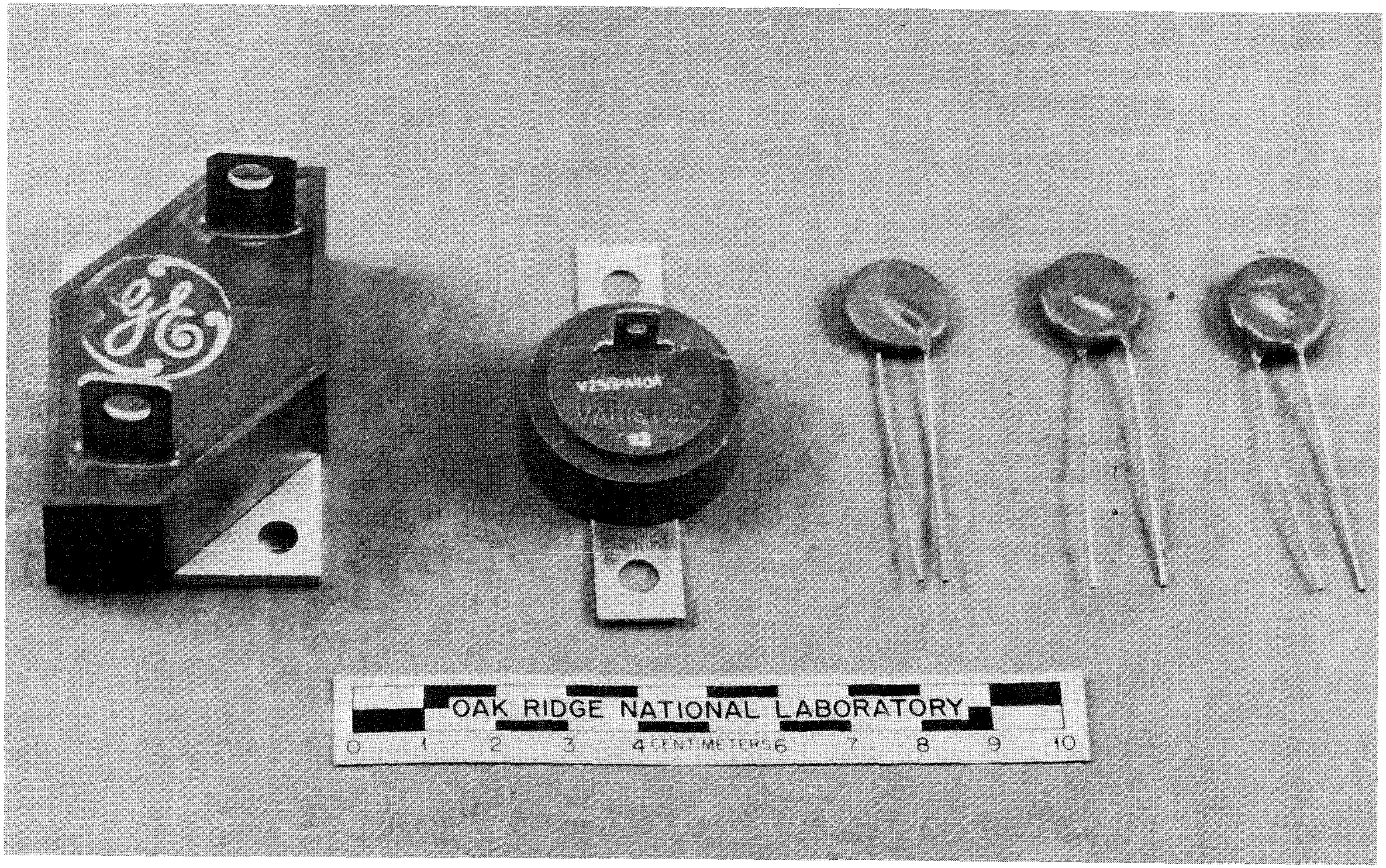


Figure 28. Metal oxide varistors used as transient arrestors on power circuits.

Additional detail concerning implementing transient suppression protection can be obtained from the following referenced publications:

1. Miletta et al. (1982)
2. FEMA (1986)
3. AT&T (1985)

4.4 General Regenerator Enclosure Characteristics

The enclosure is the primary protection for the regenerator electronics, the system cable-to-electronics connection, and the regenerator environmental control system. Stable operating conditions are maintained by providing a durable structure with certain design features that will ensure desired stress protection.

4.4.1 General Structure Design Guidelines

The stress resistance features can be divided into three specific areas of enhancement:

1. enhancement that will increase resistance to wind (resulting from storms) and blast (surface or near-surface explosions)

2. protection enhancement to increase resistance to nuclear radiation (resulting from surface or near-surface nuclear detonation)

3. enhancement that will increase resistance to EMP (resulting from high-altitude nuclear detonation)

Enhancements for wind and blast resistance The structure can be constructed using either precast wall, ceiling, and floor concrete sections or poured-in-place concrete methods. Reinforcement may be necessary to meet winds expected as a result of naturally occurring storms. The expected wind speeds are determined by the severity of the storm--with the highest velocity winds occurring less frequently. Severe winds that recur periodically (2-, 10-, 25-, 50-, and 100-year intervals) are plotted by Hollister (1970) and are presented here as Figures 29 through 33. The "return periods" data are summarized in Table 34. Maximum expected winds vary across the United States, as shown, resulting in somewhat different durability requirement depending on the location of the fiber optic system installation.

The Multitier Specification is designed to provide protection from wind, and consequently, the installation will be protected from blast effects as

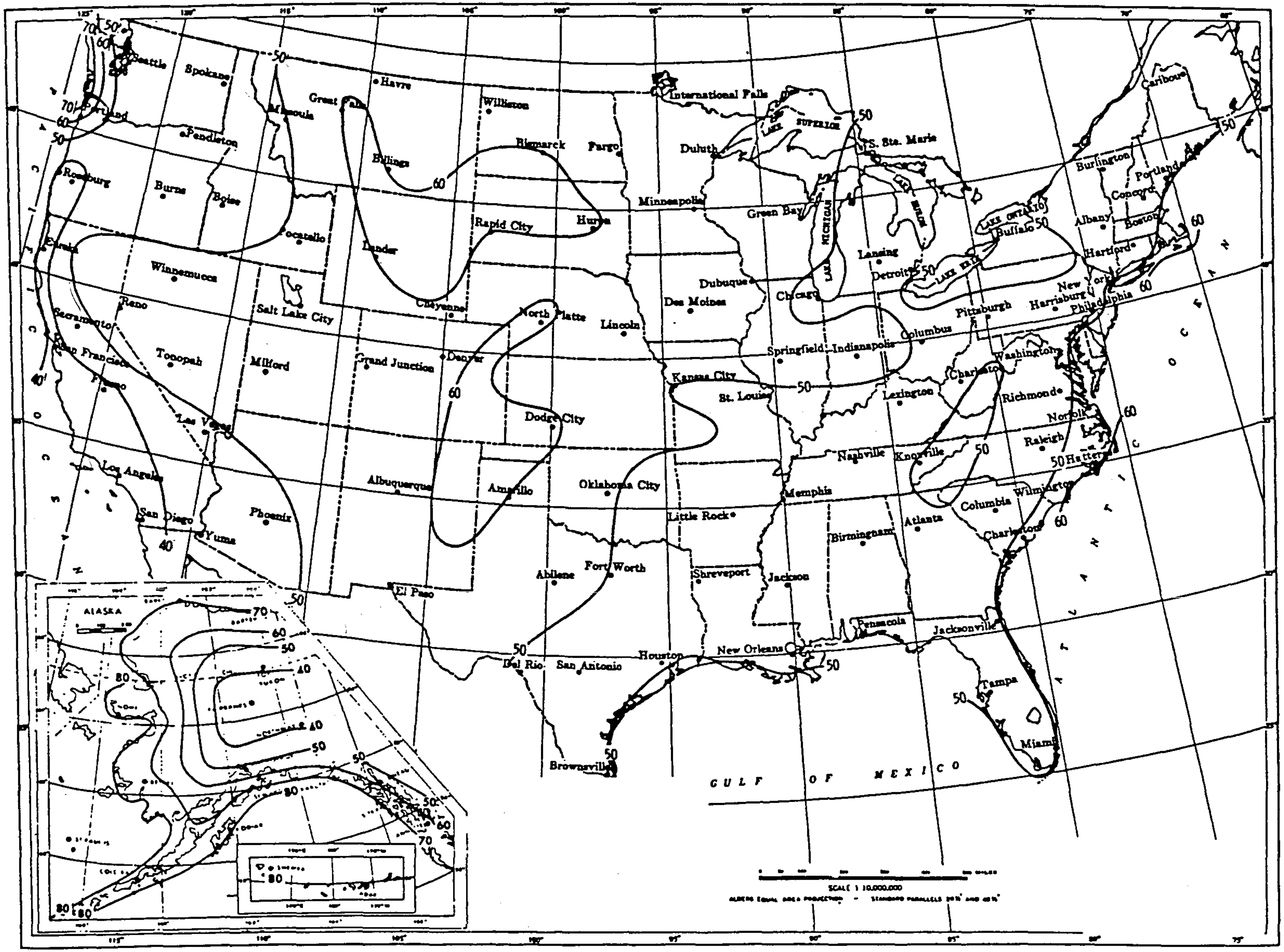


Figure 29. Isotach 0.50 quantiles, in miles per hour. Annual extreme-mile 30 ft above ground, 2-yr mean recurrence interval.

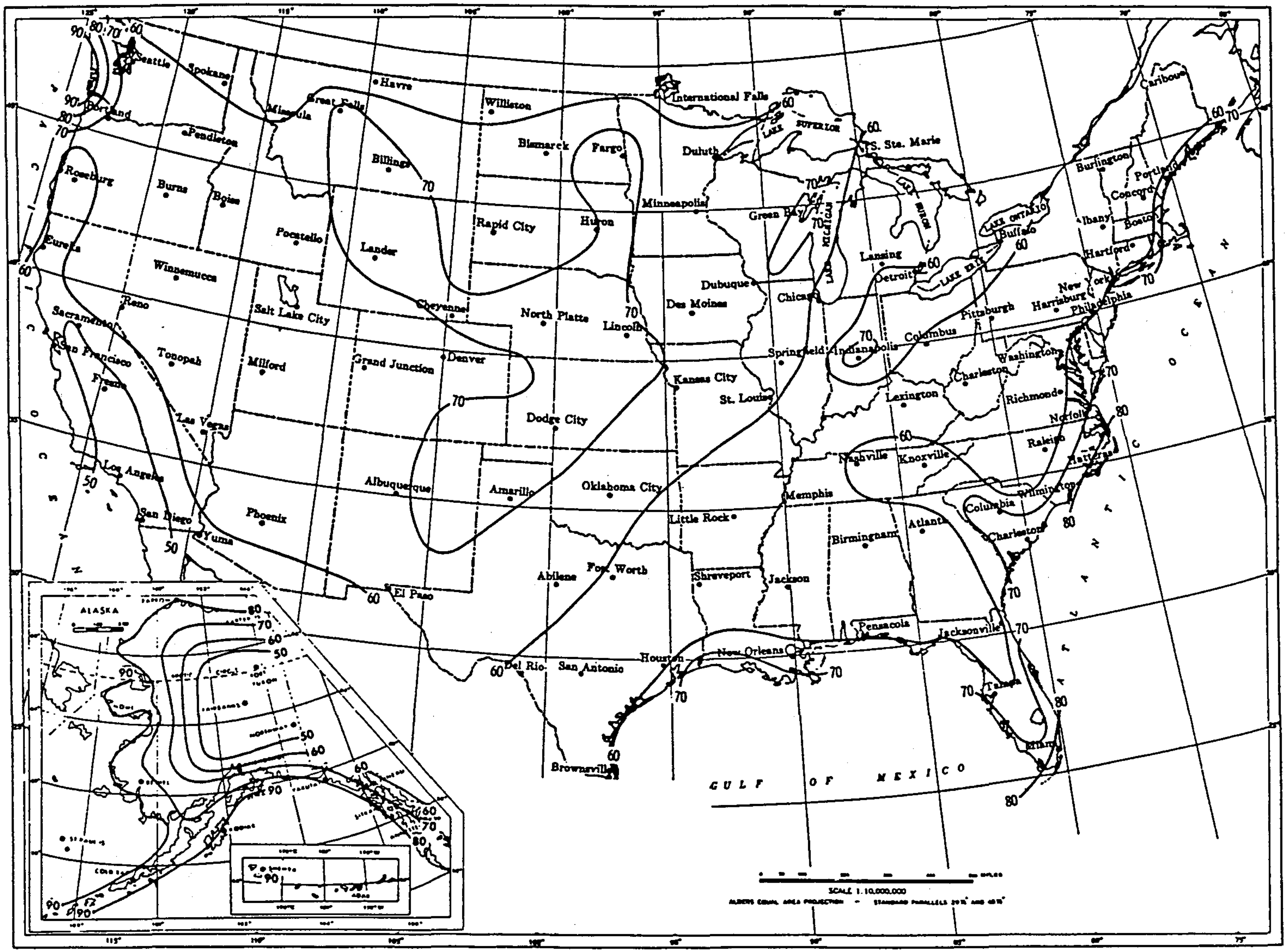


Figure 30. Isotach 0.10 quantiles, in miles per hour. Annual extreme-mile 30 ft above ground, 10-yr mean recurrence interval.

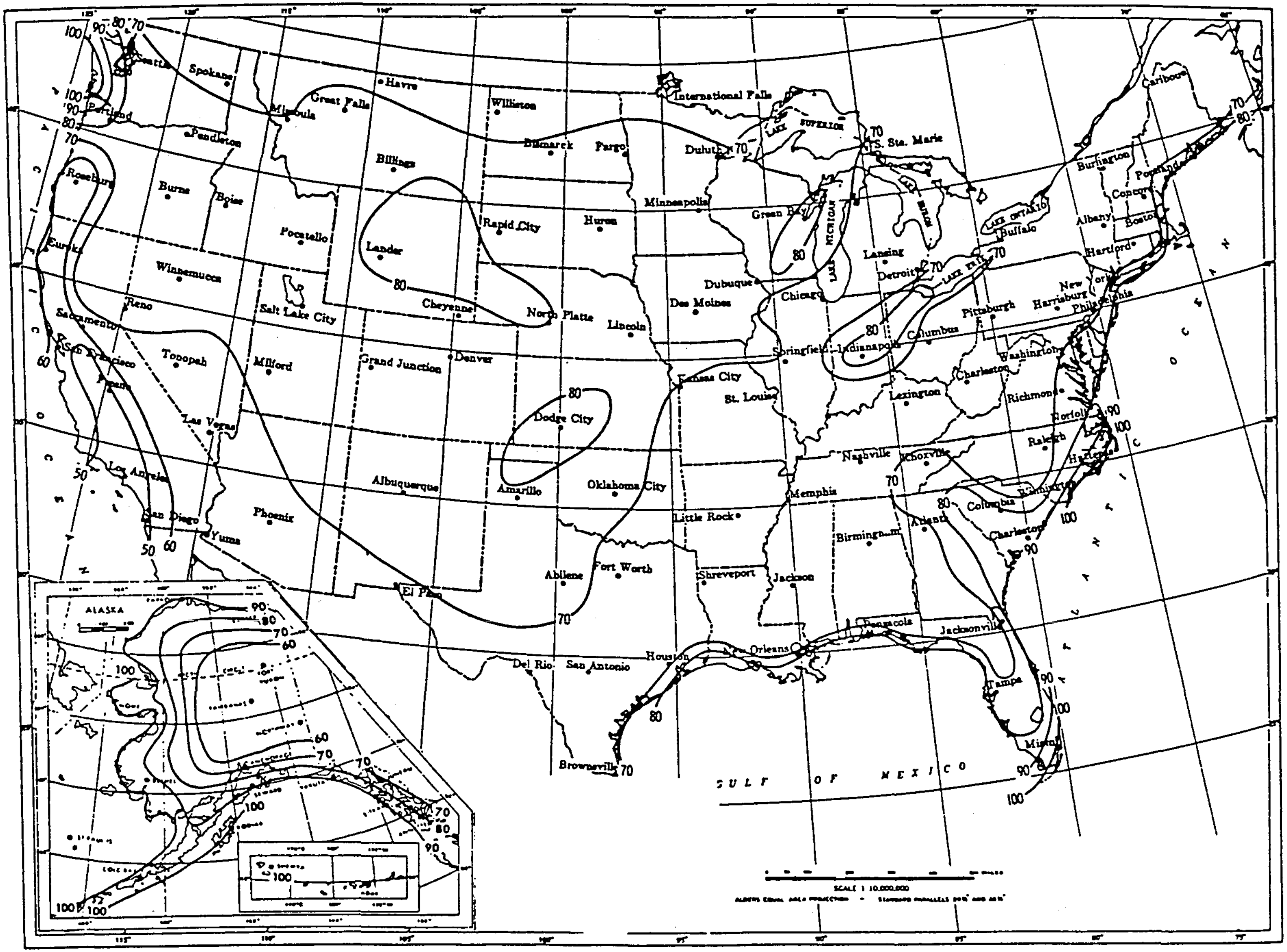


Figure 31. Isotach 0.04 quantiles, in miles per hour. Annual extreme-mile 30 ft above ground 25-yr mean recurrence interval.

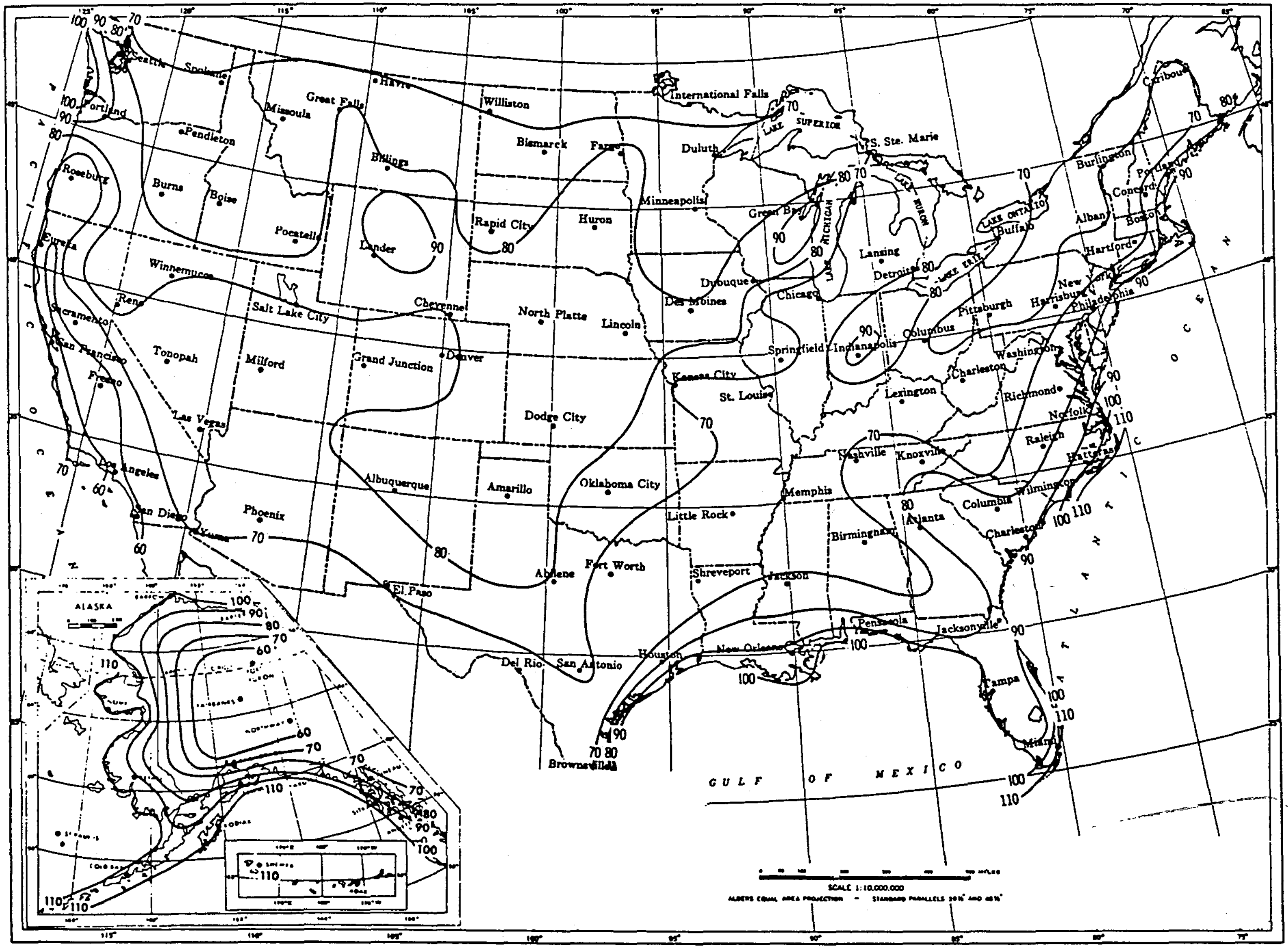


Figure 32. Isotach 0.02 quantiles, in miles per hour. Annual extreme-mile 30 ft above ground, 50-yr mean recurrence interval.

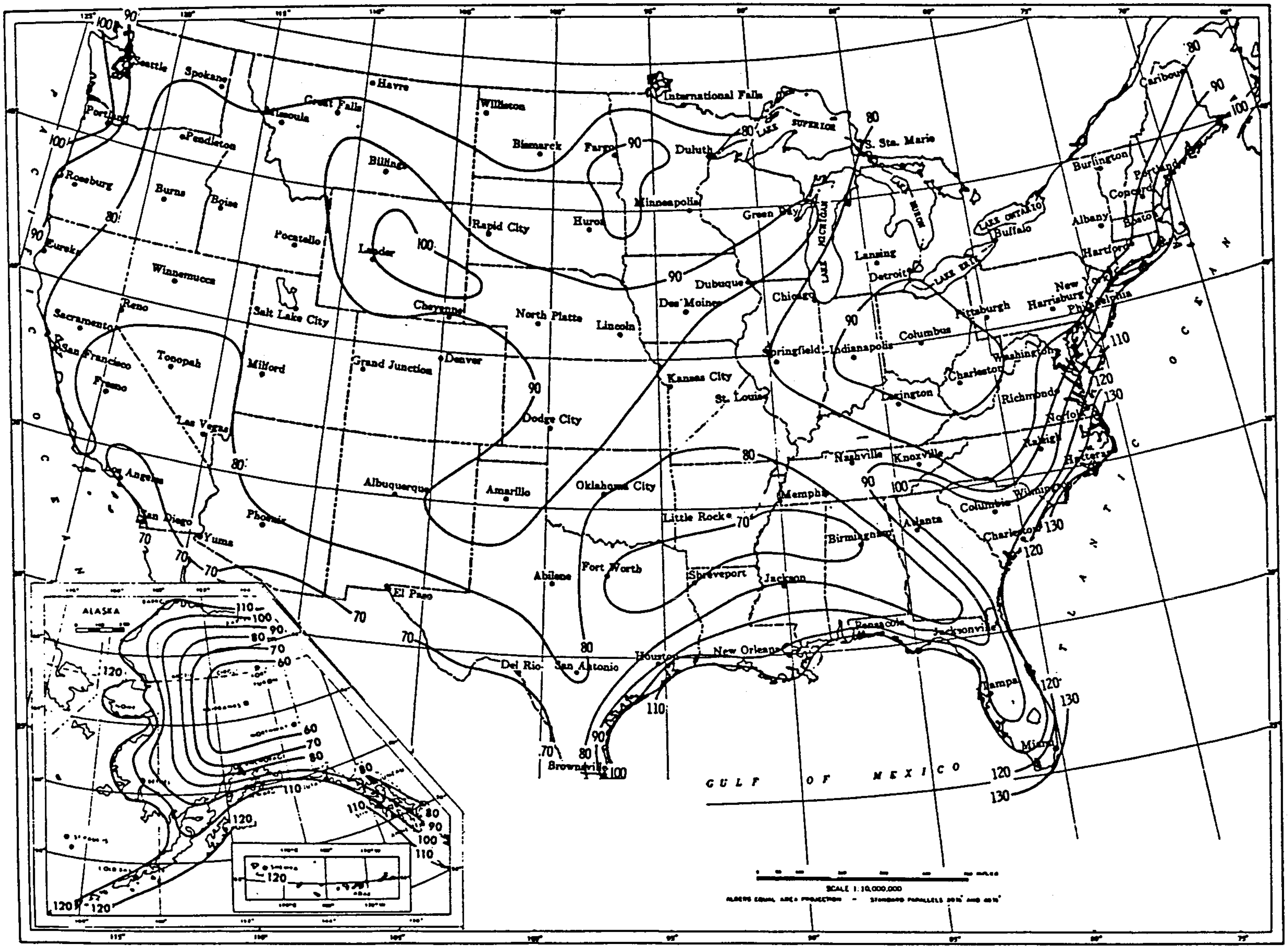


Figure 33. Isotach 0.02 quantiles, in miles per hour. Annual extreme-mile 30 ft above ground, 100-yr mean recurrence interval.

Table 34. Return Period Intervals vs. Wind Speed (Hollister, 1970)

Return Period Interval	Extreme Wind Speed -- Fastest mile of wind				
	East Coast	West Coast	Mid-U.S.	Gulf Coast	Alaska
2 YR	60	70	60	50	80
10 YR	80	90	70	70	90
25 YR	100	100	80	80	100
50 YR	110	100	90	100	110
100 YR	130	100	100	110	120

Table 35. Blast Stress Levels--Multitier Specification

ENHANCEMENT LEVEL	OVERPRESSURE (psi)	EXPECTED DYNAMIC PRESSURE (psi)	EXPECTED MAX WIND VELOCITY (mph)	SURVIVAL PROBABILITY
Minimum	<1	--	<70	--
Moderate	2	.1	70	--
Significant	5	.6	150	1
Maximum	>10	2.2	290	1
Virtual	>10*	2.2*	290	1

*Only if all links have maximum level enhancement.

well. Table 35 illustrates the wind associated with various levels of overpressure that would accompany a nuclear detonation (FEMA, 1982). Each successive higher level of the Multitier Specification specifies a larger overpressure value. Even though the expected overpressure for the area of protection is not over 2 psi (see next paragraph), the installation should withstand somewhat higher levels of blast without damage.

Blast overpressure effects Damage from the blast wave is primarily a result of the winds created by the blast. For purposes of this report the blast level will be defined in terms of peak overpressure (local instantaneous increase in atmospheric pressure) resulting from the detonation. Table 36 shows the wind velocity that can be expected as a result of the specified overpressure (FEMA, 1982). The magnitude of damage decreases with the distance away from "ground zero" as illustrated in Figure 34. For purposes of this report, only areas with overpressure of 2 psi or less will be considered for full protection. At levels of overpressure greater than 2 psi the protection required is much greater and the type of enhancement will go beyond the ideas readily available and cost effective for commercial systems.

Material damage to above-ground structures by air blast results from three primary characteristics associated with the shock wave (FEMA, 1985):

1. The increase in static air pressure above the normal atmospheric pressure, which is called "overpressure." This differential pressure between the outside and the inside of structures tends to collapse them inward.

2. The dynamic pressures due to the high velocity winds behind the shock front. These winds produce "drag" or dynamic forces on exposed structures that tend to translate them.

3. When the shock wave strikes the surface of a structure and is reflected, this dense layer of air changes direction and experiences a sudden change of momentum. The resultant reflected pressure is always larger than the overpressure behind the incident shock wave. The magnification is a function of the angle of incidence between the shock front and the reflecting surface.

The peak values of overpressure and dynamic pressure that develop at any given ground location depend on the size of the weapon, height of burst, and range or distance from the ground location to the point on the ground that is immediately below the burst.

Table 36. Blast Wave Characteristics (Surface Burst) (after FEMA, 1982)

BLAST WAVE CHARACTERISTICS (surface burst)

Peak Overpressure (psi)	Wind Velocity (mph)	Wind Duration for 5-MT Burst (sec)
1	35	9.5
2	70	8.5
5	160	6.8
10	290	6.0
20	470	5.8
30	670	5.6
100	1400	4.3

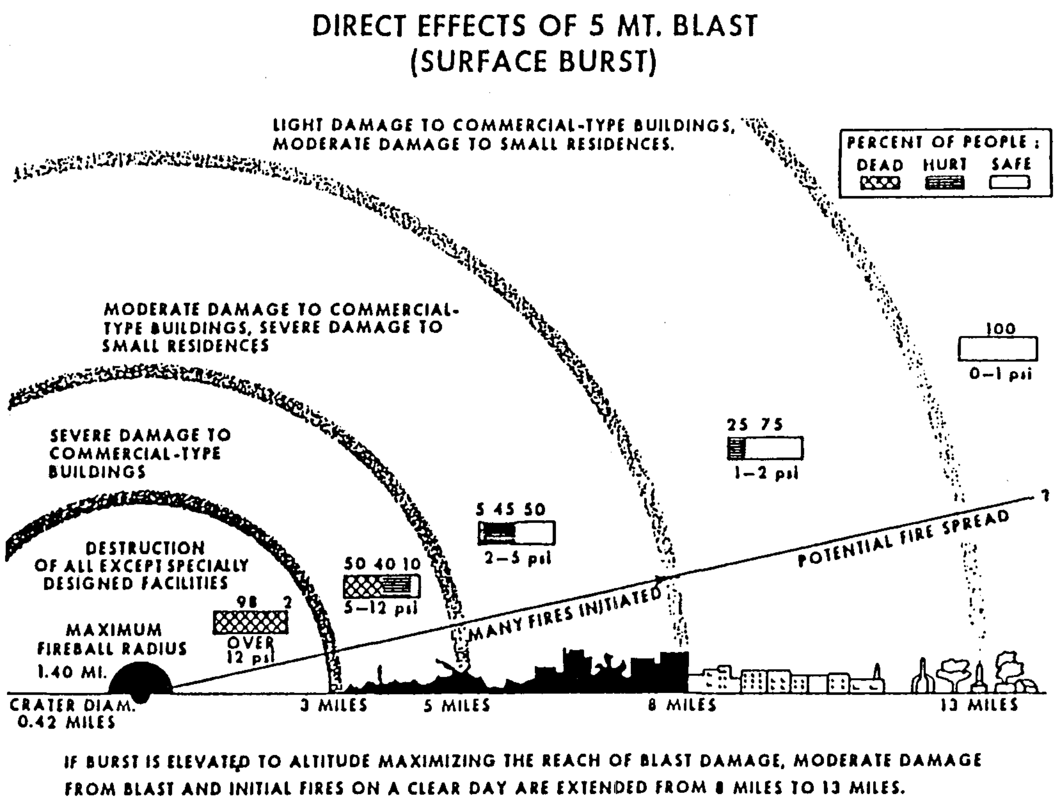


Figure 34. Direct effects of a 5 MT blast (after FEMA, 1982).

Structures that are below the surface of the Earth are subject to quite different stress. The wind and the air blast are not a threat for below-ground installations; however, Earth motion associated with the nuclear explosion must be considered in the design of underground or buried structures. The character and intensity of the ground motion and associated Earth pressures depend on weapon yield, height (or depth) of burst, the mechanical properties of the Earth medium, etc. The ground motion and associated earth pressures generated by a nuclear explosion are due to two factors (FEMA, 1985);

1. direct transmitted ground motion
2. and airblast-induced ground shock

Due to the detachment of the air blast and the ground waves, a shallow-buried structure located in the outrunning region (a distance away from the explosion where the air blast wave and the ground wave have become detached because of velocity differences) would be "bumped" twice--the first time by the outrunning ground wave, and the second time just shortly after the arrival of the airblast front at a point on the ground surface above the structure. The time lag between the two shocks increases with increasing distance from ground zero. In some instances, the second shock tends to amplify the effects of the first (FEMA, 1985). If the analysis is confined to overpressure levels less than 2 psi, the effect from ground motion can be ignored. Of course, if one is to design a structure hardened against ground motion and the overpressure is more than 2 psi, a design guide such as that produced by the Federal Emergency Management Agency (FEMA, 1985), can be referred to for guidance in order that the threat can be understood and necessary structural features can be included.

4.4.2 Resistance to Weathering and Degradation

The construction used for fabrication of the regenerator enclosure should be of such quality and integrity that the enclosure will maintain its mechanical parameters for the lifetime of the system. If this requirement cannot be met, the enclosure should be replaced periodically to continually meet this requirement.

4.4.3 Earthquake Structural Damage and Hazard Reduction

The loads or forces that a structure is called upon to sustain due to earthquake motions result directly from the distortions induced in the structure by the motion of the ground on which it rests. This base motion is characterized by displacements, velocities and accelerations that are erratic in direction, magnitude, duration, and sequence. Uncertainties in the nature of the earthquake loading arise from a number of factors, among the more important of which are (FEMA, 1985):

- The difficulty of predicting the character of the earthquake motions (i.e., intensity, duration, frequency characteristic) to which a structure is subjected
- The difficulty of ascertaining the values of the structural parameters affecting the response (i.e., stiffness and damping), as well as the dynamic properties of the soil or supporting medium

As far as earthquake motion is concerned, the quantity most often used in analysis is the variation with time of the acceleration in the immediate vicinity of the structure. The risk of earthquake at a particular point or area of the United States is important when allocating the capital to upgrade the durability of structure to earthquake hazard. Figures 35 through 37 illustrate the risk of earthquake hazard as a function of the probability of reoccurrence during "return periods" of 10, 50, and 250 years (preliminary data from U. S. Geological Survey). The acceleration is expressed in percent of gravity (referred to as the "seismic coefficient") across the United States. Figures 38 through 40 show the velocity expressed in centimeters per second (preliminary and unpublished data from U. S. Geological Survey). Because buildings are relatively more flexible with respect to horizontal or lateral distortions, it has been the practice in most instances to consider only the structural response to the horizontal components of the earthquake acceleration. The vertical motion (as well as any rocking motion) has either been assumed to be negligible or considered to produce effects which do not materially influence the behavior of the structure (FEMA, 1985).

Earthquake magnitude is a measure of the size of the earthquake. Since there is no way to make a direct measurement of released energy, an arbitrary definition, suggested by C. F. Richter, is universally used today. The Richter value is calculated by taking the common logarithm of the recorded maximum amplitude in microns taken at a distance of 100 km from the epicenter of an

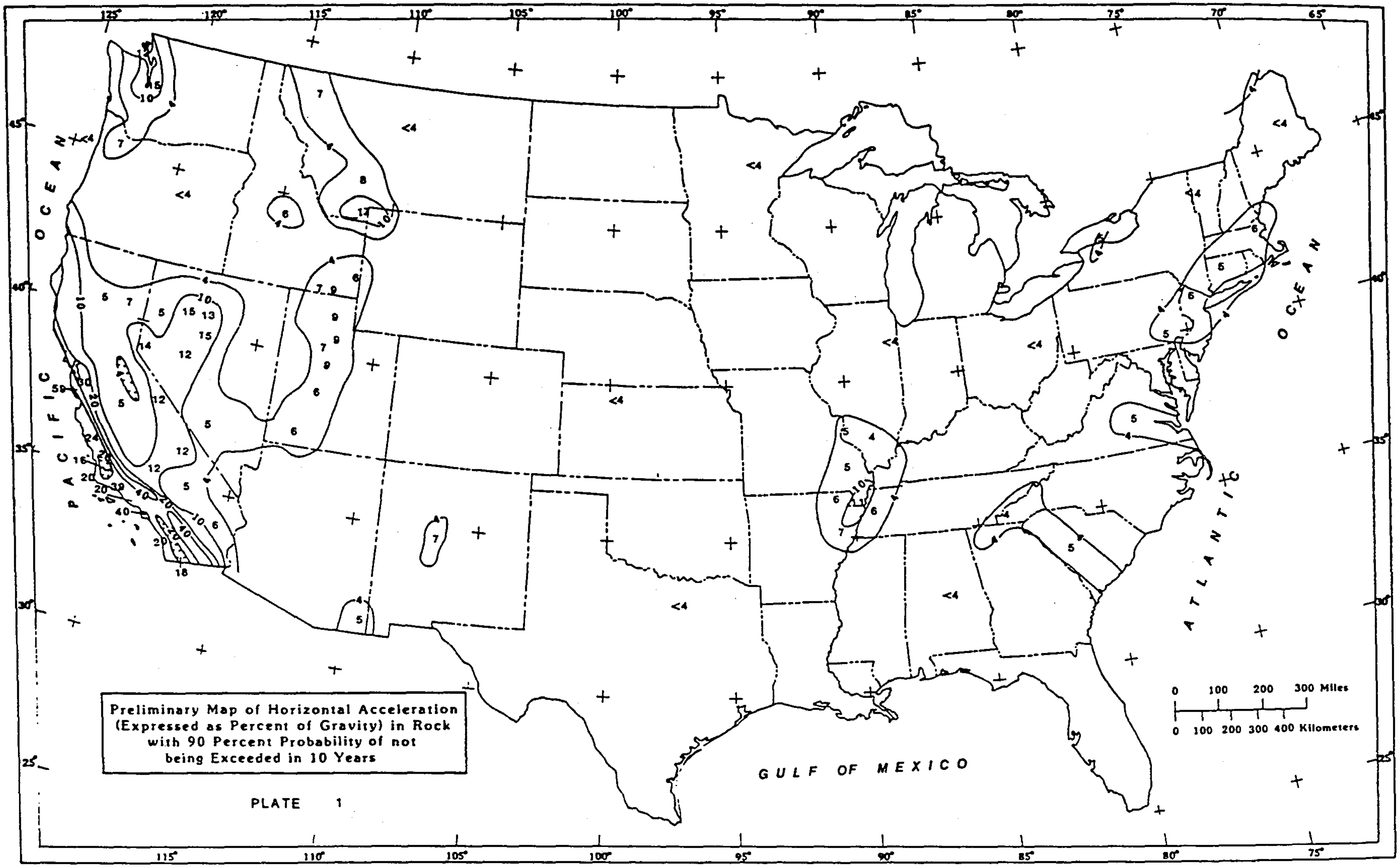


Figure 35. Horizontal acceleration--10-year return period.

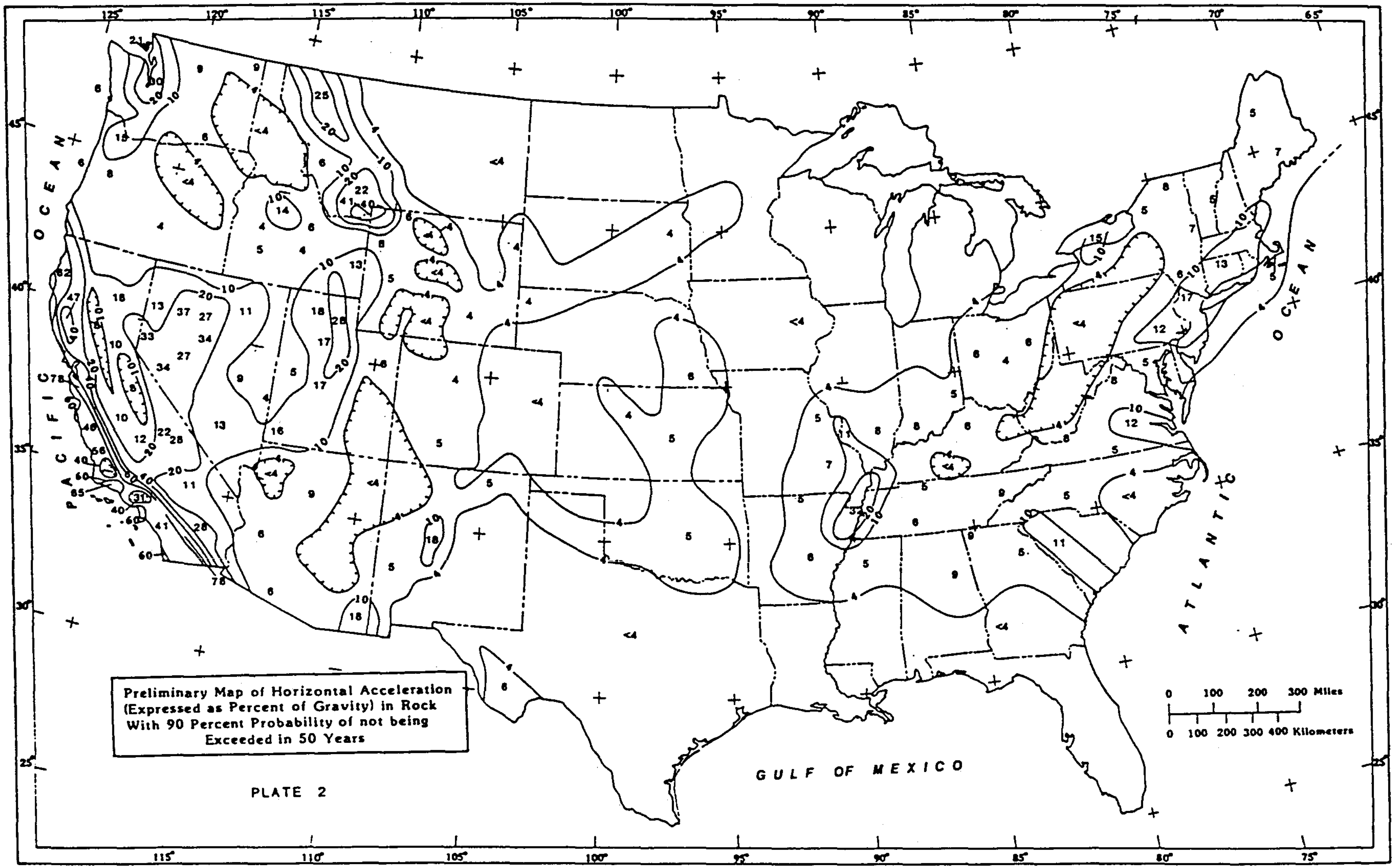


Figure 36. Horizontal acceleration--50-year return period.

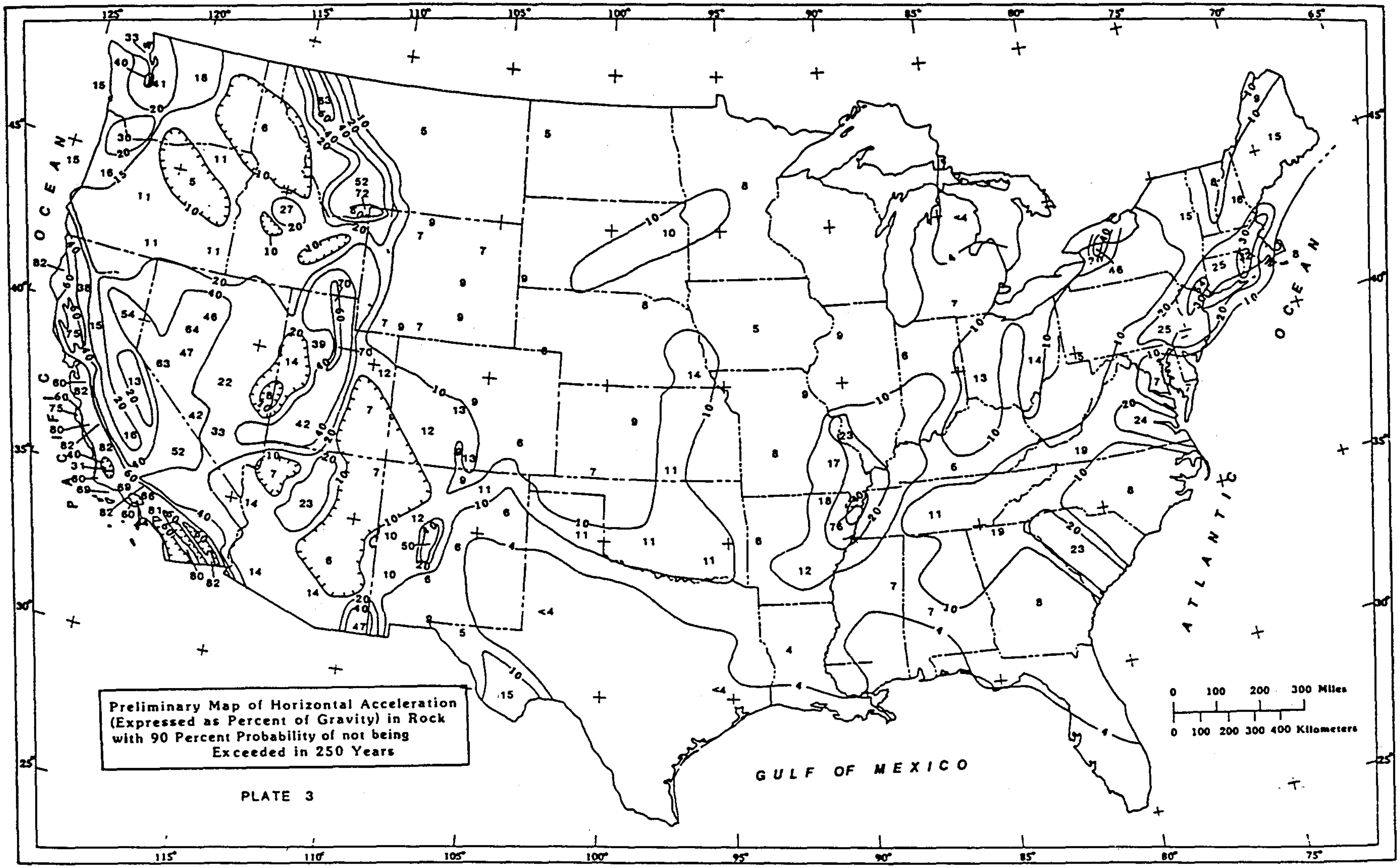


Figure 37. Horizontal acceleration--250-year return period.

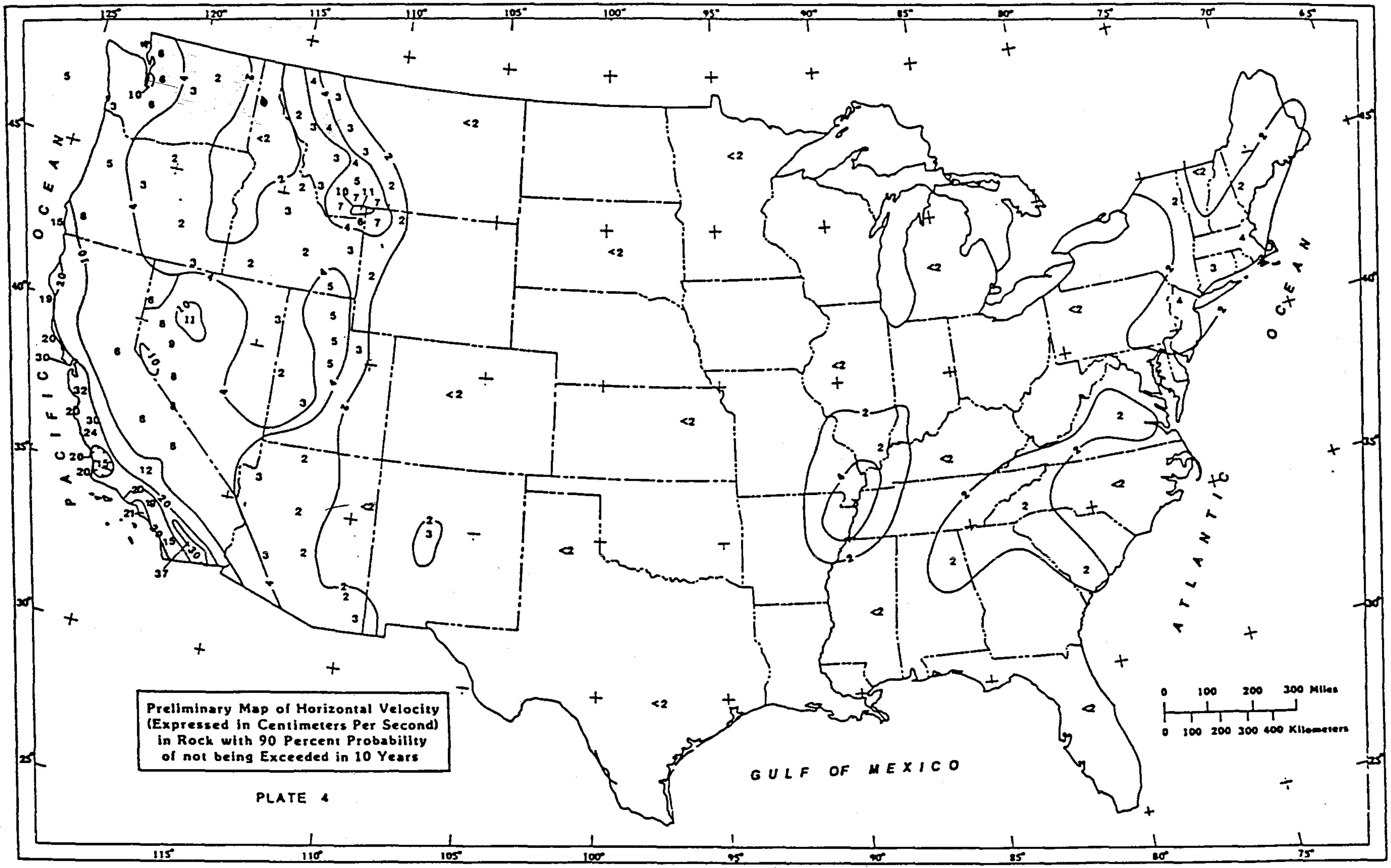


Figure 38. Horizontal velocity--10-year return period.

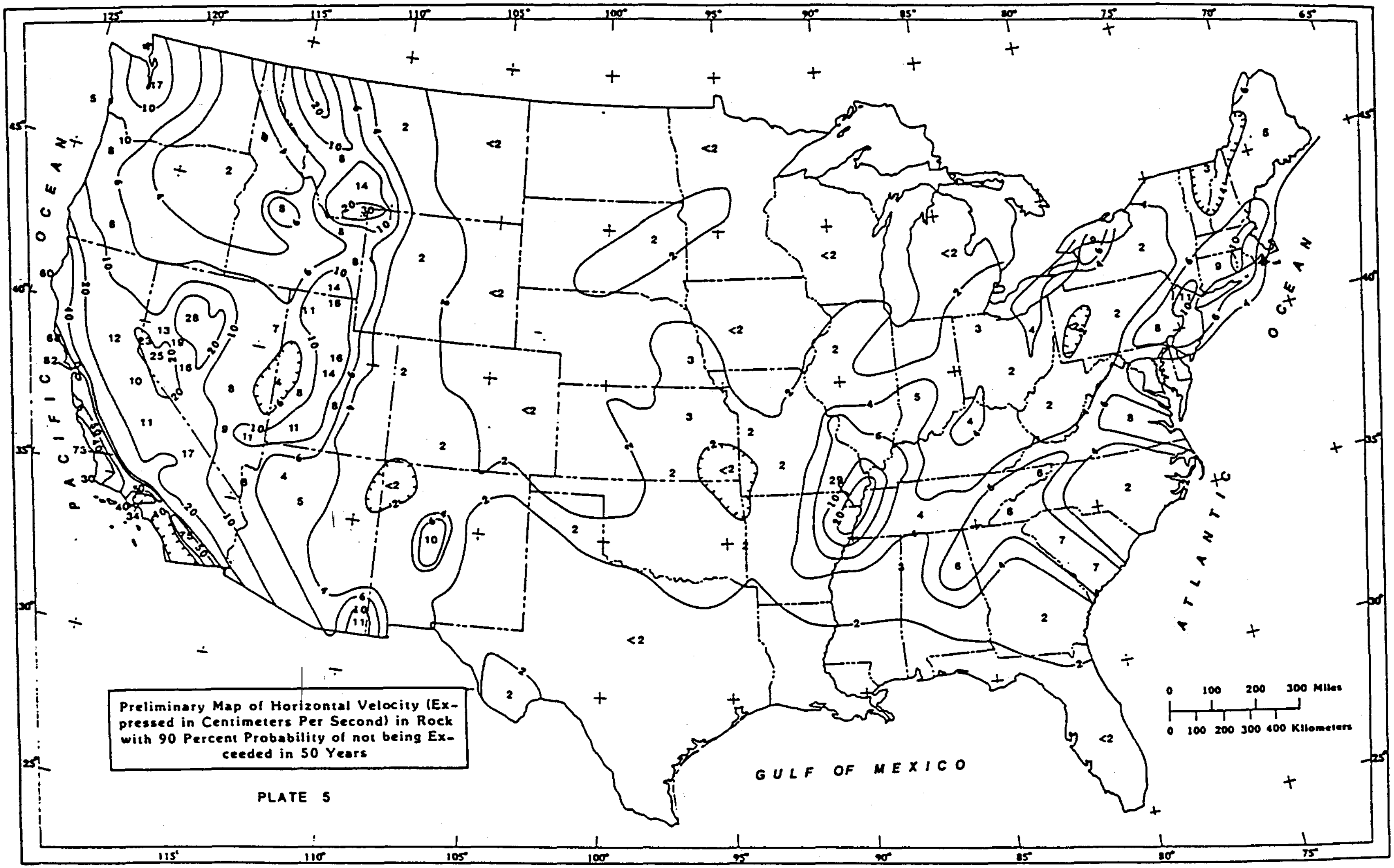


Figure 39. Horizontal velocity--50-year return period.

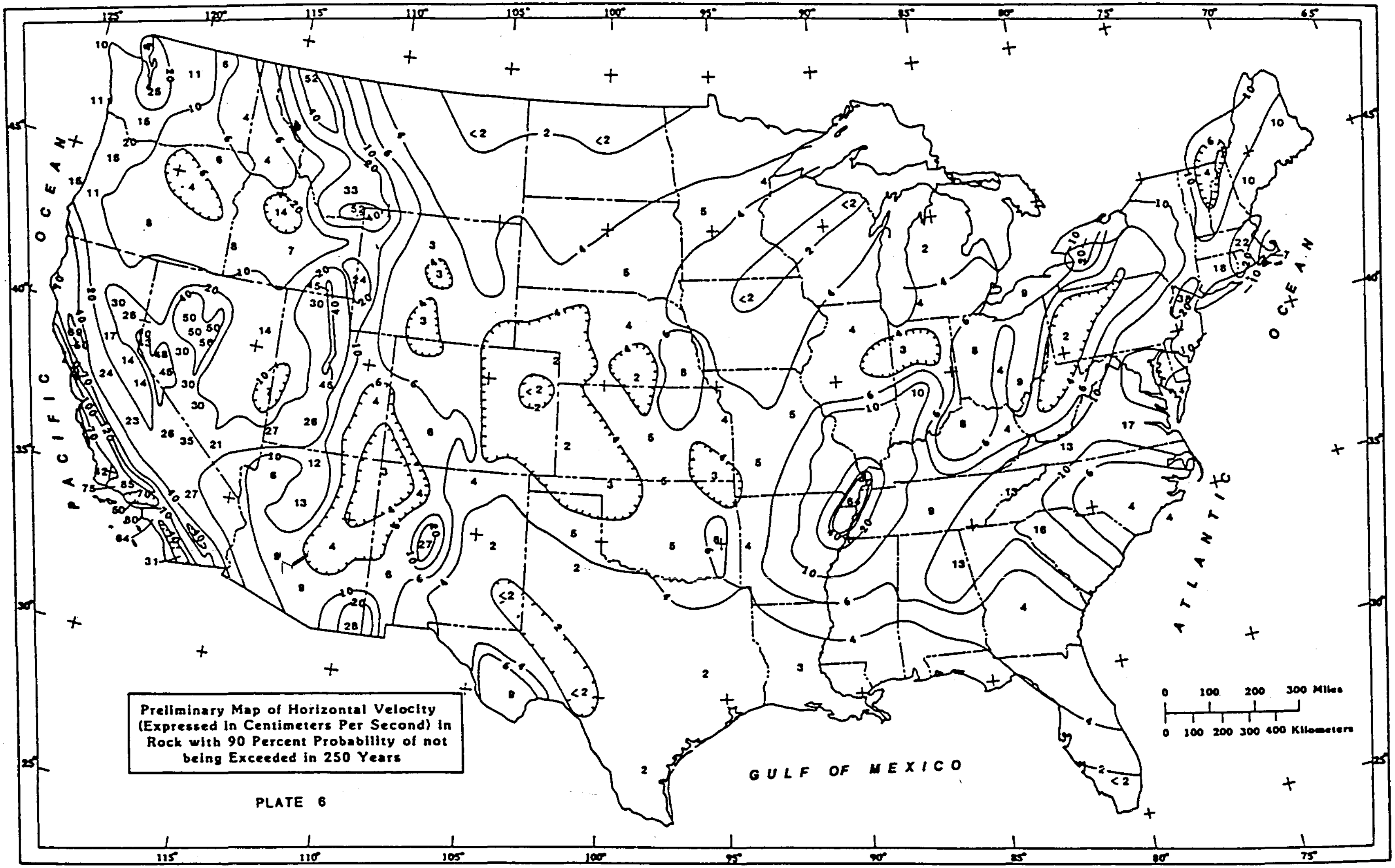


Figure 40. Horizontal velocity--250-year return period.

earthquake (FEMA, 1985). Magnitudes of some well-known earthquakes are shown in Table 37.

The Richter value appears to be a good measure of the relative intensity of the earthquake, but does not necessarily give a good indication of the total energy released--and it's a measure of the ground movement only in one location. The acceleration value seems to be a better measure of potential effect on a structure.

The dynamic response of a rigid structure is developed by Federal Emergency Management Agency publication, Protective Construction (FEMA, 1985). If both the foundation and the structure are rigid so that the ground motion is transmitted to the building, an effective lateral force F_t equal to the product of the ground acceleration, x, and the mass of the structure is developed:

$$F_t = mx = xW/g = Wx/g \tag{10}$$

Table 37. Magnitudes of Some Important Earthquakes

Earthquake	Richter Value
1906 San Francisco	8.3
1940 El Centro	6.7
1960 Chile	7.5, 8.5
1964 Alaska	8.4
1964 Niigata, Japan	6.2
1966 Parkfield	5.5
1971 San Fernando	6.6
1972 Managua	6.5
1987 Los Angeles	6.3

in which W is the weight of the structure and g is the gravitational acceleration. For analysis and design purposes it is common practice to express F_t in terms of base shear V and denoting x/g as a seismic coefficient C yielding

$$V = CW. \tag{11}$$

<u>Earthquake damage hazard</u> Factors affecting earthquake damage are numerous but these factors can be categorized into two categories (FEMA, 1985):

1. Site factors--that include the following parameters

- Earthquake size and distance--The maximum acceleration at a site depends on earthquake magnitude and distance to its source or epicenter. Shockwaves sent out by the earthquake induce an acceleration on the basement rock underlying the site. This rock is the reference for calculating acceleration in the soil above.

- Earthquake intensity--This refers to the severity of shaking at a "free-field" site (i.e., without a structure present).

- Site resonance--Every building site vibrates to certain preferential frequencies irrespective of earthquake type, location, or magnitude. For example, Mexico City, an unusually soft, water-laden deep site, has a well-defined natural frequency.

- Soil dynamics--Soft soil sites usually shake more severely than rock sites. This was clearly demonstrated in the 1906 San Francisco earthquake. Structural damage was consistently greater for buildings erected on filled land; whereas, on the higher bedrock hills, damage was much less than in some areas closer to the earthquake epicenter.

- Foundation types--The depth, stiffness, and extent of a foundation will modify earthquake effect. For example, deep basements on piles inhibit the movement of soft soils, thereby reducing risk of earthquake damage.

- Foundation-structure interaction--The soil must be very soft before this becomes important for typical buildings.

2. Structural factors--that include the following parameters

- Structure's natural frequency--Just as a bell has its own natural frequency of pitch, a structure has its own natural frequency. Every earthquake sends out shockwaves having a distinct set of frequencies, these frequencies depending primarily on quake magnitude. If the forcing frequencies of the earthquake do not match natural frequency of the structure, a lower resonance--even a deamplification of structural vibrations--may occur. Larger earthquakes give off shockwaves with a greater number of low frequencies.

- Ductility--A measure of a material's ability to undergo deflection without rupture. The ductility of a structure affects the way it responds to earthquake vibrations.

- Damping--Vibrational energies are absorbed by internal "rubbing" within the structural elements. Providing damping in the critical stress-carrying members of a structure helps absorb this vibrational energy, thereby increasing structural resistance. Damping also depends on composite behavior; the interaction between walls, partitions, elevator cores, and major framing elements of the building.

Features that enhance the building's earthquake resistance (FEMA, 1985)

- Adequate foundations--Differential movement of foundations that is due to seismic motions is an important cause of structural damage, especially to heavy, rigid structures that cannot accommodate these movements. Adequate design must minimize the possibility of relative displacement between the foundation and superstructure.

- Small mass--With other things being equal, the greater the mass of the structure, the greater is the seismic force. Lightweight construction materials minimize seismic forces but do not necessarily result in lower cost.

- Structural symmetry--Past experience has shown that buildings that are unsymmetrical in plan have greater susceptibility to earthquake damage than symmetrical structures. The effect of dissymmetry is to induce torsional (out-of-phase) oscillations of the structure. Dissymmetry in plan can be eliminated or improved by separating L-, T-, and U-shaped buildings into distinct units by use of seismic joints at junctions of the individual wings. In regular structures, dissymmetry can usually be avoided by better conceptual planning, or may be improved by modifying the stiffness of the walls, or by the judicial insertion of rigid structural partitions so as to make the center of rigidity of the vertical resisting elements more nearly coincident with the center of the lateral forces.

- Damping--The damping characteristics of the structure have a major effect on its response to ground motions because a small amount of damping significantly reduces the maximum deflections due to resonant response. In this connection, reinforced concrete has a higher degree of damping than structural steel. However, damping in itself is not a complete index of the earthquake resistant value of a material or system.

- Ductility--Ductile materials are highly desirable for earthquake-resistant design. Brittle material such as concrete and unit-masonry should not be used to resist seismic forces unless properly reinforced. Under the combined effect of compression (overturning of the structure as a whole) and flexure, a common mode of failure for concrete columns is by buckling of the main steel and spilling of the concrete cover near the floor levels. Columns with spiral reinforcing or hooping have greater reserve strength and are less vulnerable to this type of failure.

- Diaphragms--In floor and roof slabs used as diaphragms, it is desirable to provide for tensile stresses by means of flange steel reinforcement concentrated at the edges of the slabs (or in steel spandrel beams). These flanges must be made continuous at columns.

- Shear walls--Tensile stress due to bending moments in shear walls are also provided for by steel concentrated at the vertical edges of walls. Since the walls are acting as cantilever beams, the tensile stress in the boundary steel must be anchored into a foundation that is capable of transferring the forces to the ground.

Reference to a reputable design manual that deals with responses to lateral forces is in order when designing a structure that is in a high risk area. The gravitational acceleration charts included earlier in this section will note the areas of the country where the stress will be greatest.

4.5 Gamma Radiation Stress Reduction

The primary radiation stress to be considered in this report is from gamma photons. Gamma photons will be the most common radiation residue from a nuclear detonation. Fallout from a nuclear blast or an industrial accident involving a nuclear source will produce photons of approximately 1 MeV of energy. Photons with higher energy can be produced by isotopes that are used in industry, but are much less likely to occur in quantities that would be of concern to the fiber optic system.

There are two enhancements that are feasible to reduce the effect of gamma radiation on the fiber optic system:

- placement of the system components underground
- use of radiation hard optical fibers

The use of radiation hard electronic components is also a method of reducing radiation effects, but is probably not cost effective for commercial use at present. In addition, some of the unique optoelectronic components have not yet been designed with radiation resistance.

A limited analysis of the susceptibility of fiber optic regenerator electronics to nuclear generated gamma radiation is provided in NCS (1985a), completed by AT&T on the FT3C lightwave system. The results show that some families, e.g., MOS, are more susceptible to radiation than types such as bipolar linear devices. Components unique to a lightwave system vary in sensitivity to radiation also--the bit error rate is roughly proportional to the radiation dose. The bottom line is that 1,500 rads dose is sufficient to cause upset and possible inoperability due to excessive bit error rate (NCS, 1985a).

4.5.1 Underground Placement

By far the most cost effective radiation shield is the ground--the earth layer that is positioned between the radiation source and the fiber optic system component. The benefits of placement underground can be measured by the reduction in radiation energy provided by the soil. The shield effectiveness of the soil will vary depending on the density of the material--obviously soil in all locations will not be the same. For example, soils with a high concentration of organic material will not be as dense as a pure clay or sand soil. A worst-case condition would be if the soil was dry and loosely packed.

The absorption of radiation flux by the shield is the reason that a material functions as a shield. As a rule of thumb, the amount of energy absorbed is proportional to the density of the shield material. A practical measure of shield effectiveness is half-value thickness--the thickness of material to reduce the radiation energy to one-half the original value. The expression for half-value thickness is

$$T\ (\tfrac{1}{2}) = \frac{\ln 2}{\alpha} \tag{12}$$

where α is the absorption coefficient for the material used as the shield (Englert, 1987). The half-value thickness is related inversely to the absorption coefficient. Englert (1987) discusses the shield effectiveness in a more thorough manner. A study that describes the shielding effect of soils is included in Appendix A. An attempt has been made by Nesenbergs to predict the shielding effect of various materials that surround an underground (buried) fiber optic cable.

A comparison of half-value thicknesses for several shielding materials is provided in Table 18 (Section 3.2). Actual materials (dry and loose soil) are evaluated for shielding effectiveness. The dry and loose soil should represent the worst-case condition for a component placed underground.

The requirement for an effective shield is an absorption factor of 300 based on the requirement to reduce the flux to a safe level for the components of the system (See Volume I). The optical fiber is the most vulnerable, the safe radiation level being 100 rads for standard commercial fiber. Recovery of the fiber parameters is improved with use of a radiation-hard fiber; however, the effect during radiation does not appear to be significantly improved.

The data from Table 21 show that a depth of 36 inches (0.9 meter) is adequate for effectively shielding the components--providing an absorption factor of 300 or more. However this would be true for gamma radiation with energies of about 1 MeV or less. For higher energy levels, the shield effectiveness is somewhat lower.

The technique for placement of cable underground is not important as long as the stress limits for tensile and bending are not exceeded during placement. In open areas the cable can be plowed in--either with a duct surrounding the cable or as bare cable. A polyethylene duct provides physical protection for the cable from puncture, cutting, breaking, or other damage to the cable or the sheath. In either case the cable must be designed with a rodent-proof sheath to prevent damage from gophers.

The Multitier Specification, described in Volume I, integrates the benefits of underground placement. Each successive higher level of hardness specifies a greater depth of placement--yielding a larger shield factor. Based on the data included in Section 3.2 (Table 18), a projection of the shield factor at each level of hardness is calculated. Tables 38 and 39 present the estimated protection factors for each level of the specification at two energy levels (1 MeV and 6 MeV). These numbers are thought to be worst-case values because the soil used for this analysis probably represents the least dense combination of moisture and compacted conditions.

4.5.2 Radiation Hard Fibers

The development of radiation-hard fibers is in its infancy. Section 3 of this report discusses the optical fiber design variations that affect the effect of gamma radiation on optical fiber. These design changes affect only the recovery rate of the optical fiber after an impulse of radiation. It is not clear what the response will be when exposed to a continuous dose of radiation.

Radiation-hard fibers are available from several manufacturers, but at a premium price. If the results of tests in the future show that there will be a benefit, then the radiation-hard fibers should be used as an added protection against gamma-radiation stress.

A summary of test data showing the beneifts of radiation hardening of fibers is presented by Hull (1987).

Table 38. Gamma Radiation Shielding @ 1 MeV Particle Energy (Standard Optical Fiber)

ENHANCEMENT LEVEL	CABLE PROTECTION FACTOR (@1 MeV)	REGENERATOR PROTECTION FACTOR (@1 MeV)	CABLE/REGEN DOSE (RADS) (@1 MeV)	PERSONNEL SAFE DOSE (RADS) (@1 MeV)	SURVIVAL PROBABILITY
Minimum	0	Neg	100/200	50	**
Moderate	35	2	3500/400	100	**
Significant	50K	50K	10^7	2.5×10^6	1
Maximum	2M	2M	4×10^8	10^8	1
Virtual	2M*	2M*	4×10^8*	10^8*	1*

* Only if all links have maximum level enhancement
**Depends on threat level

Table 39. Gamma Radiation Shielding @ 6 MeV Particle Energy (Standard Optical Fiber)

ENHANCEMENT LEVEL	CABLE PROTECTION FACTOR (@6 MeV)	REGENERATOR PROTECTION FACTOR (@6 MeV)	CABLE/REGEN DOSE (RADS)	PERSONNEL SAFE DOSE (RADS)
Minimum	0	Neg	200/200	50
Moderate	4	Neg	800/200	50
Significant	200	200	40000/40000	10000
Maximum	400	400	80000/80000	20000
Virtual	400*	400*	80000/80000*	20000*

*Only if all links have maximum level enhancement

4.6 Protection from EMP

4.6.1 Limits of Protection

The stress effects of electromagnetic pulse (EMP) will result from a nuclear detonation that occurs either in the atmosphere (or on the Earth's surface) or above the atmosphere. An EMP field will be produced by a nuclear detonation in either region.

An air burst occurs between 2 and 20 km above ground. The EMP produced is characterized by a radial field. EMP effects would be confined within the 2-psi overpressure region and thus would not be of concern to a system outside of this region. The damage from blast would probably destroy the system if it was located closer than the 2-psi region negating any concern from EMP. The range for the EMP field of a surface burst is 3 to 6 km--a distance that will be easily confined within the 2-psi region. Neither the air burst nor the surface burst will produce an EMP field of concern unless the system is within the 2-psi region. Figure 41 shows the distance away from the center-of-burst for 2-psi overpressure defining the region of concern that is outside of the 2-psi line (Glasstone and Dolan, 1977).

A high-altitude burst is of greatest threat to a fiber optic telecommunication system. High-altitude EMP can illuminate a much larger geographical area than either surface- or air-burst EMP. It is shown by BTL (1975) and others that a high-altitude burst can cover the entire continental United States and as a result a whole national telecommunication network will be affected. The maximum peak electric field is thought to be not more than 50 kilovolts per meter (BTL, 1975; Naval Facilities Engineering Command, 1986; and Antinone, 1987).

4.6.2 Mitigation of EMP Stress

Mitigation of EMP stress effects can be accomplished in two ways:

1. designing the system components for reduced sensitivity to outside electromagnetic fields

2. reducing the magnitude of the electromagnetic field that reaches the system components by shielding the system

<u>Regenerator electronics</u> Design enhancements that render the electronics less sensitive to EMP encompass a wide variety of ideas. Most of the ideas that will help with EMP sensitivity fall into the types of things that would be done

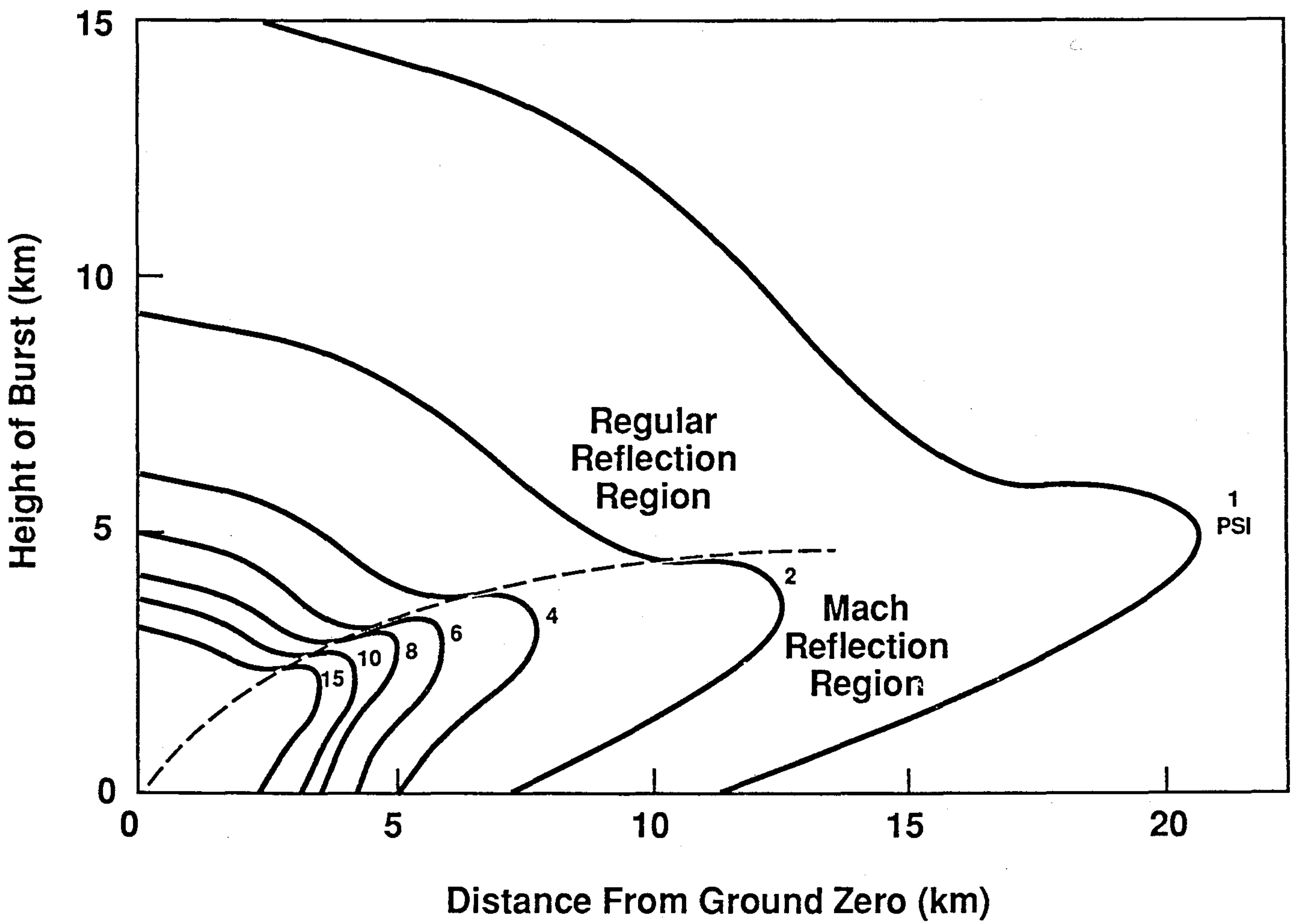


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Figure 41. Overpressure (psi) vs. height of burst.

to reduce noise sensitivity. Most manufacturers are implementing these features to improve reliability of their systems--thus this protection comes at very little cost. Additional benefit can come from installation of transient protection devices that are discussed in Section 4.3 of this report, but this is not the total solution.

Reducing the EMP field with a shield is the only sure method of protecting the components of the system. The Multitier Specification specifies two options for shielding from EMP--with or without a shielded enclosure that is integral to the regenerator enclosure. When employing the first option, without the shielded enclosure, there is some reduction in field strength from either the regenerator enclosure structure or the soil covering the components. A structure that is placed above the ground can provide significant shielding, if the structure is constructed using metal rebar reinforcing rods. The rebars must be properly bonded together, and the rebar loop array properly grounded. The approximate magnetic shielding effectiveness is given by BTL (1975) as shown in Table 40. Procedures and standards for bonding and grounding are provided in DOD (1984), AT&T (1985), or DOD (1982).

Table 40. Approximate Magnetic Shielding Effectiveness (BTL, 1975)

Rebar Spacing (in)	Shielding Effectiveness (dB)
6	36
8	31
12	26

Without the integral rebar loop array in the structure the shielding effect is reduced to 5-20 dB when using either typical 6 inch (15 cm) thick concrete walls or concrete blocks. The most effective structure will be a poured-in-place wall and ceiling with an integral rebar cage. Precast tilt-up panels are very convenient for construction, but the reinforcing rods in the precast panel cannot be individually connected to the adjacent section; thus the shield effectiveness is reduced or negated altogether.

Placement of the components underground adds additional shielding. The shield effectiveness varies with frequency, the worst case being about 15 KHz. The analysis done by Nesenbergs in Appendix B predicts the amplitude spectra of the HEMP field at different depths below the Earth's surface. Figure 42, taken from Appendix B shows the variation in attenuation of the HEMP field with frequency at a number of depths below the Earth's surface. It should be noted that the worst case (least attenuation) is approximately $\omega = 10^6$/sec (approximately 15 KHz).

The limits of protection for the Multitier Specification can be estimated from the data presented in Appendix B--and presented in Table 41. Protection factors for regenerator protection without a shield have been compiled from the above data and have been presented as a separate option. Additional protection can be provided by adding a shielded enclosure as part of the regenerator enclosure with the results shown in Table 41. A shield factor of 1,000 (60 dB) is adequate to protect the type of electronics used for regeneration of the telecommunication signal (NCS, 1978). This shield factor is also substantiated by approximations presented and shield effectiveness recommendations of Naval Facilities Engineering Command (1986) and per Defense Communication Agency Instruction 350-175-1, 1986. However, the level of protection necessary for the optoelectronic components is unknown at present. The results of AT&T tests (NCS, 1985b) on the FT3C fiber optic telecommunications link show no adverse effects on the system operation. These tests were done without any shield, except the system component chassis and associated hardware. Based on this limited data, additional external shielding may not be necessary if the system components are placed underground. Underground placement is necessary to adequately protect the system from the effects of gamma radiation.

A second option available to reduce the EMP field involves the integration of a shielded room within the regenerator enclosure. This method of EMP protection would be mandatory if the regenerator enclosure is located above ground. A lesser shield may be appropriate if the system components are underground because of the shield effect of the soil. The data from Figure 42 give an estimate of the field attenuation at incremental depths below the Earth's surface. The amount of additional shielding required to provide full protection is not easily defined since neither the threat level of the EMP field nor the field safe level are clearly defined in the open literature. The Federal Emergency Management Agency (FEMA) recommends for their Emergency Operating Centers (EOCs) that the enclosure provide an attenuation of 80 dB in the frequency range of 10 kHz to 100 MHz for the electric fields and 50 dB in the frequency range of 10 kHz to 100 kHz for the magnetic field (DCPA, 1972).

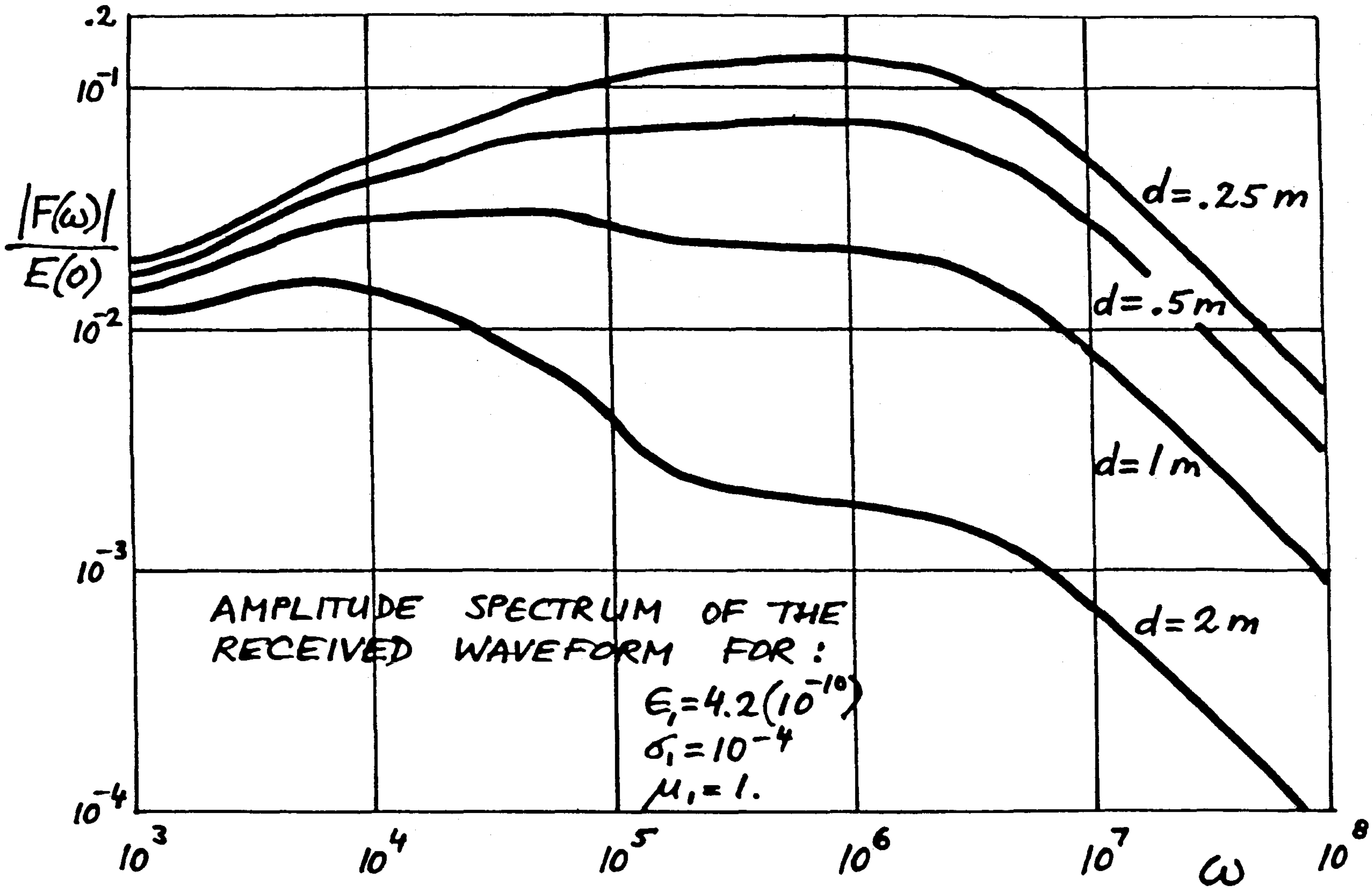


Figure 42. Normalized amplitude spectra of the received HEMP waveform at different depths below Earth surface.

Table 41. Electromagnetic Pulse Protection Factors (@ 15 kHz*)

ENHANCEMENT LEVEL	CABLE PROTECTION	REGEN PROTECTION w/SHIELD	REGEN PROTECTION w/o SHIELD	SURVIVAL PROBABILITY w/SHIELD
Minimum	0	N/A	10 dB	UNKNOWN
Moderate	10 dB	80 dB	25 dB	1
Significant	20 dB	80 dB	40 dB	1
Maximum	20 dB	80 dB	50 dB	1
Virtual	20 dB**	80 dB**	50 dB**	1**

*Frequency with least attenuation (See Appendix B-Distortion of HEMP Waveform in Homogeneous Earth)
**Assuming that all links have maximum enhancement

An analysis by Sims (1987) recommends a minimum of 100 dB of attenuation for the HEMP plane wave to ensure an environment that will not affect the operation of a regenerator station.

Input from a number of sources has been compiled in the course of this study. Based on these data, full protection for the regenerator electronics is as noted in the Multitier Specification (Table 41) and defined as 80 dB attenuation of all components of the HEMP plane wave for all frequencies from 10 kHz to 100 MHz. This attenuation includes all sources of attenuation (e.i., shielded enclosure, ground attenuation, structure attenuation, chassis shielding) resulting from the particular installation. It follows that more attenuation must be provided by the shielded enclosure for Level 2 (Moderate) hardness than for Level 4 (Maximum) hardness because of the attenuation resulting from the underground placement requirement for Level 4 (Maximum) hardness. Level 2 (Moderate) hardness suggests a regenerator enclosure placement on the Earth's surface.

<u>Fiber optic cable</u> The options for reducing the HEMP electromagnetic field that reaches the cable are limited. Surrounding the cable with an electromagnetic shield (shielded enclosure) is impractical. However, placement of the cable underground provides some protection, depending on the depth of burial. Table 41 shows the level of protection (HEMP plane wave attenuation) for each level of the Multitier Specification based on data presented in Appendix B. Figure 41 presents the actual field attenuation for the cable since there is no other shielding provided by adjacent components.

The HEMP field is a threat to the fiber optic cable because the field will couple current to the metallic sheath or other metallic component (e.g., metallic central strength member) resulting in damage to the cable if this current exceeds the safe value. In addition, EMP test results by NCS (1985b) on their FT3C fiber optic telecommunication link suggest that arcing can occur between multiple metallic layers (e.g., central strength member to sheath or sheath to metal vapor barrier, etc.) of the cable. The arcing can damage the cable, reducing the useful life of the cable, or damaging the fibers. The solution lies in three areas:

1. reducing the field intensity through underground placement

2. grounding the cable sheath or central strength member in a manner that will limit the coupled current to a safe value

3. eliminating the metallic components

The reduction of the field intensity through underground placement was discussed above. While the ground does attenuate the field significantly, the field is not totally eliminated.

Elimination of the metallic components seems to be the simplest solution; however, without a metallic sheath the cable is subject to rodent damage. None of the nonmetallic materials are hard enough to repel the gopher's chewing. Elimination of the metallic central strength member is possible and is being done by several cable manufacturers--the tensile support being provided by a nonmetallic material.

Proper grounding of the metallic sheath in a way that the induced current does not damage the cable or inject transients into the regenerator electronics is the goal. The ideal ground would be a continuous ground, so that the current could be drained off without any large flow build up. This is not possible since all cable has a plastic outer sheath that insulates the metal sheath from the soil.

Two enhancements that will provide excellent protection (recommended and required for all levels of the specification) are:

1. providing an Earth ground for the cable sheath at every point that the cable sheath is exposed (e.g., splices and points of entry or exit to a regenerator site)

2. separation of the cable sheath from the regenerator enclosure ground (Sims, 1987)

The goal of each Earth ground should be to penetrate the water table at each location. Different techniques will be required, depending on the location, to achieve a meaningful ground. MIL-HDBK-419 (DOD, 1982) should be consulted for procedures necessary for an effective installation.

4.7 Protection From Lightning

4.7.1 Definition of the Problem

Lightning surges can occur in various parts of a communication system and produce explosive effects from arcing, dielectric failures, and fusing of conductors. The magnitude of threat to a particular installation will depend on the type of hardware and the method of installation. All installations are susceptible to lightning damage--no method of installation is immune to lightning discharges.

A lightning stroke has the same damaging effect as does an EMP pulse. A comparison of the EMP and the lightning pulse is illustrated in Figure 43. Note the rapid rise time of the EMP pulse as compared to the lightning pulse. It should also be noted that the lightning pulse may have more total energy than the EMP pulse; however, the rapid rise of the EMP pulse creates a more dangerous transient threat. Figure 44 compares the frequency spectrum of the lightning energy waveform and the EMP energy waveform plotted together with the spectrum of radio communications and radar.

The frequency of occurrence of damaging lightning strokes varies with the location of the installation. Figure 45, compiled from National Weather Service data, illustrates on an isoceraunic map showing the frequency of thunderstorm occurrences across the United States (AT&T, 1985). Thunderstorms are of two types: 1. convection storms, which are local in extent and of relatively short duration, and 2. frontal storms, which extend over greater areas and may continue for several hours. Convection-type thunderstorms account for the majority of annual thunderstorm days in the United States. Experience has shown that frontal-type storms will cause appreciably more damage than convection-type storms. Frontal-type thunderstorms result from the meeting of a warm, moist front with a cold front that at times may extend for several hundred miles, exposing large areas to severe lightning discharges.

The threat to buried cable is determined by the resistivity (ρ) of the soil surrounding the cable. The mechanism for discharge of a lightning stroke to an underground cable is shown in Figure 46. The distance, d, along the Earth's surface that the arc will travel will increase with an increase in resistivity. A lower resistivity will allow the surface current to dissipate into the Earth before it reaches the point above the buried cable. Figure 47 shows the estimated average Earth resistivity across the United States.

The average area (distance) over which a buried cable will attract lightning strokes to Earth is proportional to the square root of the soil resistivity. It follows that the resultant exposure to the lightning damage is a function of soil resistivity and the number of thunderstorms expected in a particular region of the United States. A "lightning exposure factor" is

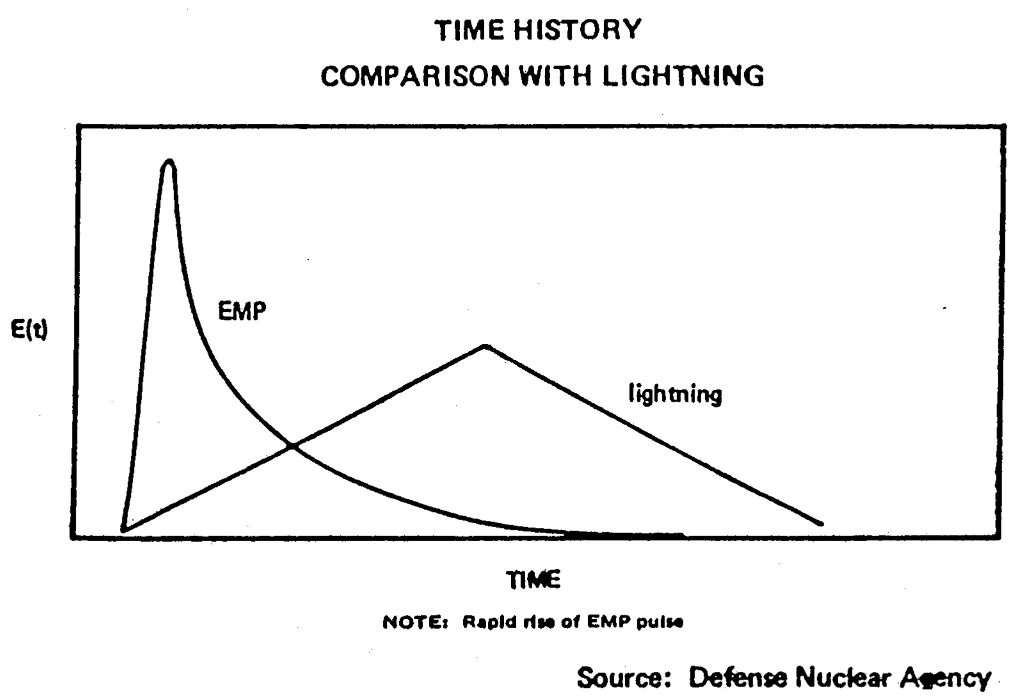


Figure 43. Time history comparison of EMP and lightning.

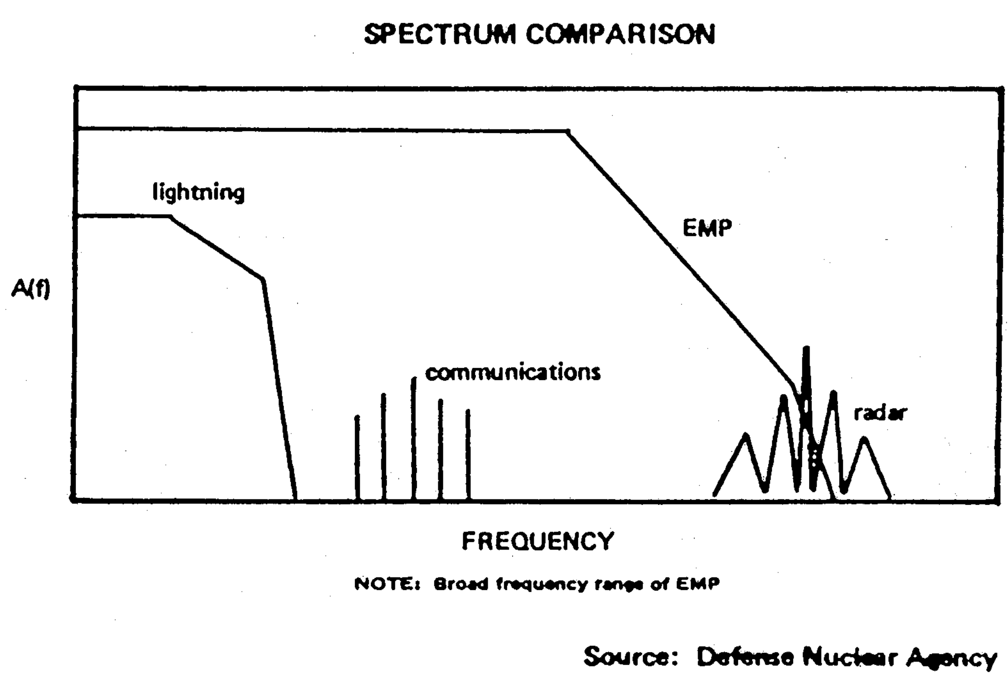


Figure 44. Frequency spectrum comparison of EMP and lightning.

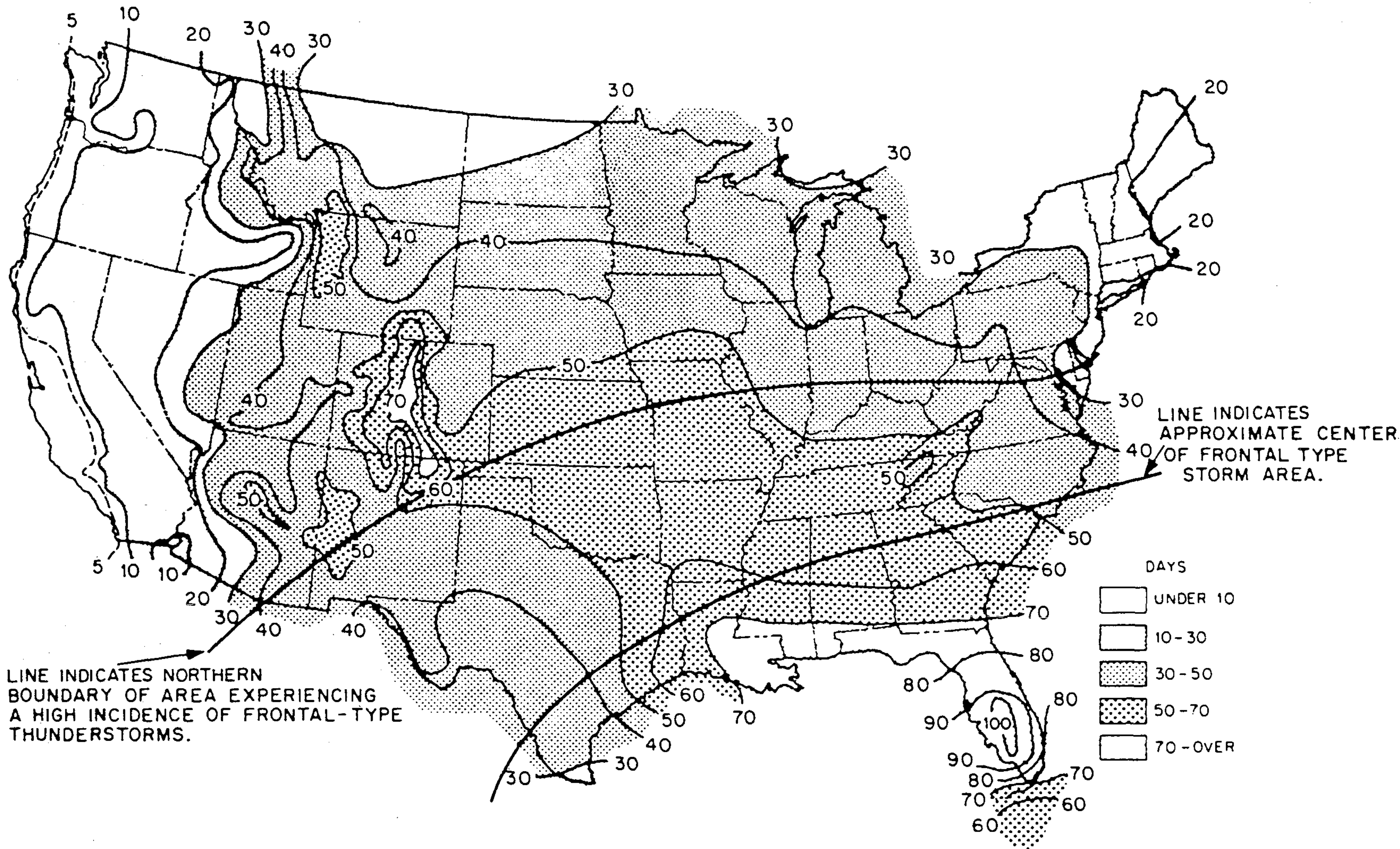
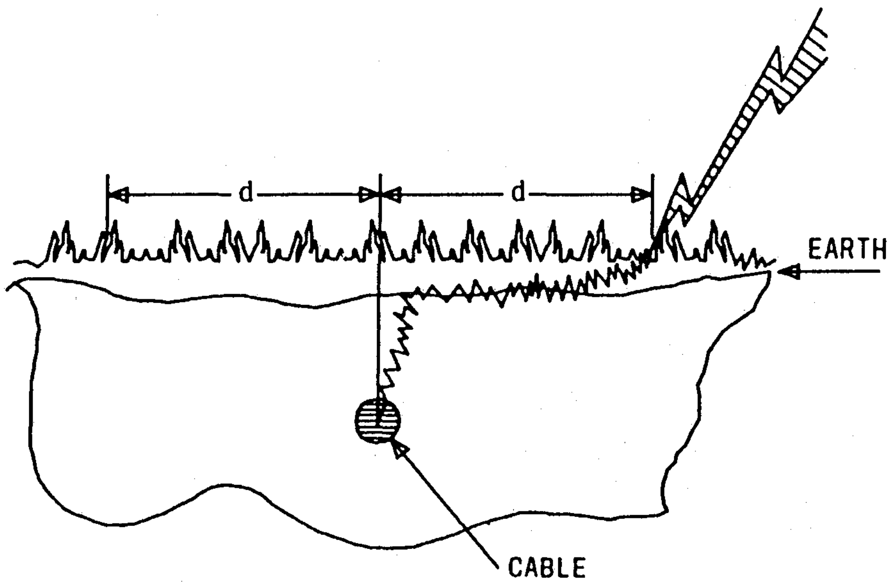


Figure 45. Average annual number of days with thunderstorms (United States) (after AT&T, 1985).



NOTES:

1. IONIZATION PATH USUALLY FOLLOWS SURFACE OF THE EARTH FROM STROKE CONTACT POINT TO SOME POINT DIRECTLY ABOVE BURIED CABLE WHERE IT THEN ARCS TO CABLE.
2. STROKE ARCING DISTANCE $d=0.8\sqrt{\rho}$ WHERE d=FEET AND ρ=METER-OHMS.
3. STROKE COLLECTING AREA = 2d X CABLE LENGTH.

Figure 46. Lightning stroke collecting area for buried cable.

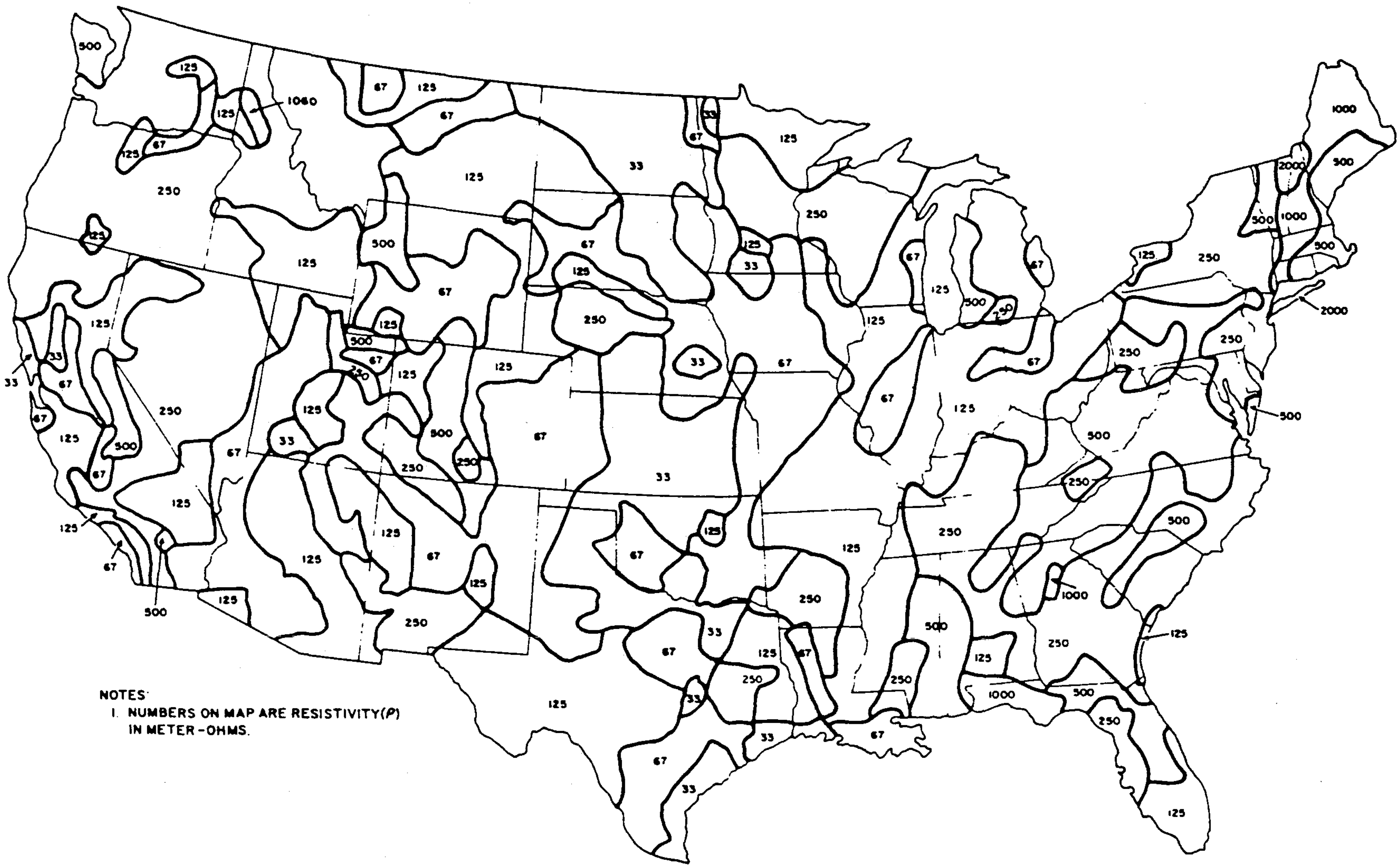


Figure 47. Estimated average earth resistivity in the United States (after AT&T, 1985).

suggested by AT&T (AT&T, 1985) as a measure of the lightning risk. These data are presented as Figure 48. The higher the exposure factor, the more severe the exposure, implying an increasing possibility of cable damage.

4.7.2 Methods of Protection from Lightning Damage

Methods of effective protection from lightning can be lumped into three solution areas: shielding, grounding, and parallel path conduction. A more detailed discussion of each area is provided below.

<u>Shielding</u> Placing a low resistance shield around the conductor or the fiber is an effective way to avoid damage to the vital components of the communication system. The shield must carry the current to a point of release to the Earth, usually causing an arc that will tend to deteriorate the outer sheath of the cable or conductor.

<u>Grounding</u> Effective grounding and bonding practices are important for protection from lightning. The current that is injected into the cable shield must be transferred to ground without causing damage to the cable or to the electronics at either end of the cable. Grounding practices referred to earlier in this section for protection from effects of EMP are applicable for protection from lightning.

<u>Parallel conduction</u> Parallel paths can be provided to aid in the shunting of current, generated by lightning, to Earth where it will not damage any of the system components. Two techniques for providing parallel paths will be mentioned. There are more effective ideas.

1. Providing intermediate Earth ground points along the cable will reduce the peak level of current sustained at any point along the cable shield. For lightning, a hard Earth ground (ground stake) will probably be sufficient; however for EMP, since there are higher frequency components, the Earth ground connection possibly should be made through an impedance equal to the characteristic impedance from the shield to Earth ground. In either case, reducing the peak currents along the cable is the goal.

2. The use of buried shield wires parallel to, and near, a buried cable is an effective way to reduce the amount of current injected on the cable shield. The buried shield wire will provide a lower resistance path to Earth ground thus shunting the lightning charge to Earth ground without affecting the cable.

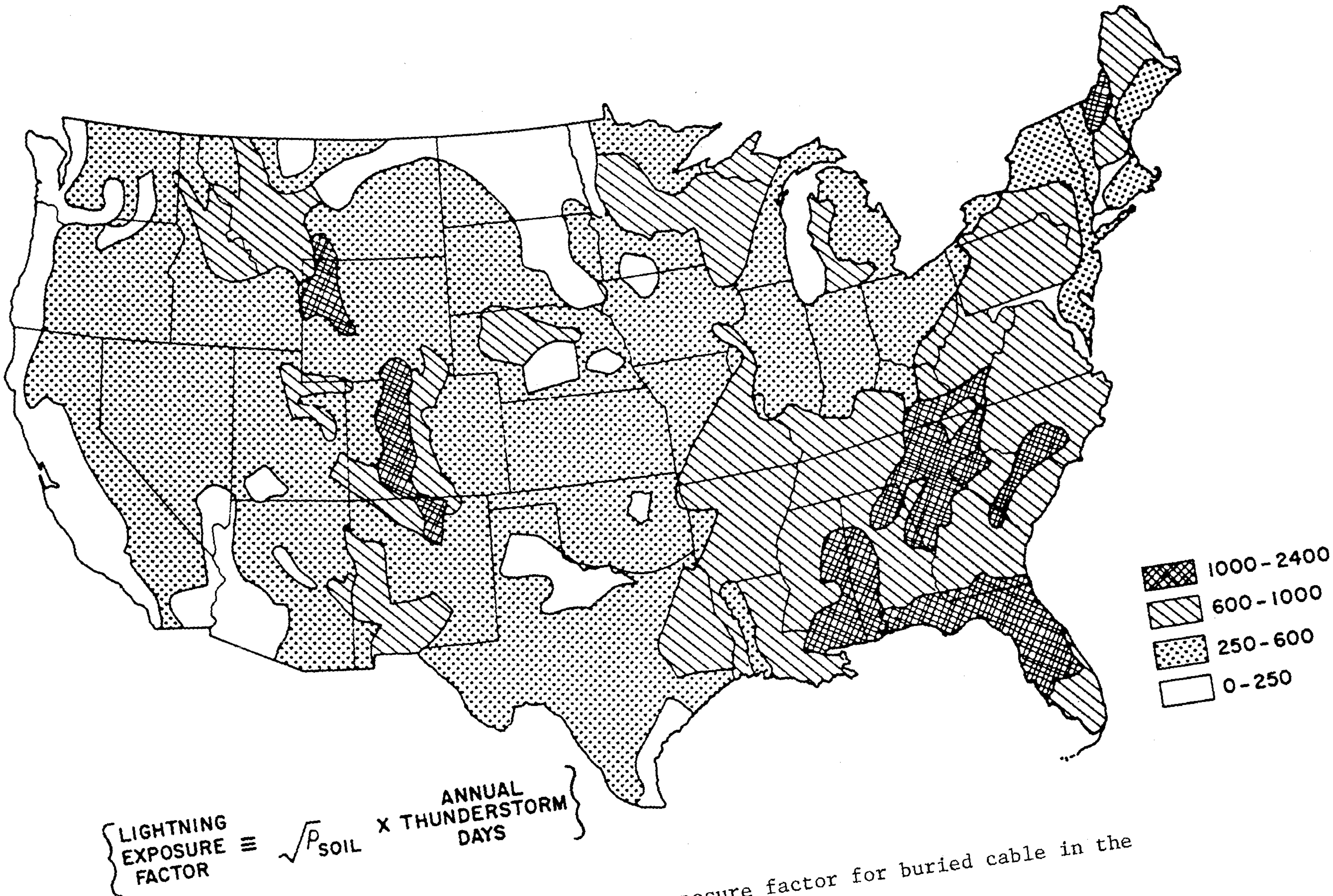


Figure 48. Estimated lightning exposure factor for buried cable in the United States, (after AT&T, 1985).

A common consensus seems to be that the threat from lightning is no more severe than EMP; therefore, the protection provided to harden against EMP will be sufficient to protect the installation from lightning damage. Techniques for EMP hardening have been presented earlier in this section.

4.8 Providing an Effective "Ground"

4.8.1 Importance of a Good "Ground"

The best system design can be negated with implementation of a poor ground. Maximizing the protection against electromagnetic interference (EMI) and other transient sources sometimes involves empirical procedures in order that the most effective method is used for grounding a system. Problems often result from parts of the ground system not being properly bonded together yielding multiple ground potentials. The different ground potentials can manifest themselves in large transients when current is injected into the ground by lightning or EMP. Thus the solution lies in using (specifying) correct bonding and grounding methods.

4.8.2 Recommended Bonding and Grounding Practices

Based on experience of others who have successfully implemented grounding systems, several excellent guides have been written detailing the best known methods for bonding and grounding. MIL-HDBK-419 (DOD, 1982) is an excellent guide to bonding and grounding methods, written as a generic guide for electronic equipment and facilities, but relevant for a telecommunication system. This handbook also presents a chapter on techniques for EMP protection--including relevant information concerning transient suppression. MIL-STD-188-124A, a standard written for Common Long Haul/Tactical Communication Systems (DOD, 1984), and the Defense Switched Network Design Practices (Miletta et al., 1982), deal with the recommended bonding and grounding techniques for telecommunication systems.

5. OPERABILITY DETERMINATION

The durability of the fiber optic link (path) is determined by the stress enhancements that have been included in the system design or the installation practices. This report discusses the stress resistance provided by enhancements that are currently being implemented by carriers or enhancements that can be included in the installation if the need demands their addition to the design. Survivability of the link is determined by the set of enhancements utilized and the stress level (threat) that is expected along the route (path). The intent is for the information provided in this report to aid in the "determination of operability."

5.1 Parameters that Affect Operability

Any fiber optic cross-country (long haul) link can be broken down into segments that include a pair of regenerators and the cable between them. This is simply a transmitter, a receiver, and the cable connecting them. The distance that can be spanned is determined by the receiver sensitivity, the transmitted power, and the loss along the cable.

If the receiver sensitivity and the transmitted power are known, the loss allowable for the cable can be calculated. This total loss is commonly known as the "link loss budget"--and is usually noted in decibels (dB). The total loss of the cable is made up of three major inputs:

- summation of the splice losses
- inherent loss/length of the cable used
- losses due to stress along the path

A number of minor inputs to the total loss accumulation also contribute to the resultant total loss, but are not significant contributors or can be lumped into one of the three categories listed above. The steady state loss can be determined by the first two loss categories, and is quite predictable. Based on the hardware selected for the transmit and receive ends, the loss allowable from the first two categories will determine the distance between the adjacent regenerator stations.

The losses due to stress will add to the summation of losses from the first two categories; thus a margin for additional loss must be factored into the design. The total "link loss budget" then becomes the sum of the fixed loss contribution and the allowance for contribution from stress. As stated earlier, the loss from the first two contributors is predictable; however, the loss due to stress is not totally predictable. Data and analyses presented in this report will help in understanding the loss due to stress and will aid in predicting the amount of loss, e.g., loss due to gamma radiation.

5.2 Gamma Radiation Effects

The optical fiber loss due to exposure to gamma radiation is not yet well understood; however, some testing has taken place. The tests show that a major loss can be expected when the fiber is exposed to radiation. Results of these tests are discussed in Section 4 of this report.

Two factors affect the fiber loss: the fiber (glass) composition and the amount of shielding provided along the cable route. Both of these factors can be variables along the path, making the calculation of the accumulated loss a tedious task. For example, the cable depth of burial will vary along a particular path due to placement over or around obstacles, resulting in less protection from radiation.

As an aid in calculating this total loss, a computer program has been developed to accumulate the contribution from each segment of the path (Ingram, 1987). In addition to loss calculations, the program predicts the recovery of the fiber from exposure to radiation. The resultant loss, after the expected loss due to radiation dose is integrated with the expected recovery rate of the fiber, is calculated and plotted as a function of time after the onset of radiation.

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APPENDIX A: GAMMA RADIATION INTENSITY FOR BURIED TARGETS

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APPENDIX A: GAMMA RADIATION INTENSITY FOR BURIED TARGETS

A.1 INTRODUCTION

This brief study seeks an answer to the following question: "What protection is provided by ground to buried facilities when the Earth is irradiated by gamma rays?" A number of physical conditions and parameters are expected to influence the final answer. In what follows, attempts are made to identify the key parameters, to justify their role, and to assess their protective impact in decibels (dB).

It is recognized that Earth is comprised of different composition soils. There may be inhomogeneous layering of substances, including considerable amounts of localized moisture. To simplify, this study assumes a homogeneous Earth with a constant (i.e., location independent) absorption properties. The target facility, such as an element of a fiber optic network, can be placed at a depth to be specified. The performance of the facility is affected by the received gamma ray dosages, as discussed in other documentation.

A number of assumptions are made about the radiating sources. To start, a stationary scenario is postulated. The gamma particle energies are expressed in units of million electron volts (or MeV). Different MeV gamma rays have different penetration powers through the same substance. The spatial distribution or density of sources, both in the atmosphere and on the Earth's surface, may affect the attenuation levels further. Finally, the placement and size of the radioactive cloud should have the most damaging effect when the target point is directly below said could. The impact would be even worse when the cloud were to spread indefinitely in all horizontal directions.

A.2 THE GEOMETRICAL MODEL

The model assumed is that of Figure A-1. On and above Earth surface there are many gamma ray sources. One denotes their distribution per unit volume as C(z), the premise being that the density of the radioactive particles varies significantly as a function of the vertical $z \geq 0$, but not so as a function of horizontal x and y.

Consider a target point at depth $d \geq 0$ below the surface. The intensity observed at the target location is clearly an attenuated (i.e., selectively absorbed) sum of radiation contributions of all variously dispersed radiating elements. First, one specifies the gamma ray absorption coefficients: γ_0 --

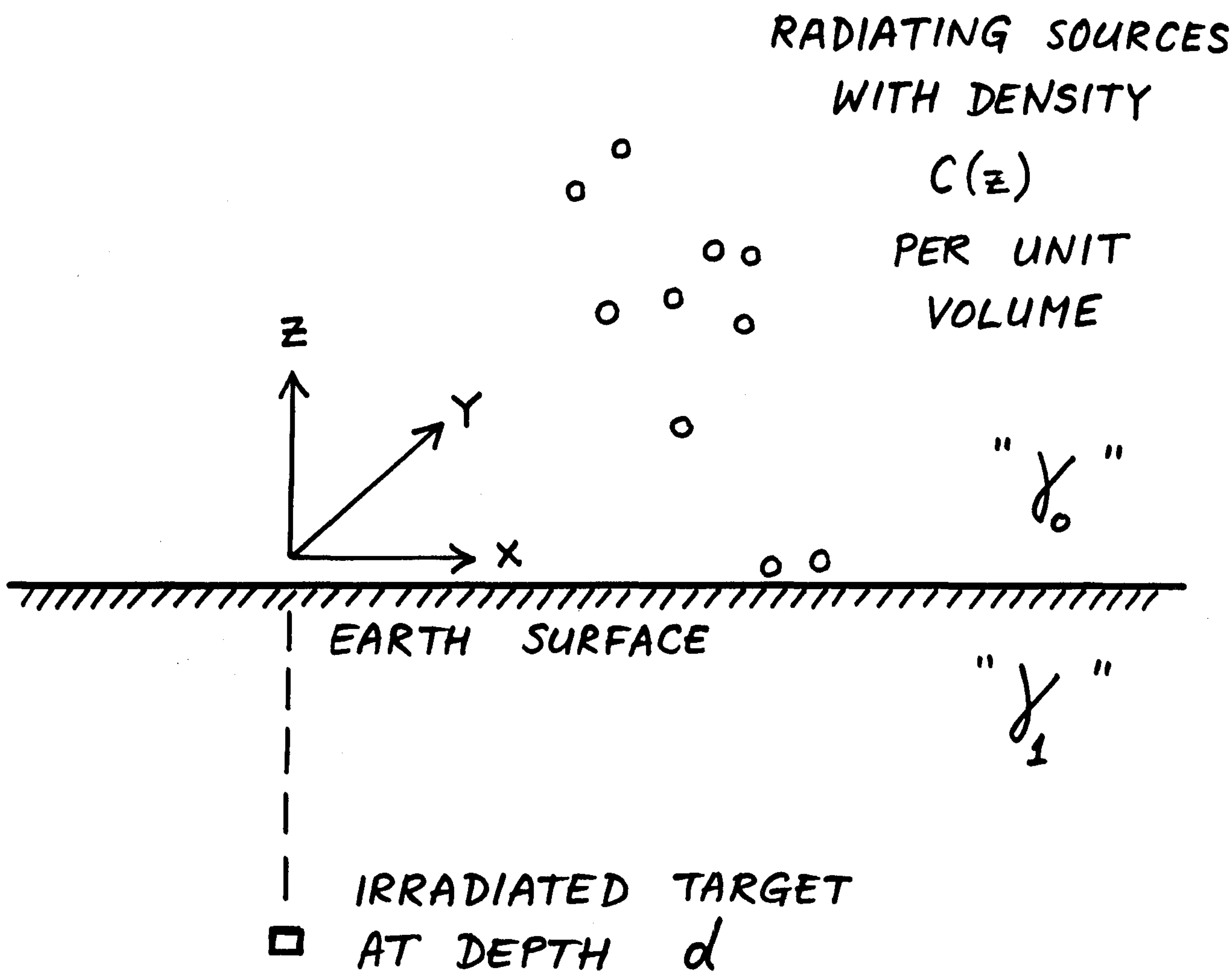

Figure A-1. Geometry of the buried target and distributed radiation sources above ground.

above ground, and γ_1 -- below ground. As is well known, the values of absorption coefficients depend on the gamma energy (typically in MeV) and on the substances encountered. We assume initially that the gamma particles are of the same energy and the absorbing materials are homogeneous in the two media. Then γ_0 and γ_1 are constants. Note also that these γ's are ordinary absorption coefficients with dimensions 1/m. For a homogeneous path element of length R, they lead to the familiar $\exp(-\gamma R)$ attenuation. That must be distinguished from the mass-absorption coefficient, which is related to the material density ρ through $\rho_m = \gamma/\rho$, and which leads to the attenuation expression $\exp(-\gamma_m \rho R)$ found elsewhere in the literature.

The radiation intensities at the target point are assumed to be primary only. By that one means the exclusion of all secondary reradiation due to particle capture and related phenomena.

If the source point is (x,y,z) and the target is (0,0,-d), then their distance is

$$R = \sqrt{x^2 + y^2 + (z + d)^2} \quad . \tag{1}$$

The contribution from an infinitesimal volume dV at (x,y,z) to the received target intensity is accordingly proportional to

$$dI = \frac{C(z)}{R^2} e^{-\frac{\gamma_0 z + \gamma_1 d}{z + d} R} dV \quad . \tag{2}$$

The total received intensity is obtained by integration over the entire upper half-space, that is $-\infty \leq x \leq \infty$, $-\infty \leq y \leq \infty$, and $0 \leq z \leq \infty$.

While the required integration may be carried out in one of many coordinate systems, things appear to go smoother if a particular (R,θ,z) system is used. The (R,θ,z) coordinates for a source point are defined in Figure A-2. The Jacobian follows immediately and is $J = R$. The infinitesimal volumes are related by

$$dV = dxdydz = RdRd\theta dz \quad , \tag{3}$$

and the integration volume extends over $z+d \leq R \leq \infty$, $0 \leq \theta \leq 2\pi$, and $0 \leq z \leq \infty$.

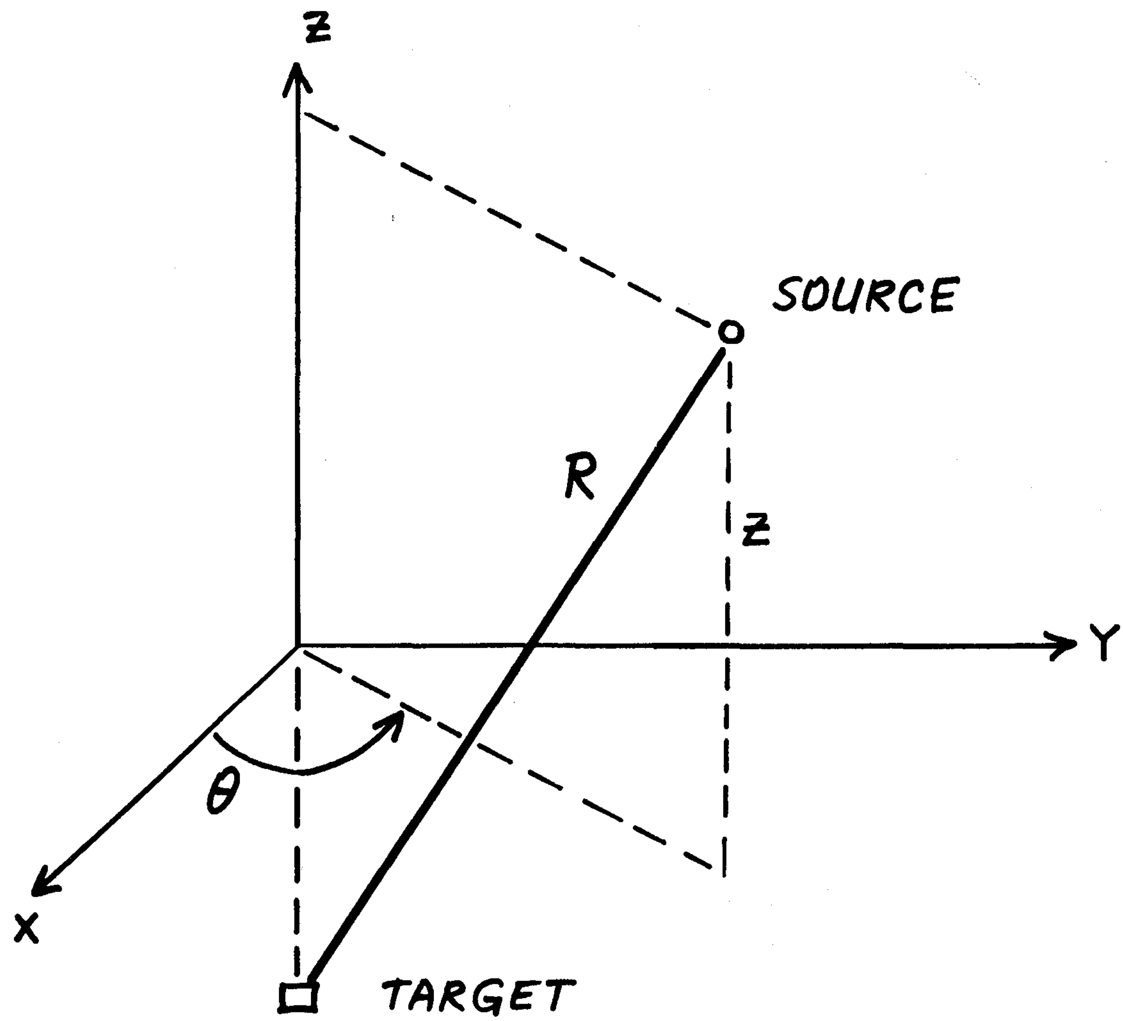

Figure A-2. Coordinate systems.

A.3 GENERAL FORMULA FOR THE RECEIVED INTENSITY

The total received intensity at depth d below the ground level is denoted by I(d). When evaluated through integration of equation (2) in the (R,θ,z) coordinates, the result is

$$I(d) = 2\pi \int_1^\infty \frac{L(\gamma_0 s)}{s} e^{-(\gamma_1 d)s} ds \quad , \tag{4}$$

where function $L(\gamma_0 s)$ is the ordinary Laplace transform of C(z), evaluated at $\gamma_0 s$. One writes that transform formally as

$$L(p) = \int_0^\infty C(z)\, e^{-pz}\, dz \quad . \tag{5}$$

Equations (4) and (5) are general in the sense that they apply to arbitrary distributions C(z). Many Laplace transforms are known and tabulated. Others require individual attention and may or may not be expressed in a closed form.

A.4 SPECIAL CASES FOR RADIOACTIVE PARTICLE DISTRIBUTIONS

This section illustrates the exposures I(d) that result from the previously derived general formulas, when they are applied to a number of special cases for C(z).

A.4.1 Constant

Let

$$C(z) = \alpha \quad , \qquad 0 \leq z \leq \infty \quad . \tag{6}$$

It follows that

$$I(d) = \frac{2\pi\alpha}{\gamma_0} E_2(\gamma_1 d) \quad , \tag{7}$$

where $E_n(x)$, n = 1, 2, 3, ..., stands for the Exponential Integral function. It is formally defined as

$$E_n(x) = \int_1^\infty t^{-n} e^{-xt} dt \quad . \tag{8}$$

Section 5.1 lists several useful properties of $E_n(x)$. Among them one finds $E_n(0) = (n - 1)^{-1}$, which enables one to set $I(0) = 2\pi\alpha/\gamma_0$.

The relative ground attenuation is defined as

$$i(d) = \frac{I(d)}{I(0)} \quad . \tag{9}$$

For the constant source distribution it yields

$$i(d) = E_2 (\gamma_1 d) \quad . \tag{10}$$

A.4.2 Low Altitude Layer

Assume

$$\begin{aligned} C(z) &= \alpha && \text{for } 0 \leq z < a \quad , \\ &= 0 && \text{otherwise.} \end{aligned} \tag{11}$$

Then

$$I(d) = \frac{2\pi\alpha}{\gamma_0} [E_2(\gamma_1 d) - E_2(\gamma_1 d + \gamma_0 a)] \quad , \tag{12}$$

and

$$i(d) = \frac{E_2(\gamma_1 d) - E_2(\gamma_1 d + \gamma_0 a)}{1 - E (\gamma_0 a)} \quad . \tag{13}$$

A.4.3 High Altitude Band

For $a < b$ and

$$C(z) = 0 \qquad \text{for } 0 \le z < a \ ,$$
$$\quad = \alpha \qquad \text{for } a \le z < b \ , \qquad (14)$$
$$\quad = 0 \qquad \text{for } b \le z \le \infty \ ,$$

one obtains

$$I(d) = \frac{2\pi\alpha}{\gamma_0} [E_2(\gamma_1 d + \gamma_0 a) - E_2(\gamma_1 d + \gamma_0 b)] \qquad (15)$$

and

$$i(d) = \frac{E_2(\gamma_1 d + \gamma_0 a) - E_2(\gamma_1 d + \gamma_0 b)}{E_2(\gamma_0 a) - E_2(\gamma_0 b)} \ . \qquad (16)$$

Note that both previous cases (Sections 4.1 and 4.2) are special cases of this, and that arbitrarily constructed step-function $C(z)$'s will result into sums and superpositions of these terms.

A.4.4 Exponential

Let

$$C(z) = \alpha \, e^{-\beta z} \ , \qquad 0 \le z \le \infty \ . \qquad (17)$$

It follows that

$$I(d) = \frac{2\pi\alpha}{\beta} \left[E_1(\gamma_1 d) - e^{\gamma_1 d \frac{\beta}{\gamma_0}} E_1\left(\gamma_1 d (1 + \frac{\beta}{\gamma_0}) \right) \right] \ . \qquad (18)$$

Despite its cumbersome "$\infty - \infty$" appearance at $d = 0$, $I(d)$ is always bounded for the exponential $C(z)$. At $z = 0$ it has the value $2\pi\alpha/\gamma_0$.

$$i(d) = \frac{\gamma_0}{\beta} \left[E_1(\gamma_1 d) - e^{-\gamma_1 d \frac{\beta}{\gamma_0}} E_1\left(\gamma_1 d (1 + \frac{\beta}{\gamma_0}) \right) \right] \quad . \tag{19}$$

A.4.5 Delta Function

For an extremely thin radioactive particle layer on or above the ground, assume

$$C(z) = \alpha \delta(z - a) \quad , \qquad a \geq 0 \quad . \tag{20}$$

It follows immediately that

$$I(d) = 2\pi\alpha \; E_1(\gamma_1 d + \gamma_0 a) \tag{21}$$

and

$$i(d) = \frac{E_1(\gamma_1 d + \gamma_0 a)}{E_1(\gamma_0 a)} \quad . \tag{22}$$

Note that these intensities are not bounded for all values of a and d. Examples: I(d) is infinite when both a = d = 0, while i(d) vanishes when a = 0 and d $\neq$ 0.

A.4.6 Powers of z

If for n = 1, 2, 3, ...,

$$C(z) = \alpha z^n \quad , \qquad 0 \leq z \leq \infty \quad , \tag{23}$$

then

$$I(d) = \frac{2\pi\alpha \; (n!)}{\gamma_0^{\,n+1}} \; E_{n+2} \; (\gamma_1 d) \quad , \tag{24}$$

and

$$i(d) = (n+1)\, E_{n+2}\, (\gamma_1 d) \quad . \tag{25}$$

Despite its simple mathematical appearance, this case may have doubtful physical significance. One wonders whether such unbounded C(z) distributions are possible in the real world.

A.4.7 Inverse Square Root

For a distribution that is concentrated near the earth surface, consider

$$C(z) = \frac{\alpha}{\sqrt{z}} \quad , \qquad 0 \leq z \leq \infty \quad . \tag{26}$$

Then

$$I(d) = 2\pi^{3/2} \alpha \sqrt{\frac{\gamma_1 d}{\gamma_0}}\ \Gamma\left(-\frac{1}{2}\ ,\ \gamma_1 d\right) \quad , \tag{27}$$

where Γ(s, x) is the Incomplete Gamma function

$$\Gamma(s,\ x) = \int_x^\infty t^{s-1}\ e^{-t}\ dt \quad . \tag{28}$$

Function $\Gamma(-\frac{1}{2},\ x)$ does not exist at x = 0. However, $\sqrt{x}\ \Gamma(-\frac{1}{2},\ x)$ does exist and has the value 2. Conclusion:

$$i(d) = \frac{1}{2}\sqrt{\gamma_1 d}\ \Gamma\left(-\frac{1}{2},\ \gamma_1 d\right) \quad . \tag{29}$$

A.4.8 Linear - Exponential Product

A distribution

$$C(z) = \alpha z\ e^{-\beta z} \quad , \qquad 0 \leq z \leq \infty \quad , \tag{30}$$

has a density peak at $z = 1/\beta$, while it vanishes at both $z = 0$ and $z = \infty$. If one abbreviates

$$A = \gamma_1 d(1 + \frac{\beta}{\gamma_0}) \tag{31}$$

then

$$I(d) = \frac{2\pi\alpha}{\beta^2}\left[E_1(\gamma_1 d) - e^{A-\gamma_1 d}\left(E_1(A) + \frac{E_2(A)}{1 + \frac{\gamma_0}{\beta}}\right)\right], \tag{32}$$

and

$$i(d) = \frac{E_1(\gamma_1 d) - e^{A-\gamma_1 d}\left(E_1(A) + \frac{\beta}{\beta + \gamma_0} E_2(A)\right)}{\ln \frac{\beta + \gamma_0}{\gamma_0} - \frac{\beta}{\beta + \gamma_0}}. \tag{33}$$

A.4.9 Piecewise Linear

In practice one can encounter empirical distributions C(z). Their shapes may resemble no simple equations, yet they may be approximated by piecewise linear segments. The terminology for such an approximation is given in Figure A-3. Formulas are simpler if one assumes a fixed spacing of points, such as $z_{n+1} - z_n = \Delta$. For such a model one obtains $z_n = z_0 + n\Delta$ and

$$I(d) = 2\pi\left[C_0\gamma_0\Delta\, E_2(\gamma_1 d + \gamma_0 z_0) + \sum_{n=1}^{max} (C_{n+1} - 2C_n + C_{n-1})\, E_3(\gamma_1 d + \gamma_0 z_n)\right]. \tag{34}$$

If follows that

$$I(0) = 2\pi\left[C_0\gamma_0\Delta\, E_2(\gamma_0 z_0) + \sum_{n=1}^{max} (C_{n+1} - 2C_n + C_{n-1})\, E_3(\gamma_0 z_n)\right], \tag{35}$$

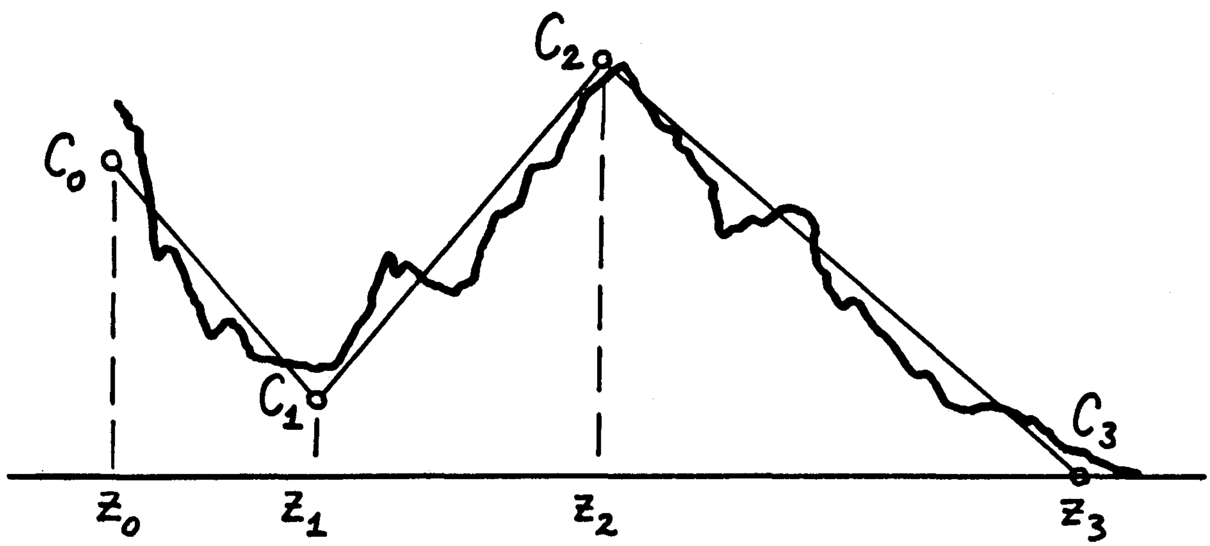

Figure A-3. Piecewise linear approximation with linear segments.

with the ratio of the two being the relative intensity i(d) at depth d.

A.5 APPLICATIONS

A.5.1 Properties of Exponential Integrals

The Exponential Integral $E_n(x)$, as defined in equation (8), has a number of potentially useful properties.

Special values:

$$E_n(0) = \infty \qquad \text{if } n = 1 \,,$$
$$\qquad = \frac{1}{n-1} \qquad \text{if } n \geq 2 \,. \tag{36}$$

$$E_n(\infty) = 0 \qquad \text{for all } n \,. \tag{37}$$

Recurrence relation:

$$nE_{n+1}(x) = e^{-x} - x\,E_n(x) \tag{38}$$

It can be used to express any $E_n(x)$ in terms of others with either lower or higher indices.

Bounds:

$$\frac{1}{n+x} e^{-x} \leq E_n(x) \leq \frac{1}{n-1+x} e^{-x} \qquad \text{for } 0 \leq x \leq n-1 \,,$$
$$\leq \frac{1+x}{x(n+1+x)} e^{-x} \qquad \text{for } n-1 \leq x \leq \infty \,. \tag{39}$$

Series expansions:

For $x \ll 1$, and $\gamma = .577\ 216$ being the Euler constant,

$$E_n(x) = \frac{(-x)^{n-1}}{(n-1)!} \left[\left(\sum_{m=1}^{n-1} \frac{1}{m} \right) - \gamma - \ell n x \right] - \tag{40}$$

$$- \sum_{\substack{m=0 \\ (m \neq n-1)}}^{\infty} \frac{(-x)^m}{(m - n + 1)m!} \quad .$$

For $x >> 1$,

$$E_n(x) \approx \frac{e^{-x}}{(n-1)!x} \sum_{m=0}^{\infty} \frac{(n - 1 + m)!}{(-x)^m} \tag{41}$$

asymptotically.

Needless to say, tables of $E_n(x)$ exist for n and x ranges of interest. Graphical illustrations are shown in Figure A-4.

A.5.2 Numerical Results

The gamma radiation effects at depth d have been shown to depend heavily on the absorption coefficient of the ground (γ_1), and to a lesser extent on the absorption coefficient of the air (γ_0). To demonstrate the penetration intensities as derived in the equations of Section 4, one requires numerical values for the absorption coefficients. A brief listing of $\gamma(m^{-1})$ values for the more common ground substances is given in Table A-1. Note that γ_0 is the coefficient for air, while all the other solid materials could correspond to γ_1.

Several of the substances, like clay, concrete products, and wood, come in a wide variety of chemical compositions. Their respective absorption coefficients vary over the indicated numerical ranges. When for a given substance (e.g., clay) the range is $11.3 \leq \gamma_1 \leq 14.3$ for 1 MeV gamma rays, the highest value 14.3 is said to be "best" and the lowest value 11.3 is "worst" for our purposes.

Note also that the absorption coefficients of all materials show a significant dependence on the energy level of the gamma rays. There is less absorption and more penetration, as the gamma MeV values are increased.

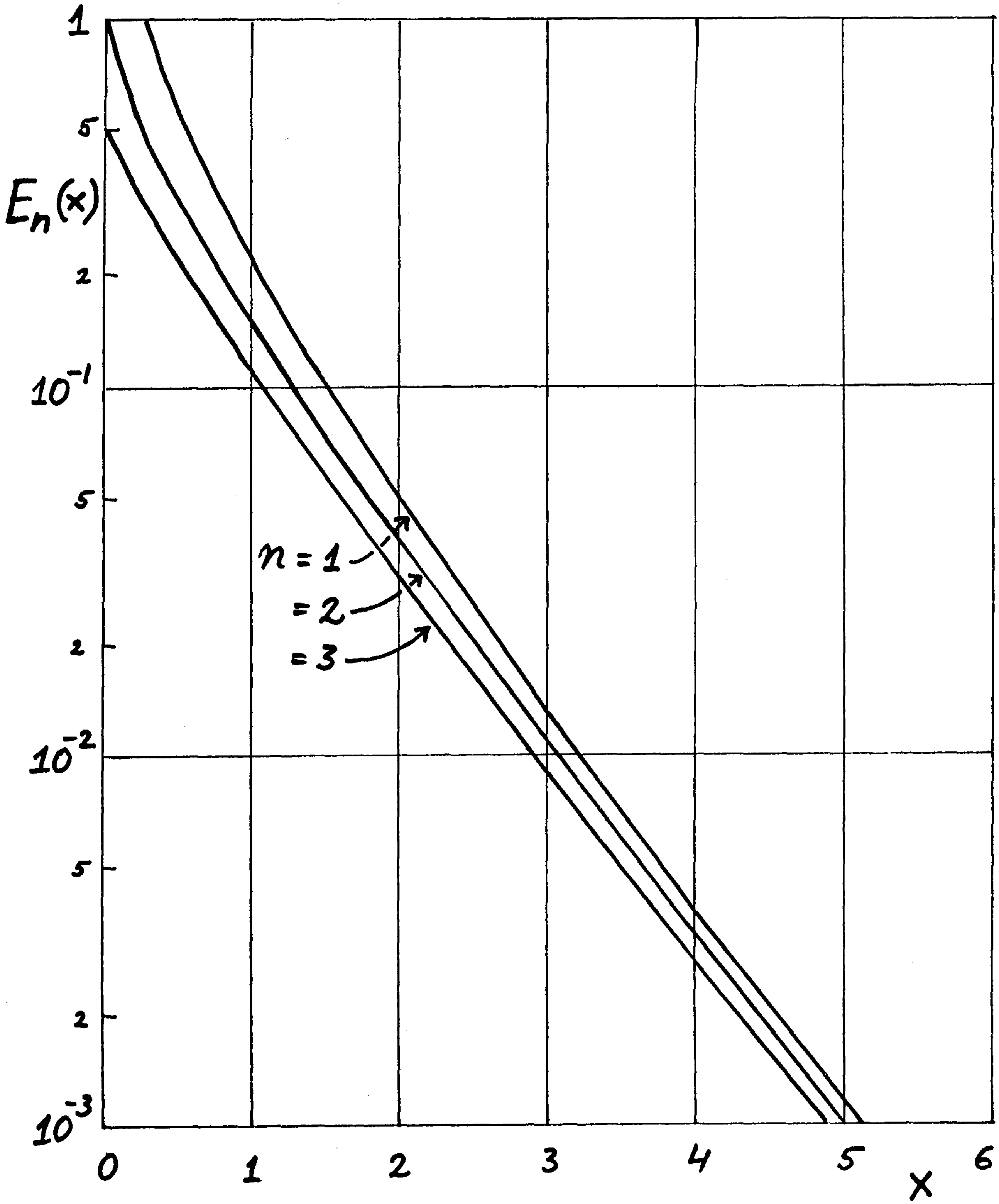

Figure A-4. The exponential intergral $E_n(x)$.

Table A-1. Absorption Coefficient, $\gamma(m^{-1})$, for Gamma Rays of Different Energy Levels

Absorbing Material	Gamma Ray Energy (in Mev)		
	1.0	3.0	6.0
Air	.0077	.0043	.0030
Clay	11.3 - 14.3	6.46 - 8.01	4.73 - 5.90
Concrete + Cement	12.8 - 37.4	7.25 - 22.2	5.28 - 18.4
Rock	15.2 - 18.7	8.71 - 10.9	6.41 - 8.24
Sand	14.0	8.25	5.87
Water	7.06	3.96	2.77
Wood	3.45 - 5.21	1.93 - 2.93	1.34 - 2.03

As the next example, consider the constant C(z) distribution of gamma radiation sources introduced in Section 4.1. Instead of the absolute I(d), let us illustrate the functional behavior of the relative intensity i(d). See (10). Figure A-5 plots i(d) in dB (namely, 10logi(d)) versus d in meters. The energy of the rays is set at 1 MeV. The five curves depict five materials from Table A-1. They are: water, clay (worst or γ_1 = 11.3), sand, rocks (best or γ_1 = 18.7), and concrete/cement products (best or γ_1 = 37.4).

Figures A-6 and A-7 repeat the same intensity i(d) versus d plots, for the same materials, but for increased gamma energies of 3 MeV and 6 MeV, respectively. For a typical soil, which can be argued to be somewhere between sand and clay, the depth required to provide a specified decibel protection grows strongly as the MeV's increase. Suppose, that the occasionally quoted protection of 70 dB is to be an objective. Then for 1 MeV one requires at least 1.0 m = 3.3 ft of soil. For 3 MeV one needs 1.8 m = 5.9 ft, and for 6 MeV the depth grows to 2.5 m = 8.2 ft. And of course, based on best grade concrete, the same 70 dB protection would be offered by layers that are merely 1.2, 2.0, and 2.2 ft thick, respectively, for the aforementioned energy levels.

The curves in Figures A-5, A-6, and A-7, are computed for the constant source density profile, see Section 4.1. Similar calculations are possible for all other C(z) models, see Sections 4.2 to 4.9. To illustrate the impact of different C(z) choices, Figure A-8 is presented. It assumes 3 MeV gamma rays, a soil that consists of the worst of clays, and three C(z) models:

- From Section 4.1, C(z) = constant.
- From Section 4.2, Low Altitude Layer with height restricted to 1 m (i.e., a = 1 in equation (11)).
- From Section 4.6, C(z) = z^2.

Note that source densities that have the largest contributions from the high altitudes exhibit the largest i(d). From the small number of cases evaluated, this feature appears to hold uniformly over all d.

A.5.3 Comparison to Ad Hoc Models

For engineering purposes, simple approximations of the received intensity at depth d are of interest. One intuitively attractive form is

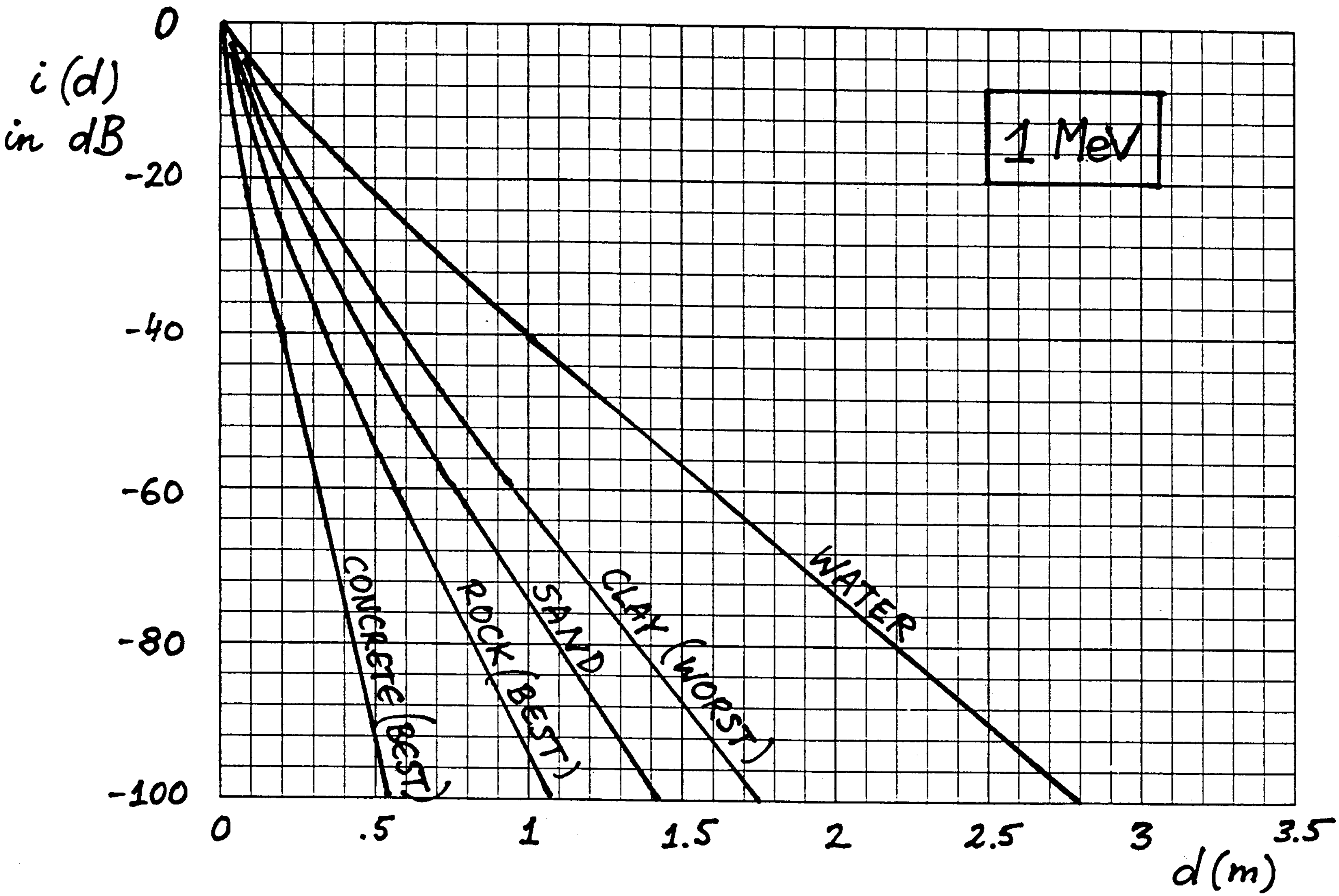

Figure A-5. Relative 1 MeV gamma penetration intensities for different substances, constant C(z).

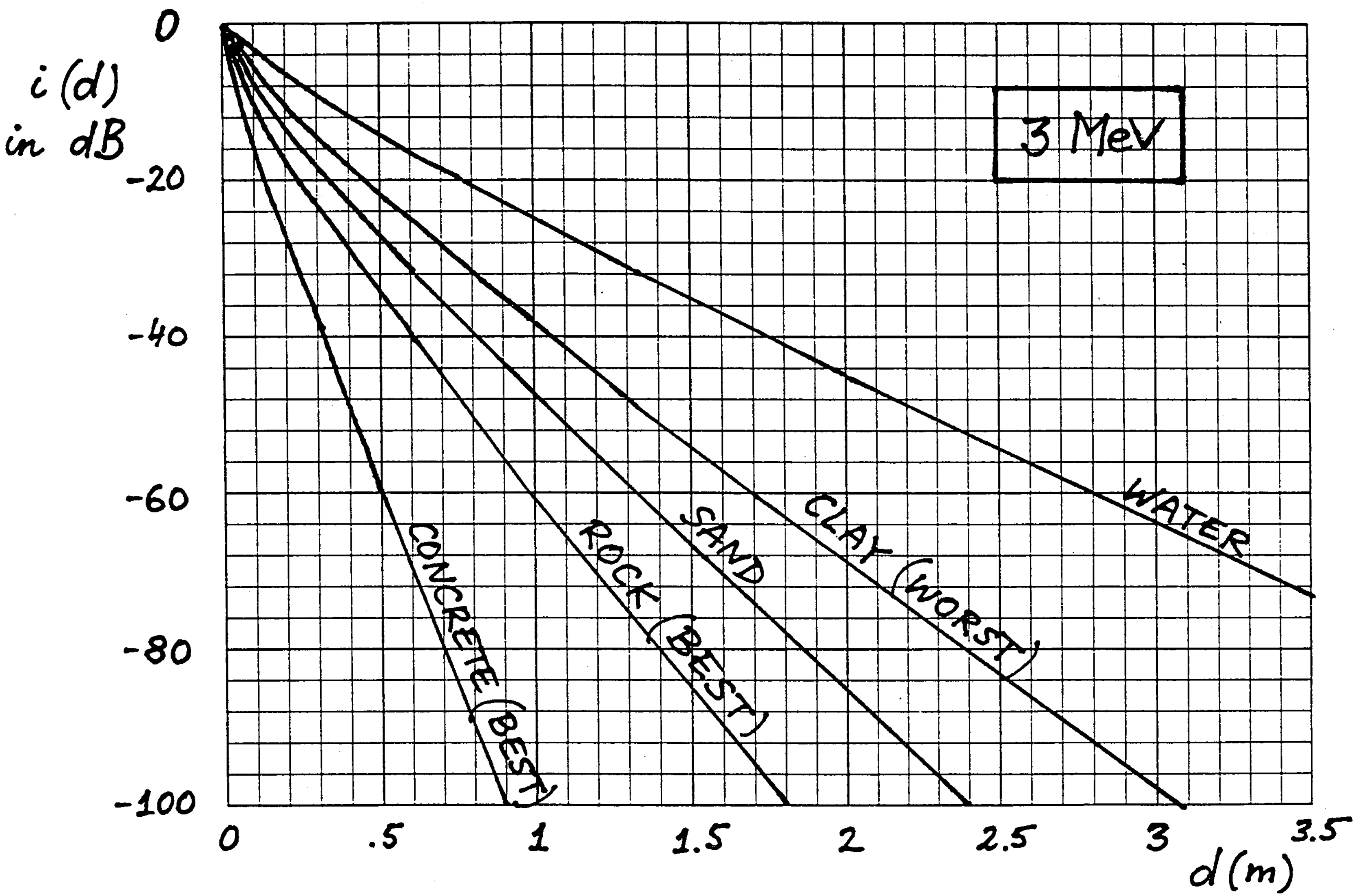

Figure A-6. Relative 3 MeV gamma penetration intensities for different substances, constant C(z).

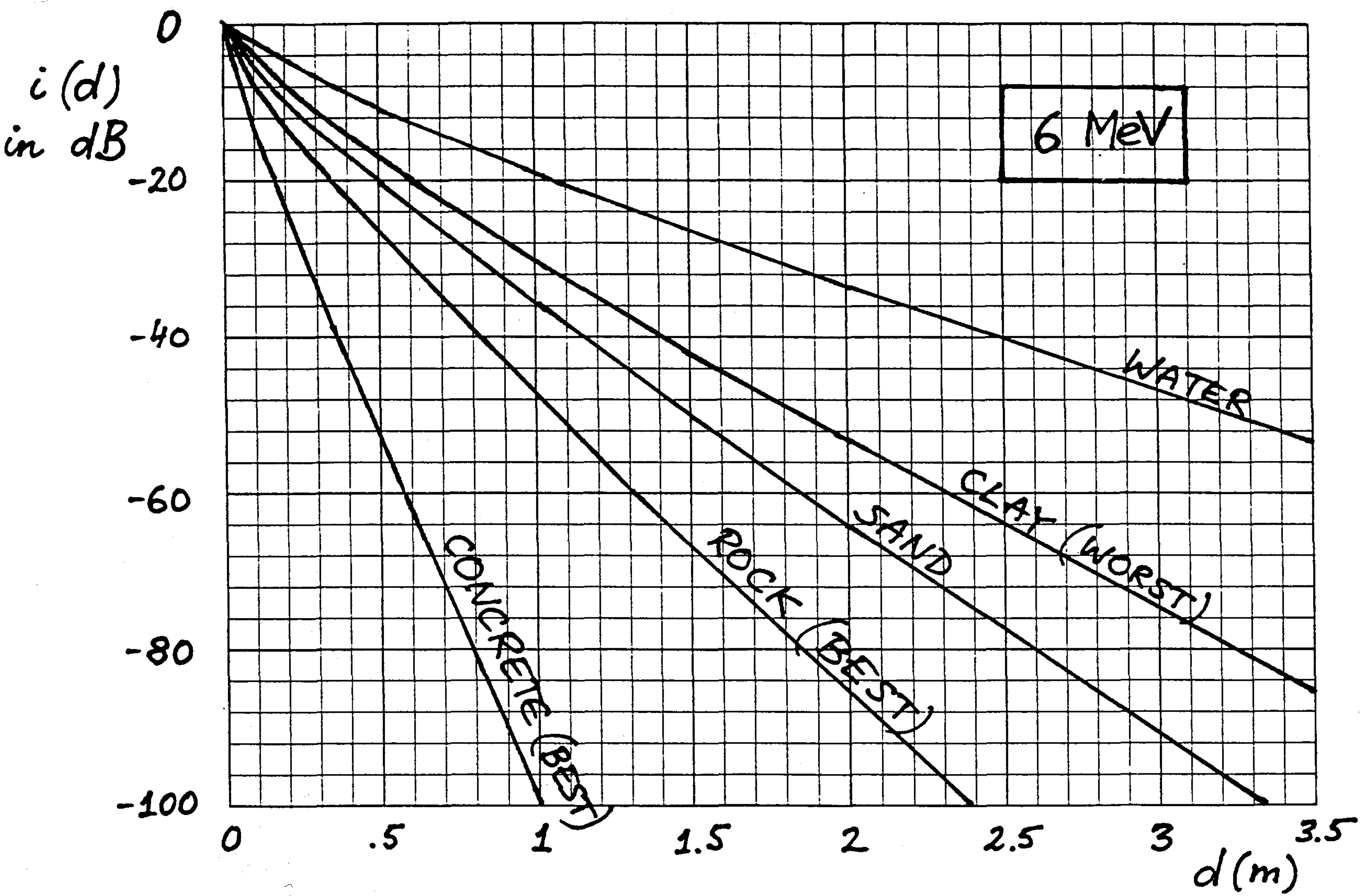

Figure A-7. Relative 6 MeV gamma penetration intensities for different substances, constant C(z).

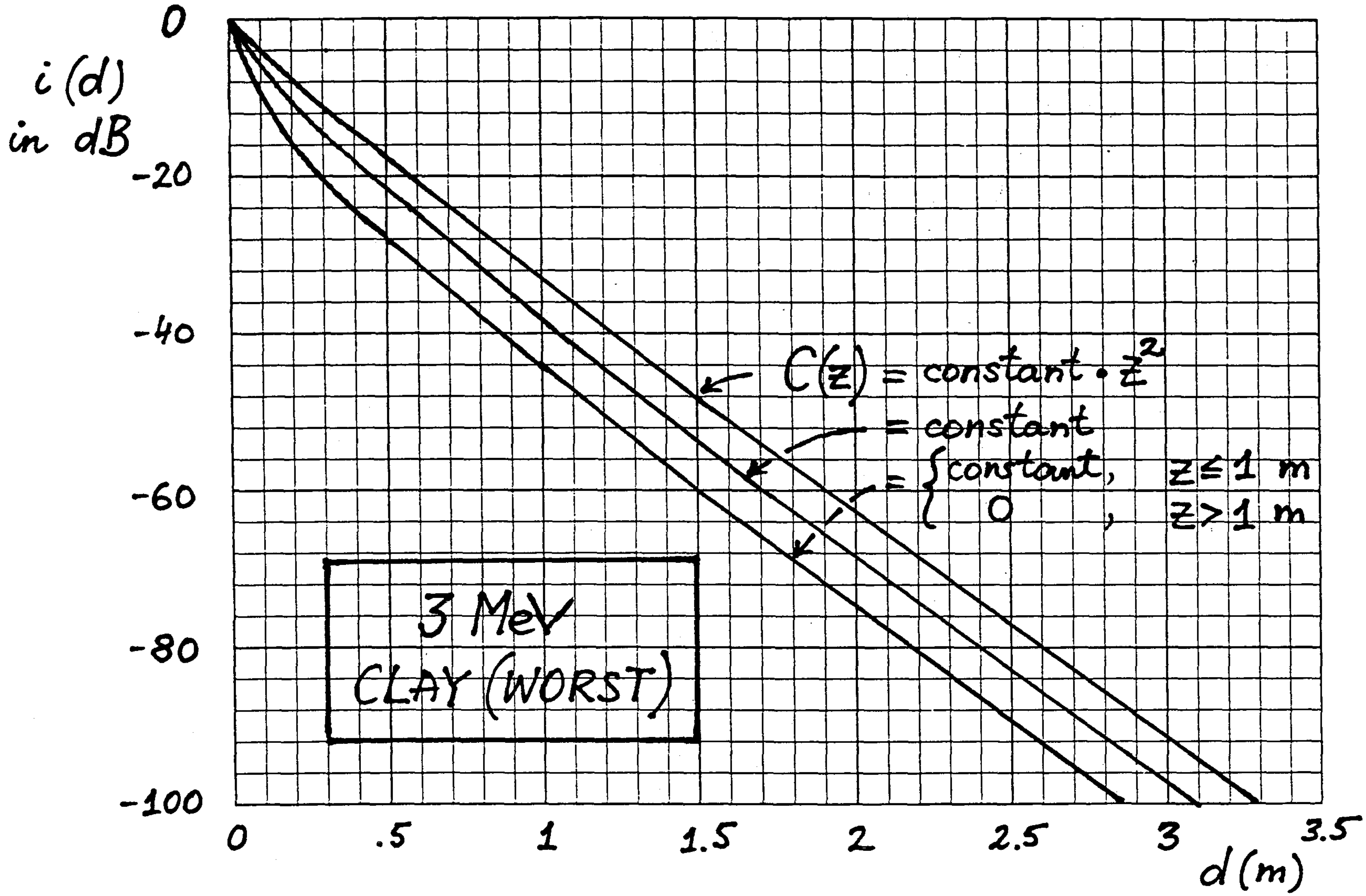

Figure A-8. Relative 3 MeV gamma penetration intensities for different radioactive source distributions.

$$J(d) = L(\gamma_0)\ e^{-\gamma_1 d} \tag{42}$$

and, consequently,

$$j(d) = \frac{J(d)}{J(0)} = e^{-\gamma_1 d} \tag{43}$$

Figure A-9 plots the straight line j(d)'s next to their respective i(d)'s. Note that the j(d) is uniformly an upper bound for its respective i(d). The bounds differ from the apparent true values by some 12 to 14 dB in the protection region of 70 dB. The error decreases as d decreases. It vanishes at d = 0.

A.6 CONCLUSIONS

From the equations and curves presented in this document, it is apparent that the ground attenuation of gamma radiation depends on several factors. In decreasing order of significance, the three main factors are

(a) gamma ray energy in MeV

(b) the absorbing material in the ground

(c) the distribution of radioactive particles on or above the earth surface

The quantitative effects of these three factors are summarized in numerous equations (Sections 3 and 4) and in graphs (Section 5). Given a fixed requirement of 70 dB ground attenuation, the comparative magnitudes of the effects appear to be as follows:

(a) For a typical soil that is halfway between clay and sand, an energy swing from 1 to 6 MeV causes the depth requirement to increase from around 1.0 to 2.5 m.

(b) For a typical gamma ray energy of 3 MeV, a material replacement of best rocks with worst clay warrants a burial depth increase from 1.2 to 2.0 m.

(c) For 3 MeV gamma rays through the worst clay, the impact of modifying the radioactive particle distribution C(z) (see Figure A-8) may cause the depth requirement to vary between 1.85 and 2.25 m.

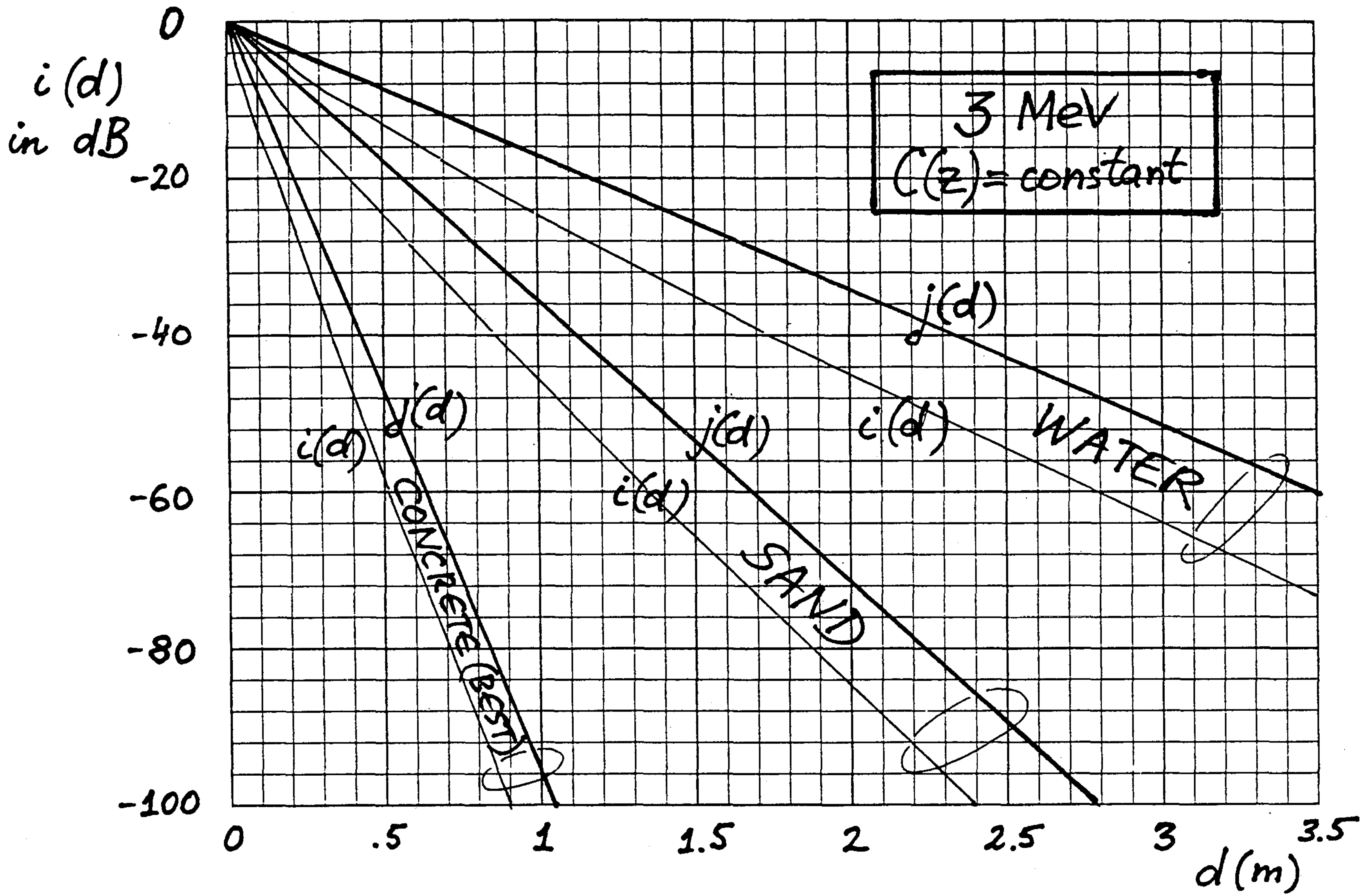

Figure A-9. Comparison of the ad hoc bound j(d) with the derived i(d).

To generate more reliable and more useful design results for future deployment, a number of quantitative questions should eventually be answered.

- What specific gamma ray energies, in MeV, are to be considered? What are the extreme MeV ranges? What known energy distributions apply to future implementations?

- The absorption coefficient, γ, varies from soil to soil, from place to place, and even from time to time (as the water content changes). What are average (or 50%-percentile), the best (or 95%-percentile), and the worst (or 5%-percentile), γ values for system deployment in the CONUS?

- What spatial distributions, for example C(z), are to be assumed for radiating gamma sources in the atmosphere and on the ground? What factors (e.g., MeV's) are likely to influence the shapes of these distributions?

- If absorption of gamma rays is to cause secondary emission, or reradiation, what additional assumptions are then to be made? What energy level and spatial distributions are to be used for the secondary sources, above ground and within ground?

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APPENDIX B: DISTORTION OF THE HEMP WAVEFORM IN A HOMOGENEOUS EARTH

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APPENDIX B: DISTORTION OF THE HEMP WAVEFORM IN A HOMOGENEOUS EARTH

B.1 INTRODUCTION

This Technical Brief is concerned with the high-altitude electromagnetic pulse (HEMP) and its ability to penetrate into the ground of typical geophysical composition. As motivated elsewhere, optical fibers, associated electronics, and any conducting elements--if placed at some depth d (meters) under the surface--would be subject to the effects of the penetrating waveform.

Here, exact attenuation and distortion factors for the HEMP are expressed as formulas in the frequency domain. The given factors appear to be more valid than what one finds in the customary "good conductor" approximations for the soil. For comparison purposes, both the good conductor and the good insulator extremes are retained as special cases in this study.

Since the obtained factors and their products are quite complicated, closed-form inverse Fourier transforms appear impossible. Standard applications of computer based algorithms are recommended as future work, to transform the spectral function $F(\omega)$ into the HEMP time response $f(t)$.

B.2 PROBLEM STATEMENT

Assume a high-altitude electromagnetic pulse (HEMP) wavefront that descends vertically (i.e., with normal incidence) upon an ideally flat and homogeneous Earth surface. As shown in Figure B-1, the initial waveform in time is denoted by $e(t)$. After reflection at the surface and absorption within the ground, some residual wave energy will reach depth $d>0$. The waveform observed at depth d is called $f(t)$. The objective here is to derive a good enough description of $f(t)$, so that its key features (for instance, its peak amplitude) can be estimated.

Judging from past EM propagation work, the problem is more tractable if addressed in the frequency domain. The spectral approach to the problem is outlined in Figure B-2. Standard Fourier transforms are used. Waveforms $e(t)$ and $f(t)$ become spectra $E(\omega)$ and $F(\omega)$, respectively. The transfer function for surface penetration or transmittivity is indicated by $T(\omega)$. The subsequent frequency selective attenuation or absorption within the Earth further distorts the pulse. The resultant attenuation at depth d is given by the exponential

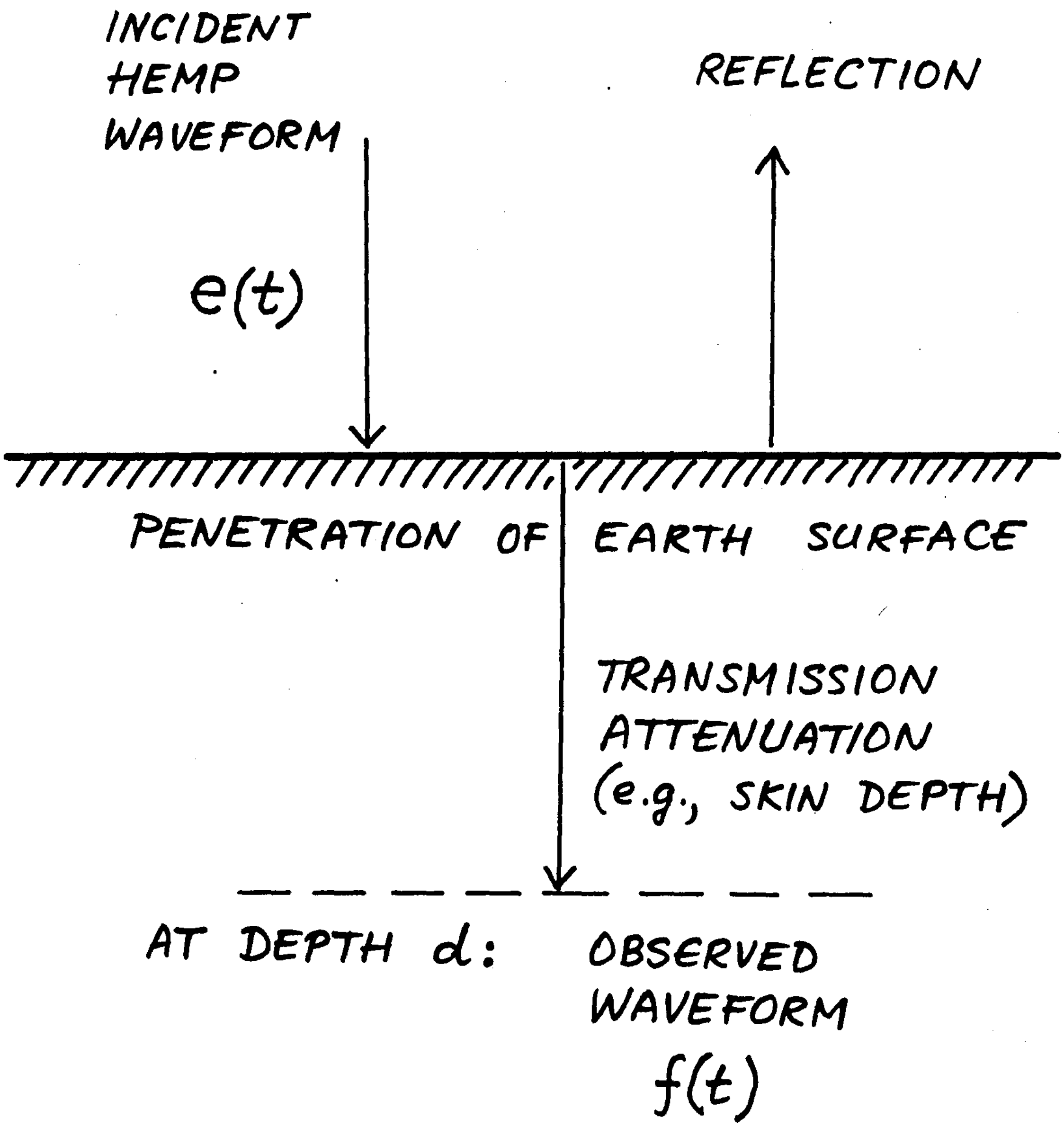

Figure B-1. Incidence and penetration by the HEMP waveform.

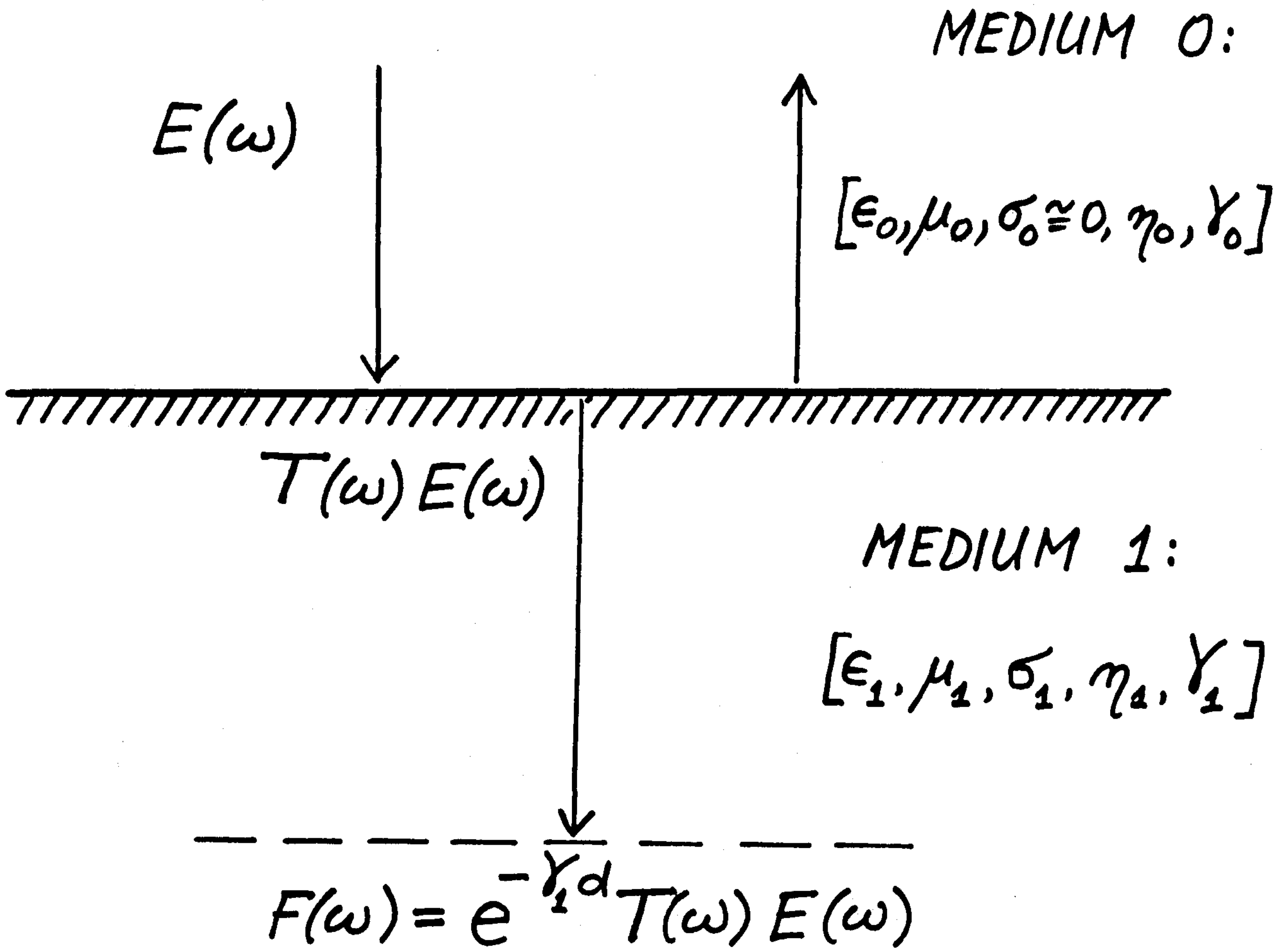

Figure B-2. Fourier transforms and parameters.

factor $e^{-\gamma_1 d}$ where γ_1 is the complex propagation constant in the ground.

In this context, note that Figure B-2 refers to air above ground as "Medium 0" and to ground as "Medium 1." The relevant physical constants (for example, dielectric constant ϵ, permeability μ, conductivity σ, intrinsic impedance η, and propagation constant γ) are indexed by subscripts 0 or 1 to distinguish between the two media. Of course, not all of these entities are strict constants, as some of them exhibit a strong dependence on frequency ω. The details of that dependence will be covered in the next section that deals with the formal solution to the problem.

B.3 THE FORMAL SOLUTION

The resultant waveform, f(t), is the inverse Fourier transform of the received spectrum at depth d. One writes

$$f(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} F(\omega) e^{j\omega t} \, d\omega \; , \tag{1}$$

where

$$F(\omega) = e^{-\gamma_1 d} \; T(\omega) \; E(\omega) \; . \tag{2}$$

The individual components are specified as follows.

B.3.1 HEMP Waveform

The published standard is

$$\begin{aligned} e(t) &= E_0 k (e^{-\beta t} - e^{-\alpha t}), & t \geq 0 \; , \\ &= 0 & \text{otherwise} \; , \end{aligned} \tag{3}$$

and

$$E(\omega) = \frac{E_0 k \; (\alpha - \beta)}{(\alpha + j\omega)(\beta + j\omega)} \; , \tag{4}$$

where E_0 is the peak field amplitude, k is a normalizing factor, α is the rise constant (i.e., the reciprocal of the rise time), and β is the decay constant. To the extent that these constants are unclassified and known to this author, their values are given in Table B-1.

B.3.2 Penetration Factor

The transmission coefficient for the electric field vector at a boundary implies that

$$T(\omega) = \frac{2\eta_1}{\eta_1 + \eta_0} , \tag{5}$$

where the two intrinsic impedances are

$$\eta_0 \cong \sqrt{\frac{\mu_0}{\epsilon_0}} \qquad \text{(as for free space)}$$

$$\eta_1 = \sqrt{\frac{j\omega\mu_1}{\sigma_1 + j\omega\epsilon_1}} \qquad \text{(for any medium)} \tag{6}$$

It follows that after substitution

$$T(\omega) = \frac{2}{1 + \sqrt{\frac{\epsilon_r}{\mu_r} (1 - j \frac{\sigma_1}{\omega\epsilon_1})}} \tag{7}$$

where $\epsilon_r = \epsilon_1/\epsilon_0$ is the relative dielectric constant (also known as the permittivity) and $\mu_r = \mu_1/\mu_0$ is the relative permeability. Typical values are known for the constants. Available cases are summarized in Table B-2.

Of special interest appears to be the range of values for typical soils. However, water also may be important in flood zones or wetlands. Dry, rocky ground may contain silica or various metallic deposits. Or sediments of dried plants may resemble wood or paper.

Table B-1. HEMP Parameters

Entity	1979 Value (DNA-2114-H)	Revised (DNA-EMP-1)
E_0	50 kV/m	-----
k	1.050	1.285
α	4.76 (10^8) s^{-1}	-----
β	4.00 (10^6) s^{-1}	3.00 (10^7) s^{-1}

Table B-2. Values of Electromagnetic Constants for Selected Substances

Substance	Typical Values or Ranges of Values for				
	$\varepsilon \left(\frac{\text{farad}}{\text{m}}\right)$	ε_r	$\mu \left(\frac{\text{henry}}{\text{m}}\right)$	μ_r	$\sigma \left(\frac{\text{S}}{\text{m}}\right)$
Air (1 atm, 20°C)	$8.860(10^{-12})$	1.000 6	$1.2566(10^{-7})$	1.000 000 4	0
Aluminium			$1.2566(10^{-7})$	1.000 02	$3.5(10^{7})$
Free Space (vacuum)	$8.854(10^{-12})$	1	$1.2566(10^{-7})$	1	0
Glasses	$4.4(10^{-11})$-$8.8(10^{-11})$	5-10			10^{-10}-10^{-14}
Iron (cast)			$6.283(10^{-4})$	5,000.	$1.2(10^{7})$
Lead			$1.2564(10^{-7})$	.999 983	$5(10^{6})$
Paper	$3.276(10^{-11})$	3.7			10^{-11}
Quartz (fused)	$3.5(10^{-11})$	4			10^{-16}
Salt (NaCl)			$1.2565(10^{-7})$	.999 998	
Silicon (pure)	$1.05(10^{-10})$	12	$1.2566(10^{-7})$	.999 997	$1.6(10^{-3})$
Soils	$3.3(10^{-11})$-$4.2(10^{-10})$	3.7-47.4	$1.2565(10^{-7})$--$1.2567(10^{-7})$	.999 99-1.000 01	10^{-4}-10^{-2}
Steel			$2.513(10^{-4})$	2,000	
Water (distilled)	$7.2(10^{-10})$	81	$1.2565(10^{-7})$	.999 991	$2(10^{-4})$
Water (sea)	$2.2(10^{-9})$	248			5
Woods	$2.2(10^{-11})$-$7.0(10^{-11})$	2.5-8			10^{-8}-10^{-12}

B.3.3 Ground Attenuation

From the general propagation constant definition

$$\gamma^2 = j\omega\mu\ (\sigma + j\omega\epsilon)\ , \tag{8}$$

it follows that

$$e^{-\gamma_1 d} = e^{-d\sqrt{j\omega\mu_1(\sigma_1 + j\omega\epsilon_1)}} \tag{9}$$

The constants needed for the waveform attenuation in the ground are all found in Table B-2.

B.3.4 The Final Form

The total waveform spectrum at depth d is a product determined by equations (2), (4), (7), and (9). When combined, this results in a rather long expression that may be called the "conventional" form:

$$F(\omega) = \frac{2E_0 k(\alpha - \beta)\ e^{-d\sqrt{j\omega\mu_1(\sigma_1 + j\omega\epsilon_1)}}}{(\alpha + j\omega)(\beta + j\omega)\ [1 + \sqrt{\frac{\epsilon_r}{\mu_r}(1 - j\frac{\sigma_1}{\omega\epsilon_1})}]} \tag{10}$$

One notes that in this form the real and imaginary terms are mixed together in a rather hard-to-understand fashion. The arrangement may also be inconvenient for machine computation. Two other forms should be considered. One is the "polar" form that explicitly shows the magnitude and the argument of $F(\omega)$ factors. The other displays the real and imaginary parts. The last can be appropriately called the "cartesian" representation.

Since the formulas for these representations tend to be even more complicated than in the conventional representation of (10), Table B-3 is used to specify the three components $E(\omega)$, $T(\omega)$, and $e^{-\gamma_1 d}$.

Table B-3. Complex Representations for the HEMP Propagation Factors

Entity	Representation		
	Conventional	Polar	Cartesian
$E(\omega)$	$\frac{E_0 k(\alpha-\beta)}{(\alpha+j\omega)(\beta+j\omega)}$	$\frac{E_0 k(\alpha-\beta)\, e^{-j\tan^{-1}\left[\frac{(\alpha+\beta)\omega}{\alpha\beta-\omega^2}\right]}}{\sqrt{(\alpha^2+\omega^2)(\beta^2+\omega^2)}}$	$\frac{E_0 k(\alpha-\beta)}{(\alpha^2+\omega^2)(\beta^2+\omega^2)}[(\alpha\beta-\omega^2)-j(\alpha+\beta)\omega]$
$T(\omega)$	$\frac{2}{1+\sqrt{\frac{\epsilon_r}{\mu_r}(1-j\frac{\sigma_1}{\omega\epsilon_1})}}$	$2\,\frac{e^{j\tan^{-1}\left[\frac{A\sqrt{C(\omega)-1}}{1+A\sqrt{C(\omega)+1}}\right]}}{\sqrt{1+2A^2C(\omega)+2A\sqrt{C(\omega)+1}}}$ *	$2\,\frac{[1+A\sqrt{C(\omega)+1}]+jA\sqrt{C(\omega)-1}}{1+2A^2C(\omega)+2A\sqrt{C(\omega)+1}}$ *
$e^{-\gamma_1 d}$	$e^{-d\sqrt{j\omega\mu_1(\sigma_1+j\omega\epsilon_1)}}$	$e^{-\omega dB\sqrt{C(\omega)-1}}\cdot e^{-j\omega dB\sqrt{C(\omega)+1}}$ *	$e^{-\omega dB\sqrt{C(\omega)-1}}\left\{\cos[\omega dB\sqrt{C(\omega)+1}] - j\sin[\omega dB\sqrt{C(\omega)+1}]\right\}$ *

*Where for simplicity: $A=\sqrt{\frac{\epsilon_r}{2\mu_r}}$, $B=\sqrt{\frac{\mu_1\epsilon_1}{2}}$, $C(\omega)=\sqrt{1+\frac{\sigma_1^2}{\omega^2\epsilon_1^2}}$.

B.3.5 Case of the Good Conductor Earth

The Earth material is said to be a good (or even a perfect) conductor if

$$\frac{\sigma_1}{\omega\epsilon_1} >> 1 . \tag{11}$$

Then the intrinsic impedance becomes

$$\eta_1 = \sqrt{\frac{j\omega\mu_1}{\sigma_1}} , \tag{12}$$

and as a consequence,

$$T(\omega) = (1 + j)\sqrt{\frac{2\omega\mu_r\epsilon_0}{\sigma_1}} ,$$

$$e^{-\gamma_1 d} = e^{-(1+j)d\sqrt{\frac{\omega\mu_1\sigma_1}{2}}} . \tag{13}$$

For a depth increment of

$$\delta(\omega) = \sqrt{\frac{2}{\omega\mu_1\sigma_1}} , \tag{14}$$

the magnitude of $e^{-\gamma_1 d}$ is reduced by 1/e or 4.34 dB. The quantity $\delta(\omega)$ is called the "skin depth" of the medium.

The validity of the good conductor approximation for typical soils can be assessed with the aid of Table B-4. This table shows the quantity $\sigma_1/\omega\epsilon_1$ for the expected typical soil values of σ_1/ϵ_1 and for frequencies that range from 1 kHz to 1 GHz.

One notes that the good conductor approximation, see (11), is indeed valid for lower frequencies and for higher σ_1/ϵ_1. For example, f = 10 kHz and $\sigma_1/\epsilon_1 = 10^8 \ (\frac{1}{s})$ yield $\sigma_1/\omega E_1 = 1,590 >> 1$. On the other hand, in the middle of

Table B-4. Variation of $\sigma_1/\omega\varepsilon_1$ as a Function of Frequency and Soil Properties

At Frequency	For σ_1/ε_1 $(\frac{1}{s})$ Values for Typical Soils						
	$.3(10^6)$ min	10^6	$.3(10^7)$	10^7	$.3(10^8)$	10^8	$.3(10^9)$ max
1 kHz	$.477(10^2)$	$.159(10^3)$	$.477(10^3)$	$.159(10^4)$	$.477(10^4)$	$.159(10^5)$	$.477(10^5)$
10 kHz	$.477(10^1)$	$.159(10^2)$	$.477(10^2)$	$.159(10^3)$	$.477(10^3)$	$.159(10^4)$	$.477(10^4)$
100 kHz	.477	$.159(10^1)$	$.477(10^1)$	$.159(10^2)$	$.477(10^2)$	$.159(10^3)$	$.477(10^3)$
1 MHz	$.477(10^{-1})$	.159	.477	$.159(10^1)$	$.477(10^1)$	$.159(10^2)$	$.477(10^2)$
10 MHz	$.477(10^{-2})$	$.159(10^{-1})$	$.477(10^{-1})$	.159	.477	$.159(10^1)$	$.477(10^1)$
100 MHz	$.477(10^{-3})$	$.159(10^{-2})$	$.477(10^{-2})$	$.159(10^{-1})$	$.477(10^{-1})$	.159	.477
1 GHz	$.477(10^{-4})$	$.159(10^{-3})$	$.477(10^{-3})$	$.159(10^{-2})$	$.477(10^{-2})$	$.159(10^{-1})$	$.477(10^{-1})$

Table B-4 one finds a broad band of values that are on the order of unity. For instance, f = 1 MHz yields $\sigma_1/\omega\epsilon_1$ between .159 and 1.590, as σ_1/ϵ_1 ranges from 10^6 to 10^7. Finally, at the very highest frequencies plus lowest σ_1/ϵ_1, the term $\sigma_1/\omega\epsilon_1$ appears to be almost negligible with respect to unity. In such cases, the "good insulator" approximation,

$$\frac{\sigma_1}{\omega\epsilon_1} \ll 1 \quad , \tag{15}$$

would be appropriate.

B.3.6 Case of the Good Insulator Earth

For the good insulator assumption of (15), the intrinsic ground impedance becomes

$$\eta_1 = \sqrt{\frac{\mu_1}{\epsilon_1}} \quad , \tag{16}$$

and

$$T(\omega) = \frac{2}{1 + \sqrt{\frac{\epsilon_r}{\mu_r}}} + \frac{j\sigma_1}{\omega\sqrt{\epsilon_0\epsilon_1\mu_r}(1 + \frac{\epsilon_r}{\mu_r})^2} \quad ,$$

$$e^{-\gamma_1 d} = e^{-\frac{\sigma_1 d}{2}\sqrt{\frac{\mu_1}{\epsilon_1}}} \bullet e^{-j\omega d\sqrt{\mu_1\epsilon_1}} \quad . \tag{17}$$

As complex functions of frequency, the extreme cases of (17) are quite different from those of (13). For example, the effective skin depth for the good insulator case is now

$$\delta = \frac{2}{\sigma_1}\sqrt{\frac{\epsilon_1}{\mu_1}} \tag{18}$$

Excluding the intrinsic frequency dependence of constants ϵ_1, μ_1, and σ_1, it shows no frequency dependence and, as σ_1 tends to zero, it becomes unbounded.

One can derive further local approximations for conditions, such as $\sigma_1/\omega\epsilon_1 = 1$. However, the resultant complexity and limited applicability renders such approaches questionable. One may be better off to return to the basic complete transfer function forms of Table B-3.

B.4 ILLUSTRATIVE EXAMPLES

Short of actual experiments, accurate waveform cases can only be derived with the inverse Fourier transform of $F(\omega)$, see equations (1), (2), and Table B-3. That transform requires computer runs beyond the scope of this study. Simple illustrative examples, however, have been considered. As presented next, the examples illustrate the spectral behavior of signal amplitudes.

Figure B-3 presents the amplitude spectrum of the HEMP waveform. The ordinate is $|E(\omega)|/E(0)$. Parameters α and β, from the 1979 (DNA-2114-H) values of Table B-1, result in the solid curve. The revised (DNA-EMP-1) values are denoted with asterisks. The new rise constant, $\alpha*$, is assumed to be so large as to have no effect for frequencies up to 1 GHz. See the broken curve.

Figure B-4 shows the spectral composition of transmittivity, $|T(\omega)|$, for assumed soil properties: $\epsilon_1 = 4.2(10^{-10})$ (fared/m), $\sigma_1 = 10^{-4}$ (S/m), and $\mu_1 = 1$ (henry/m). For frequencies above 1 MHz, $|T(\omega)|$ is essentially constant.

Figure B-5 illustrates the skin depth (i.e., the reciprocal of the propagation constant) for the soil with the same physical properties. The good conductor approximation is plotted with a broken curve. Note that for frequencies above 1 MHz the actual skin depth becomes a constant, .410, whereas the good conductor case tends to zero as frequency increases.

Figure B-6 combines the results of Figures B-3, B-4, and B-5. It shows the normalized amplitude spectra for the received waveform at different depths below Earth surface. The solid curve (i.e., that of α and β) is used from Figure B-3, and the corresponding actual soil curve from Figure B-5. For the range of burial depths, d = .25, .5, 1, and 2 meters, significantly different amplitude spectra are obtained. The greatest variation occurs between 10 kHz and 10 MHz. At higher frequencies, the amplitudes fall around 10 dB per decade.

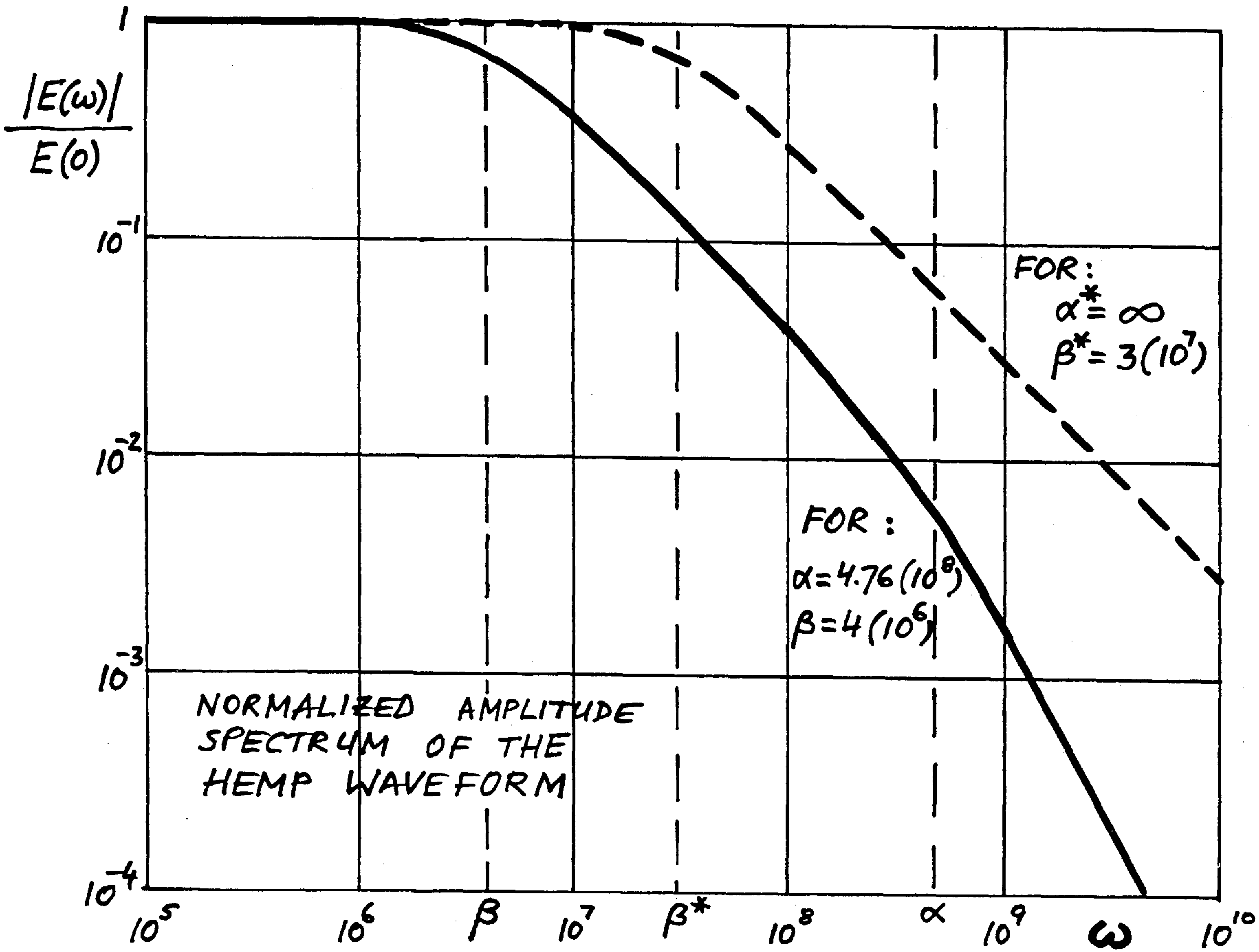

Figure B-3. Normalized amplitude spectrum of the HEMP waveform.

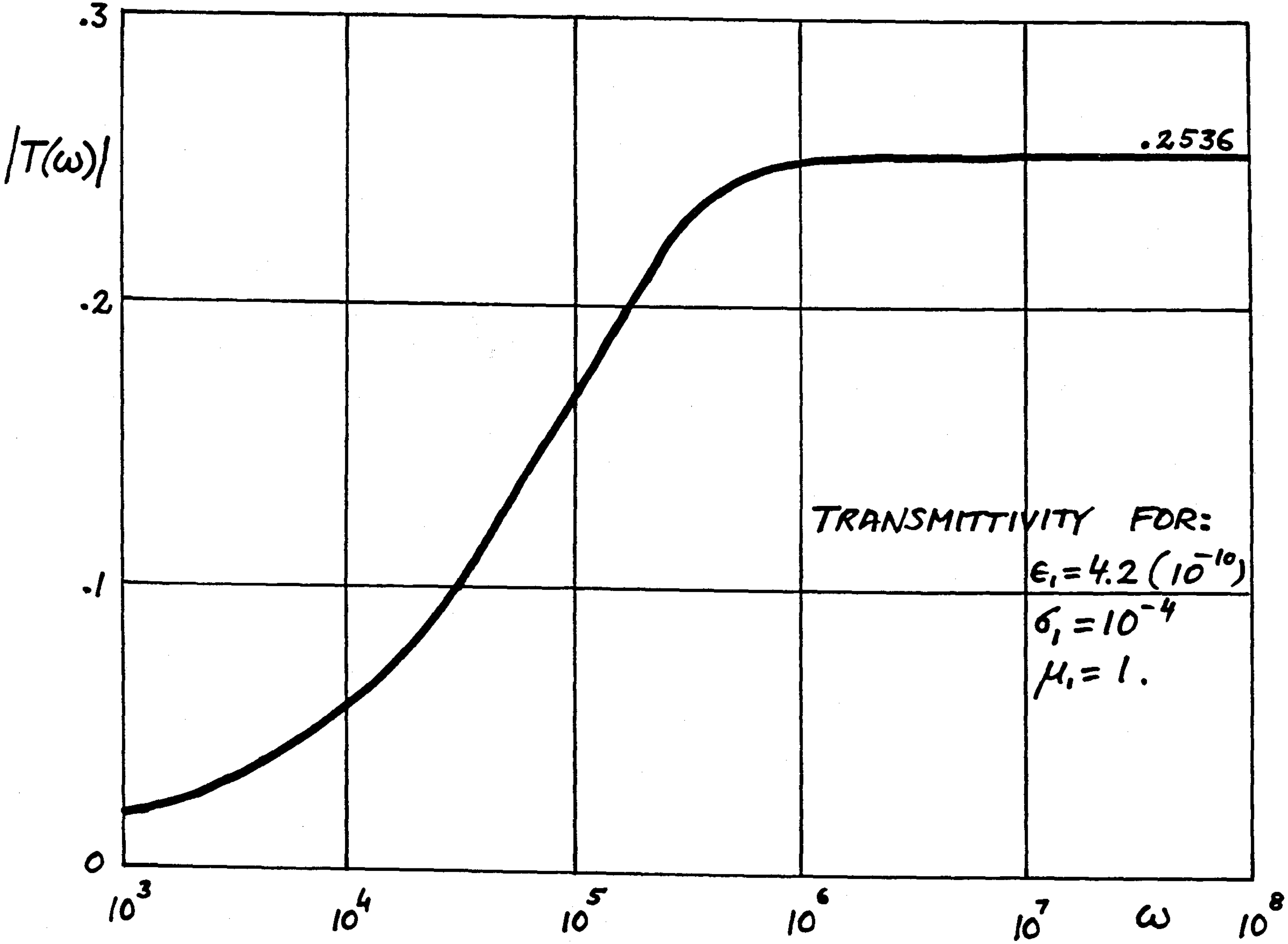

Figure B-4. Absolute value of the transmission coefficient for surface penetration at normal incidence.

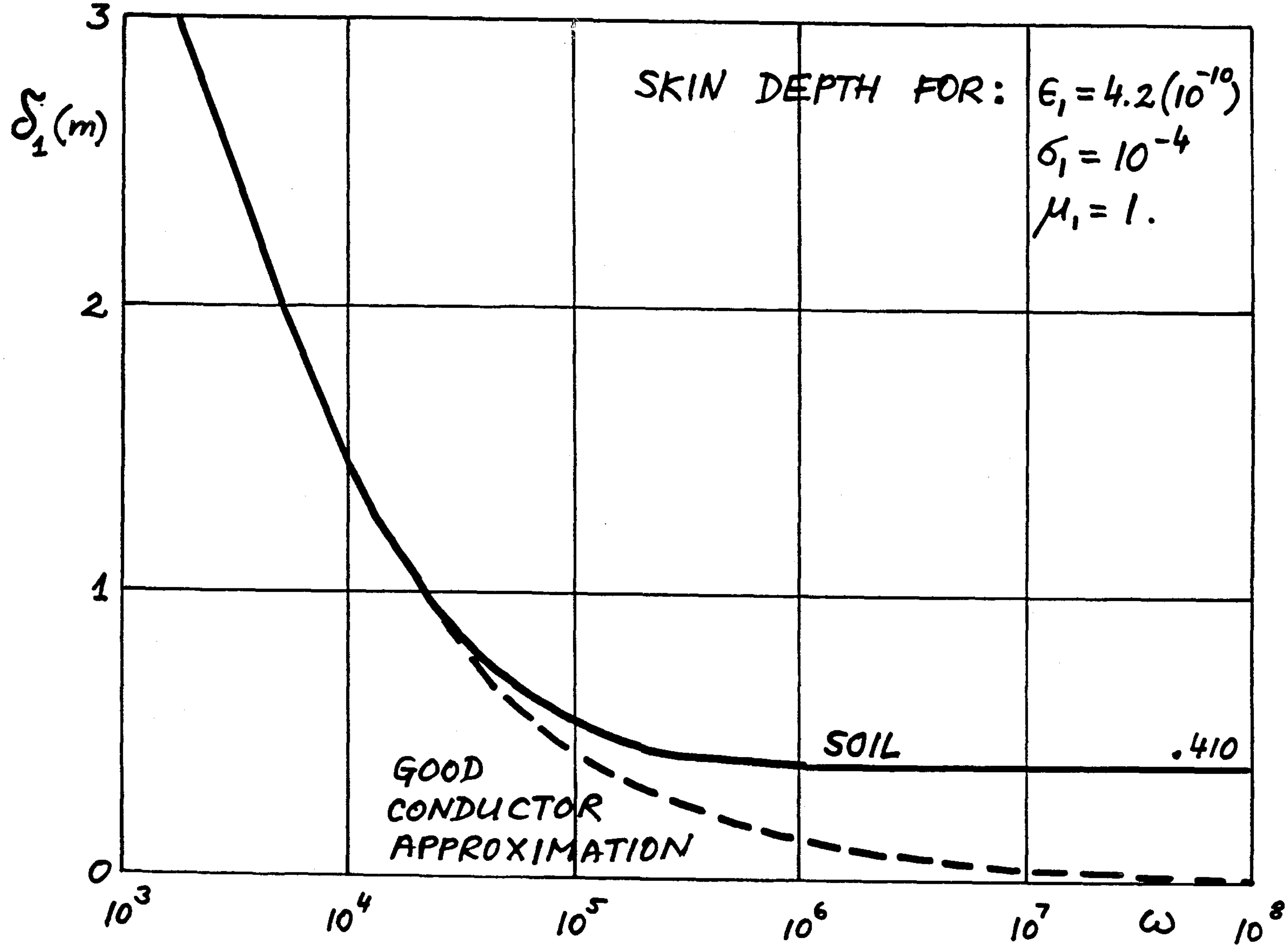

Figure B-5. Skin depth for sample soil and its good conductor approximation.

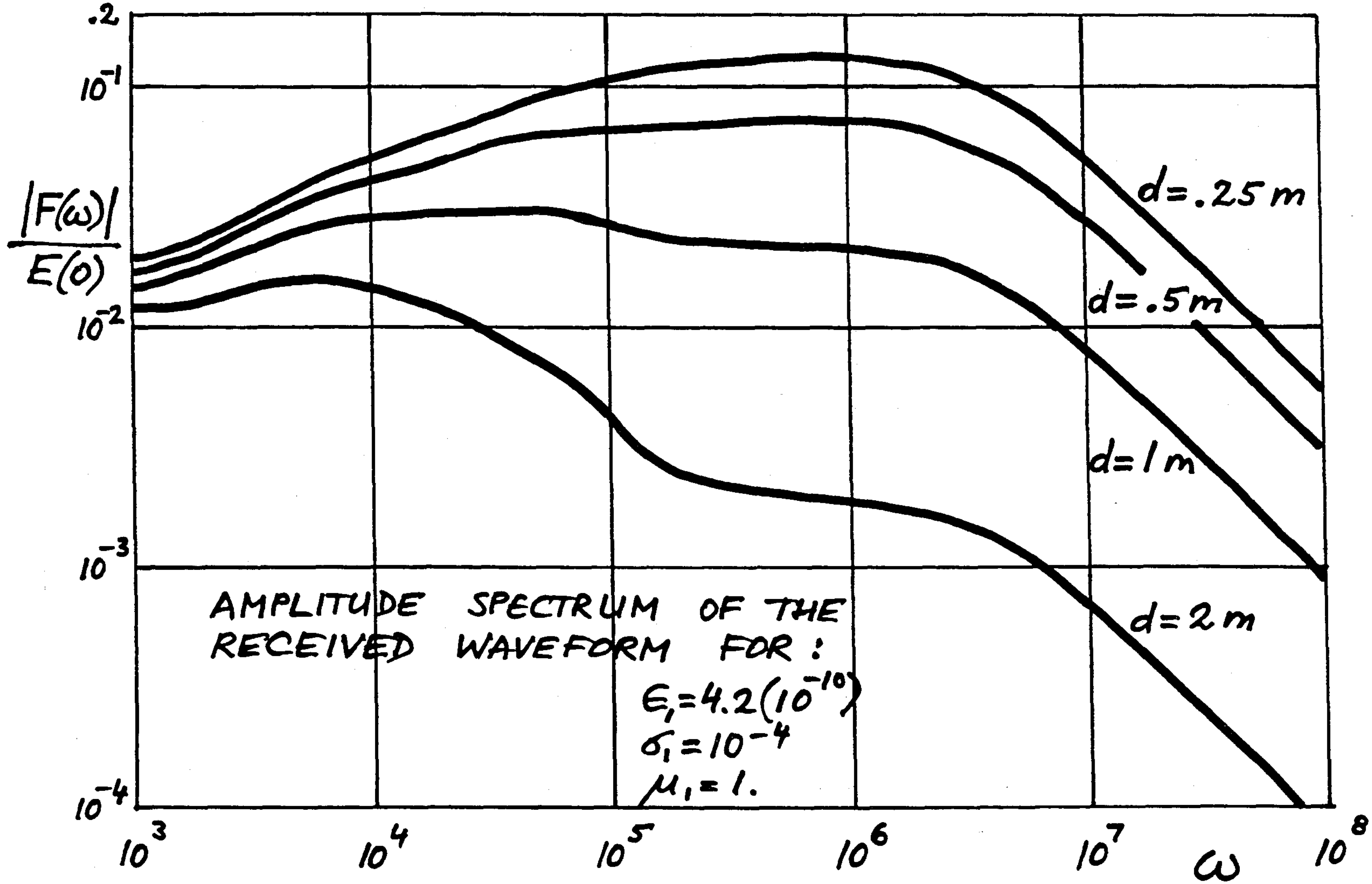

Figure B-6. Normalized amplitude spectra of the received HEMP waveform at different depths below earth surface.

Figure B-7 compares the spectral characteristics of the waveform for the assumed soil and its good conductor approximation. A typical depth of 1 m = 3.3 ft is assumed. The approximation is reasonably good for frequencies up to 100 kHz. For higher frequencies, however, there is considerable disagreement. The solid curve, not the approximation, should be used for frequencies above 100 kHz.

The final question above the shape of the received waveform cannot be settled at this time. Phase information is needed. When included in the numerical analysis, the phase and amplitude spectra will combine to determine the resultant waveform, f(t).

B.5 REMAINING WORK

Calculations of the HEMP response f(t) at depth d below the ground level have been made by others. Unfortunately, all known calculations seem to be based on the "good conductor" approximation discussed in Section 3.5. It has been noted in connection with Table B-4 and Figure B-7, that such an approximation may have a limited range of validity for the σ_1/ϵ_1 values of typical soils, as well as for the expected HEMP frequencies between 1 kHz and 1 GHz.

Computation of more representative HEMP waveforms is recommended. It should be done with the aid of a high-speed computing facility. The basic equations should be (1), (2), and (10), and their termwise definitions in Table B-3. If one is interested in both the real and imaginary parts of the received pulse, then one must compute

$$\mathrm{Re}\{f(t)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} [\mathrm{Re}\{F(\omega)\} \cos \omega t - \mathrm{Im}\{F(\omega)\} \sin \omega t]\, d\omega \quad ,$$

$$\mathrm{Im}\{f(t)\} = \frac{1}{2\pi}\int_{-\infty}^{\infty} [\mathrm{Re}\{F(\omega)\} \sin \omega t + \mathrm{Im}\{F(\omega)\} \cos \omega t]\, d\omega \quad . \tag{19}$$

The magnitude of f(t) follows from its standard definition,

$$|f(t)|^2 = \mathrm{Re}^2\{f(t)\} + \mathrm{Im}^2\{f(t)\} \quad . \tag{20}$$

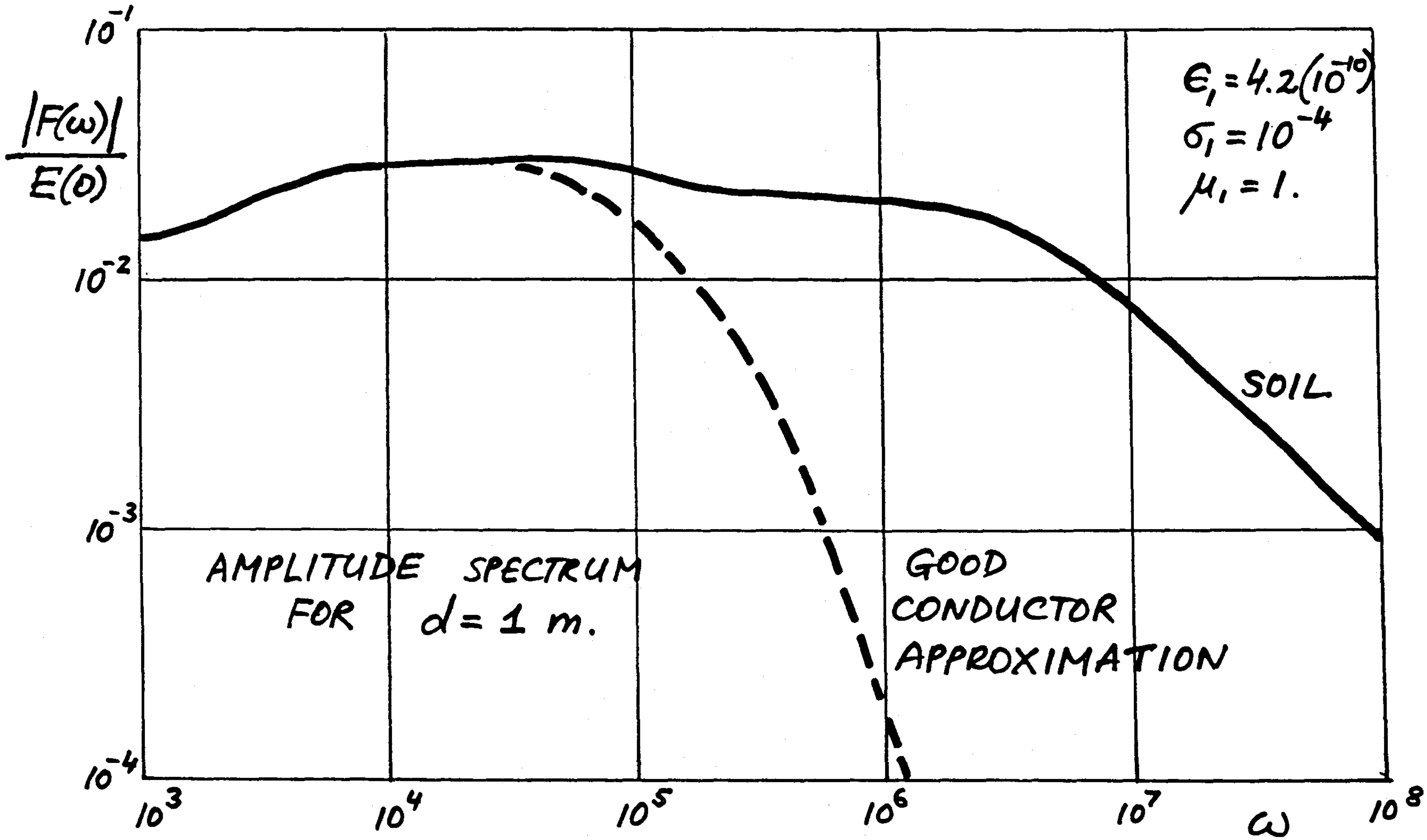

Figure B-7. Comparison of normalized amplitude spectra at 1 meter depth: actual soil vs. its good conductor approximation.

The different parameter values should be determined as follows:

The HEMP waveform parameters:

(E_0, k, α, β) - from Table B-1 or other sources.

propagation parameters:

$(\epsilon_0, \epsilon_1, \mu_0, \mu_1, \sigma_1)$ - from Table B-2 or other sources

For actual parameter values selected, the main objective is to tabulate (or to plot) the correct f(t) response. The second objective is to verify whether known approximations (such as the "good conductor" case) are or are not valid. If their relative errors are small or can be bounded, specification of said bounds would constitute the third goal of remaining work.

B.6 LIST OF SYMBOLS

C = speed of light in free space, $3(10^8)\ \frac{m}{s}$.

d = depth below Earth surface (m).

E_0 = peak field amplitude for the HEMP waveform, typically 50 kV/m.

e(t) = incident HEMP waveform.

$E(\omega)$ = spectrum of the incident HEMP waveform.

f(t) = received HEMP waveform.

$F(\omega)$ = spectrum of the received HEMP waveform.

k = normalizing factor for the HEMP waveform.

t = time (s).

T = transmission coefficient through the surface,

$$T = \frac{2\eta_1}{\eta_1 + \eta_0} ,$$

where subscript 0 denotes incidence (free space) and subscript 1 denotes penetrating medium (ground).

$T(\omega)$ = Transfer function for Earth surface penetration, showing the frequency dependence of T.

α = Rise constant for the HEMP waveform.

β = Decay constant for the HEMP waveform.

γ = Propagation constant, dependent on medium and frequency.

γ_0 = Propagation constant in air, same as $j\omega\sqrt{\mu_0\epsilon_0}$.

γ_1 = Propagation constant in ground, defined as

$$\gamma_1 = \sqrt{j\omega\mu_1(\sigma_1 + j\omega\epsilon_1)} \quad .$$

δ_m = Skin depth in a good conductor, e.g., metal

$$\delta_m = \sqrt{\frac{2}{\omega\mu\sigma}} \quad .$$

$\delta(\omega)$ = Skin depth dependence on frequency, defined by $\delta(\omega) = \frac{1}{\gamma}$.

ϵ = Dielectric constant of a material, as in

$$D = \epsilon\ E \ \left(\frac{\text{farad}}{\text{m}}\right) .$$

ϵ_0 = Dielectric constant for free space,

$$8.854\ (10^{-12})\ \frac{\text{farad}}{\text{m}} \quad .$$

ϵ_r = Permittivity or the relative dielectric constant, as in $\epsilon_r = \epsilon/\epsilon_0$.

η = Intrinsic impedance. It depends on frequency, as in

$$\eta = \sqrt{\frac{j\omega\mu}{\sigma + j\omega\epsilon}} \quad .$$

η_m = Intrinsic impedance for an ideal conductor, e.g., metal,

$$\eta_m = \sqrt{\frac{j\omega\mu}{\sigma}} \quad .$$

η_0 = Intrinsic impedance for free space,

$$\eta_0 = \sqrt{\frac{\mu_0}{\epsilon_0}} = 377 \text{ ohms}.$$

μ = Permeability, or magnetic or absolute magnetic permeability, as in

$$B = \mu H \left(\frac{\text{henry}}{\text{m}}\right).$$

μ_0 = Free space permeability,

$$4\pi\ (10^{-7})\ \frac{\text{henry}}{\text{m}}\ .$$

μ_r = Relative permeability, as in $\mu_r = \mu/\mu_0$.

σ = Conductivity $\left(\frac{S}{m}\right)$.

ω = Angular frequency, $\omega = 2\pi f$ (Hz).

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15. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

Fiber optic telecommunication systems are susceptible to both natural and man-made stress. National Security/Emergency Preparedness (NSEP) is a function of how durable these systems are in light of projected levels of stress. Emergency Preparedness in 1987 is not just a matter of--can we deliver food, water, energy, and other essentials?--but can we deliver the vital information necessary to maintain corporate function of our country? "Communication stamina" is a function of "probability of survival" when faced with stress. This report provides an overview of the enhancements to a fiber optic communication system/installation that will increase durability. These enhancements are grouped, based on their value in protecting the system, such that a Multitier Specification is created that presents multiple levels of hardness. Mitigation of effects due to electromagnetic pulse (EMP) and gamma radiation, and protection from vandalism and weather events are discussed in this report. This study concludes that the probability of survival can be significantly increased with expeditious use of design and installation (cont.)

16. Key Words *(Alphabetical order, separated by semicolons)*

electromagnetic pulse (EMP); EMP hardening; fiber optics, fiber optic cable; fiber optic systems; gamma-radiation hardening; high altitude electromagnetic pulse (HEMP); long-distance telecommunication systems; National Security/Emergency Preparedness (NSEP); singlemode fiber optic cable; stress hardening; telecommunications; telecommunications survivability; telecommunication system hardeing enhancements

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Multitier Specification for NSEP Enhancement of Fiber Optic Long-Distance Telecommunication Networks (Volume II) cont.

enhancements. The report is presented in two volumes entitled as follows:

Volume I : The Multitier Specification--An Executive Summary

Volume II: Multitier Specification Background and Technical Support Information

Volume I presents the Multitier Specification in a format that is usable for management review. The attributes of specified physical parameters, and the levels of protection stated in Volume I, are discussed in more detail in Volume II. This study is intended to be a guideline to aid the design and implementation, when the intent is to create a more durable, long-haul, fiber optic telecommunication system.

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