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NSEP Fiber Optics System Study, Background Report: Nuclear Effects on Fiber Optic Transmission Systems

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PREFACE

This report is submitted in partial completion of a study conducted by the Institute for Telecommunication Sciences (ITS), National Telecommunications and Information Administration (NTIA), for the Office of the Manager, National Communications System (NCS), Technology and Standards Office, Washington, DC, under Reimbursable Order 6-10038. Several other reports are submitted as part of this study as listed below.

Peach, David F. (1987), Multitier specification for NSEP enhancement of fiber optic long-distance telecommunication networks:

Volume I:	The Multitier Specification--An Executive Summary
Volume II:	Multitier Specification Background and Technical Support Information

These two volumes form the primary deliverable and are to be published as NTIA Report 87-226/NCS TIB 87-24 and NTIA Report 87-226/NCS TIB 87-25, respectively.

Ingram, William 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, Martin (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, Thad 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 contains summaries and illustrations from the unclassified literature that should assist telecommunication engineers to gain a needed background in nuclear effects on fiber-optic transmission media. The author wishes to express appreciation to Messrs. David F. Peach, A. Glenn Hanson, Robert T. Adair, and Dr. William A. Kissick at ITS and staff members of the Office of Technology and Standards at NCS for their review of the manuscript and encouragement to publish it as a report. Also, he would like to thank Dr. Thad J. Englert, University of Wyoming for his review and comments. Special thanks are also due to Mrs. Lenora J. Cahoon and Mrs. Evelyn M. Gray for their editorial assistance and to Ms. Kathy E. Mayeda for her word processing and final preparation of the report.

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NSEP FIBER OPTICS SYSTEM STUDY, BACKGROUND REPORT: NUCLEAR EFFECTS ON FIBER OPTIC TRANSMISSION SYSTEMS

Joseph A. Hull *

The National Communications System (NCS) is responsible for defining reasonable enhancements that could be applied to commercial common carrier (or carriers'-carrier) fiber optic systems that will be leased or owned by government agencies and which may be used for National Security/Emergency Preparedness (NSEP) purposes. This report provides background excerpted from many references used in the development of a multitier specification that identifies five levels of enhancement. (The multitier specification is presented in a separate report.) This report describes the nuclear environment for surface and in-atmosphere bursts outside of the blast region, where buildings and personnel would be expected to survive. In this environment, the vulnerability of optical fiber waveguides to fallout radiation is a primary concern. An assessment of fiber darkening, based on a review of unclassified literature, is presented. For exo-atmospheric nuclear bursts, the fiber optic system is exposed to High Altitude Electromagnetic Pulse (HEMP) radiation. Unclassified levels of these nuclear effects have been obtained from published literature. The characteristics of future generations of optical fiber systems, as described in current literature, are outlined.

Key words: common carrier optical fiber systems; fiber optic systems; gamma radiation darkening; National Security/Emergency Preparedness; nuclear effects

1. INTRODUCTION

This report 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.

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1.1 NCS Mission

Executive Order 12472 defines the National Communications System's 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: (1) 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; (2) serve as a focal point for joint industry-Government NSEP telecommunications planning; and (3) establish a joint Industry-Government National Coordinating Center. This study is to support the National Security Telecommunications policy as enunciated in 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 rights-of-way concessions by the Government. The specification has been structured in such a way that it can also 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 that the fiber optic systems must cope with from an NSEP standpoint include natural disasters (e.g., floods, earthquakes, fire); local acts of sabotage; and nuclear attacks [i.e., nuclear radiation and electromagnetic pulse (EMP) effects]. The design parameters addressed by the specification are those that tend to minimize interruptions of service in the face of these hazards by proper attention to features which facilitate quick restoral of operation or bridging around damaged terminals or repeaters.

1.3 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 five-level, 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 enhancements represent a progression of hardening steps considered feasible and desirable to be added to commercial common-carrier installations. The multitier 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 are 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 figures and graphics of this report are sketches drawn on a computer and are intended to convey concepts and relative values. Readers should consult the references for actual data plots, where applicable. The work has been based entirely on unclassified literature and information.

1.4 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

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

(2) Nontime-Critical Missions

- o Minute-to-minute continuity of communications is not essential (restoral delay is acceptable).
- o An increasing number of specific user pairs must be linked as time evolves after the stress event but the criticality 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 enhancement 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. A recovery time of 10 min has been suggested. This time requires that the system generally will automatically recover and no human intervention (except perhaps for initiating a recovery cycle) is assumed. Restoral via the replacement of components or subsystems is not assumed. For example, a recovery time of the order of 10 min 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.

1.5 Organization of Report

The remainder of this section will provide background information leading up to the divestiture and some implications of the divestiture, some definition of NSEP, and the attributes of systems required to meet NSEP requirements. Section 2 describes the environment associated with nuclear explosions with emphasis on gamma radiation. Section 3 discusses high-altitude nuclear explosions and the electromagnetic pulse produced by such nuclear events. Section 4 looks at the properties of optical waveguides and their response to gamma radiation. Section 5 addresses some aspects of future fiber optic systems. Section 6 provides some background on the radiation effects on fiber optic systems.

1.6 Background

In order to appreciate the complexity of the regulatory and policy environment in which the output of this study will be used, the following background information may be helpful.

1.6.1 Communications 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 was 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 that 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 1970's 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 telecommunication 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-premises 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 (MFJ) (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 (Dixon, 1985) that worldwide

Table 1. Planned Lightwave 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	.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	.55K/1986

(Source: The Hudson Institute)

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 connecting 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.

1.6.2 NSEP Historical Perspective

Ten years ago, before 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 (Horgan, 1985).

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 U.S. 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 agencies 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 less expensive, 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 U.S. telecommunications infrastructure, including commercial and private networks as well as Government systems, was declared to be "a crucial element of U.S. 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 were severely restricted in how they worked with other personnel in AT&T who sold transmission services. (Divestiture constrains the local operating companies in a similar way in their sales of customer premises 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 communication 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 U.S. 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 telecommunication 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. Representatives from numerous Government agencies are assigned to the Center's offices. The NCC is a private-sector extension of the National Communications System (NCS). 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.

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 Defense Communications Agency (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.

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 and/or using EMP-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.

NCS Initiative

One proposal for resolving this cost element is that of bartering. The NCS-sponsored program, for which this report serves as background, was developed on the basis of offering interstate rights-of-way for fiber optic common carrier installation in exchange for the carriers' agreement to install the system in accordance with the multitier specification developed here.

1.7 NSEP Context for This Study

Mr. Benham E. Morriss, Deputy Manager of NCS, described the NCS responsibilities for NSEP communications (Morriss, 1985). This paper, along with other personal communications with the NCS staff has been used to develop the context for this study as described below.

1.7.1 NCS Assets and Authorities

The 22 Federal organizations that make up the member agencies of NCS collectively own or lease the bulk of the telecommunication resources of 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 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 telecommunication functions, and in the coordination of planning for and provisioning of NSEP communications for the Federal Government under all circumstances. The NCS also is charged by the Executive Order to seek to ensure that a national telecommunication infrastructure is developed that satisfies priority telecommunication 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 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 telecommunication capability.

1.7.2 NSEP Services

NSEP telecommunication 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 which degrades or threatens 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 which 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; 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).

1.7.3 NSEP Attributes

Both NSDD-97 and E.O. 12472 specify that the use of all Government, commercial, and private resources must by 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
- restorability
- security
- connectivity
- redundancy
- interoperability
- mobility

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.

1.7.4 Implications for Fiber Optic Systems

In terms of hardness, fiber optic system survivability can be significantly extended by following the recommendations of the current 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 free from the effects of electromagnetic interference.

In terms of connectivity, present fiber optic long haul systems are concentrated along railway rights-of-way. The rapid introduction of intra-LATA fiber optic systems along with judicious planning of interconnecting links could add significantly to this capability. [Note: LATA is an acronym for Local Access and Transport Area (GSA, 1986).] 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 among 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 these measures are more reflective of system rather than component attributes.

Interoperability among the types of systems being 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). [Note: DS3-level denotes a multiplex level in a digital multiplex hierarchy that operates at a T-carrier rate of about 45 Mb/s (GSA, 1986).] 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 replaces copper and microwave media in the way that solid state components replaced vacuum tubes, then one can expect to see much more NSEP reliance on the fixed telecommunications plant.

1.7.5 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 communications 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.

2. NUCLEAR EXPLOSIONS

Fiber optic transmission systems are vulnerable to both gamma-ray radiation and to the electromagnetic pulse (EMP) generated by nuclear explosions. For purposes of this study, it is necessary to define environments for those transmission systems that can be protected. No attempt is made to define harsh environments in nuclear reactors or underground testing facilities. Rather, the approach has been to look at those areas where personnel, buildings, and equipments will generally survive the nuclear explosion.

One measure of the destructive power of a nuclear explosion is the peak overpressure it creates at various distances from the hypocenter. The peak overpressure in the shock wave is the maximum increase of static air pressure over ambient atmospheric pressure. The overpressure is usually measured in pounds per square inch (psi). Figure 1 (Pittock et al., 1986) illustrates the peak overpressure produced by a 1-Megaton (Mt) detonation as a function of distance from ground zero and height-of-burst (HOB). For a given overpressure, there is generally an optimum HOB to maximize the range for that overpressure. However, very close to the explosion, nearly identical peak overpressures can be achieved from bursts at the surface and up to a moderate height above the surface.

2.1 Blast Damage

All structures are vulnerable to nuclear blast. Residential wood-frame houses (with wood or brick exteriors) suffer substantial damage at 2 psi peak overpressure, and are crushed at 5 psi. Glass windows are shattered at 0.5 to 1.0 psi. Concrete and steel buildings are broken apart at 10 to 15 psi (although the interiors and facades are destroyed at much lower overpressures).

Flying debris is a major cause of damage in a nuclear explosion. People are particularly vulnerable to flying objects. For example, while the human body can withstand substantial static overpressures (greater than 10 psi is required to produce severe injuries), serious wounds due to flying glass and rubble can occur at 1 to 2 psi.

Blast damage also leads to secondary fire ignition. These secondary fires can occur anywhere within the perimeter of the 2 psi zone.

Based on the above description of blast damage effects, it seems reasonable to consider fiber optic communication system survivability and applicable NSEP-enhancement outside the 2 psi zone of nuclear explosions. This is consistent with the expectation that buildings and personnel will remain intact.

2.2 Radioactivity

In a nuclear detonation, several types of energetic ionizing radiation are produced:

1. prompt (fast) neutrons that escape during fission and fusion reactions
2. prompt gamma rays created by fission/fusion processes, including neutron capture and inelastic scattering, and by early fission-product decay

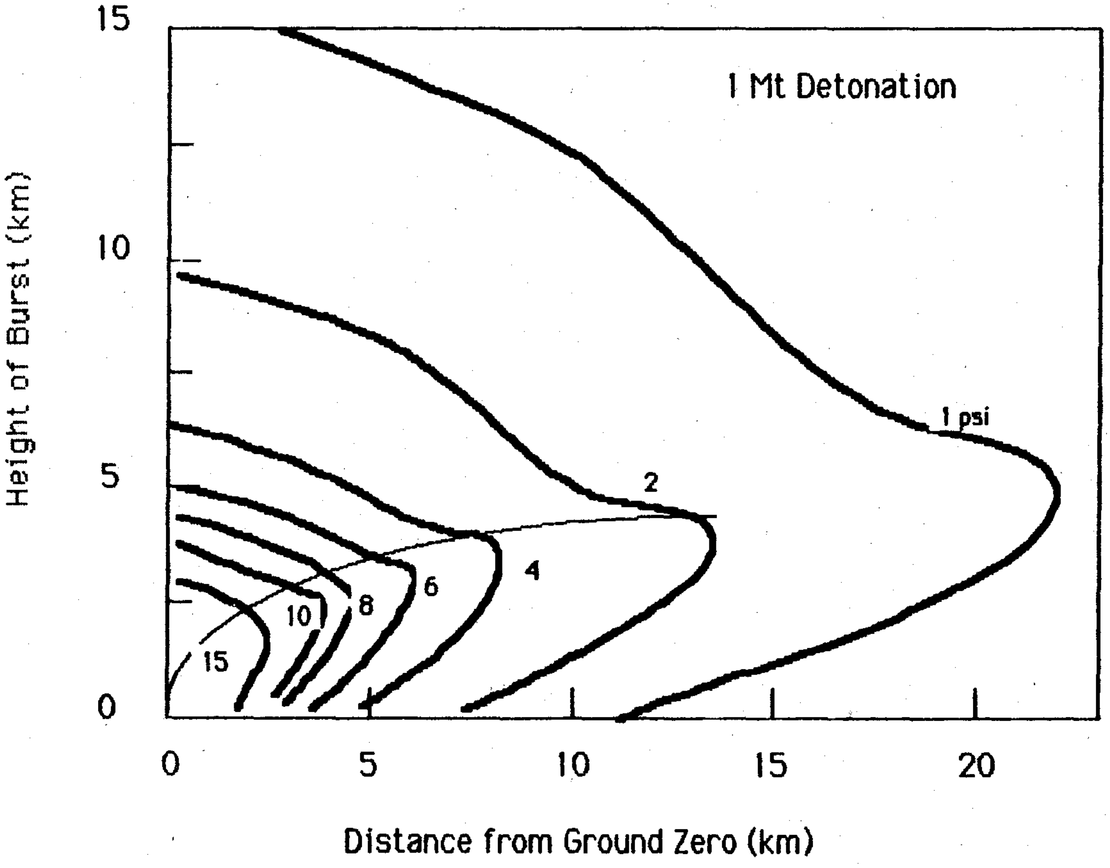

Figure 1. Peak blast overpressure (psi) at the ground for various distances from ground zero versus height of burst (after Glasstone and Dolan, 1977).

3. delayed gamma and beta radiation from induced activity in materials bombarded by prompt neutrons

4. delayed gamma and beta radiation emitted through the decay of long-lived radionuclides (lifetimes greater than minutes) produced by nuclear fission and carried in the bomb residues

For existing nuclear weapons, the prompt radiations do not propagate beyond a few kilometers because of their strong attenuation over such path-lengths in air. Greater concern centers on the delayed nuclear radiation of fallout debris.

2.3 Gamma Radiation

When a typical fission or fission-driven fusion weapon detonates, several hundred distinct radionuclides are generated (Glasstone and Dolan, 1977). These unstable species decay at different rates, emitting gamma rays and beta particles in the process. Gamma rays are members of the family of photons that are quantized manifestations of electromagnetic energy. Other members are x-rays, utlraviolet, visible, and infrared rays. The energy of these photons is expressed as $E = h\nu = hc/\lambda$. Gamma rays travel at the speed of light, are uncharged, and interact mainly with free electrons or electrons bound to an atomic system. They may also interact with atomic nuclei.

Depending on their energy, gamma rays interact with matter in three principal ways (Messenger and Ash, 1986):

(1) At the low-energy extreme for x-rays of the order of a few kilo electron volts (keV), their interactions are mainly through the photoelectric effect. When an x-ray penetrates the usually innermost electron shell structure of an atom, it may give up all its energy, thereby being annihilated. This energy excites the atom, causing it to expel one of its innermost shell electrons, thereby ionizing the atom. The expelled, swiftly moving electron carries off part of the energy supplied by the annihilated x-ray as kinetic energy. Another electron within the atom now essentially de-excites the atom by dropping into the energy vacancy in the electron shell previously occupied by the expelled electron. The energy difference of this latter electron between its old and new state is now expelled from the atom in the form of a photon. This photon has less energy than the initial one, so that its wavelength is longer, usually in the ultraviolet or visible region, depending on the material. This radiated photon is called fluorescence radiation.

(2) For higher energy photons, namely in the preponderant energy regime of those emanating from a nuclear burst, the main interaction with matter is through the Compton effect. This is

simply a collision between an incident photon and an electron that is free or relatively weakly bound to an atom. In the Compton effect, only part of the photon energy is transferred to the electron, which even if weakly bound can be propelled out of the atom thus ionizing it. In any event, the x-ray photon, as a result of the scattering (collision) careens off in a new direction, but with less energy and a longer wavelength than it had prior to the encounter.

(3) For very high energy photons, in the regime of gamma rays, a third interaction occurs called pair production, or pair creation. If a sufficiently energetic photon finds itself near an atomic nucleus, it can be spontaneously annihilated. In its place instantly appears a fast-moving electron, plus a fast-moving positron. The positron is a particle with all the properties of an electron, except that its charge is positive.

2.3.1 Energy Levels

The rate of accumulation of radiation dose depends upon the flux of radiation particles (or photons), the kind of particle, and the energy per particle (Englert, 1987). The unit of energy most commonly used when dealing with radiation particles or photons is the electron volt (eV). One electron volt is the energy acquired by one electronic charge residing in an electric potential of one volt. The conversion of energy units is easily determined as follows:

$$
\begin{aligned}
1 \text{ eV} &= (\text{electronic charge}) \times (1 \text{ volt}) \\
&= (1.6 \times 10^{-19} \text{ coulombs} \times (1 \text{ volt}) \\
&= 1.6 \times 10^{-19} \text{ joules}
\end{aligned}
$$

Energies of photons and particles found in atomic and nuclear emissions have a rather wide range. Table 2 gives approximate ranges of energies expected for various kinds of radiation along with sources and spectral ranges.

The fission radionuclides associated with fallout consist mainly of refractory elements that readily condense on particle surfaces as the fireball cools. Hence, any dust or debris entrained into the fireball is likely to be contaminated with radioactivity. The largest debris particles fall out quickly, while the smallest ones can remain aloft for months or years. The initial rapid deposition of the radioactive fission debris, or fallout, represents the most serious threat of delayed radiation.

Table 2. Radiation Sources and Approximate Energies (Englert, 1987)

Source	Type of Radiation	Approximate Energy Range	Spectral Range of Photon
Electron Transition in Atoms	Photon	< 1 eV to $\tilde{}10^3$ eV	Microwave x-ray
Nuclear Decay	Photon	$\tilde{}10^5$ eV - $\tilde{}10^8$ eV	Gamma Rays
	α-particle	$\tilde{}10^6$ eV - $\tilde{}10^8$ eV	
	β-particle	$\tilde{}10^5$ eV - $\tilde{}10^8$ eV	

From Table 2, it would appear necessary to know the distribution of gamma-ray photons in the fallout from a nuclear explosion in order to calculate the exposure and the protection factors for communication system components (e.g., fiber, detectors, lasers, and other circuit components). The average photon energy of the radionuclides found in the fallout from a nuclear explosion is approximately 0.7 MeV (Glasstone and Dolan, 1977).

2.3.2 Gamma-Ray Sources for Testing

Radioactive isotopes provide substantive amounts of radiation exposure. A popular isotope is ^{60}Co, which emits two characteristic gamma rays of 1.17 and 1.33 MeV, with a half-life of approximately 5.3 years. [For a point source strength of 100 kilo-curies (kCi), the effective gamma-ray flux is of the order of 10^{13} photons per cm^2 per second (presumably at about 30 cm from the source). One curie corresponds to 3.7×10^{10} disintegrations of the source isotope per second, each disintegration emitting one or the other of the above two gamma rays.] In terms of the corresponding dose rate of 4×10^{-3} rad (air) (1 rad = 0.01 joule/kg absorbed radiation) per second per curie, at about 1 ft from the above ^{60}Co source, dose rates of 500 to 1000 rad (air) per second can be obtained. Other sources of gamma rays include operating nuclear reactors, which provide fission product gamma rays. The average energy of fuel element gamma rays is about 0.7 MeV. (This indicates that the use of ^{60}Co as a test source for irradiating optical fiber is a good selection which should provide average measures of radiation response, i.e., the energy levels of the gamma rays are slightly higher that the average nuclear fission product gamma rays.)

Another radioactive isotope source obtained from fission products whose parameters are suitable in this context is ^{137}Cs. The energy of gamma rays from cesium is about 0.66 MeV, with a corresponding half-life of about 30 years.

2.4 Exposure Levels

The standard measure of exposure to radioactivity is the rad, equivalent to the absorption of 0.01 Joule of ionizing radiation per kilogram of material; this is equivalent to 100 ergs per gram. (Glasstone and Dolan, 1977). [The rad is a CGS unit. The international system of units (SI) defines an essentially MKS unit for absorbed dose called the gray (GY). One GY is defined as the deposition of 1 joule per kilogram in the absorbing media. Thus the equivalence is: one GY = 100 rads (Messenger and Ash, 1986)]. The rem is a biological dose unit equal to the absorbed energy in rads multiplied by a "relative biological effectiveness" factor for a specific type of radiation compared to gamma radiation. The rem for biological tissue located near the surface of the body corresponds to 88 ergs per gram. For gamma rays, x-rays, and beta particles, units of rads and rems are approximately equivalent.

The impact of radiation dose also depends on its rate of delivery. Roughly 450 rads delivered at the surface of the body within a few days' time (an acute whole-body dose) would be lethal to half the exposed population of healthy adults; 200 rads would produce radiation sickness but would not by itself be lethal (Glasstone and Dolan, 1977). Such total exposures spread over a period of months or years (a chronic dose) would not cause acute effects, but would eventually contribute to a greater frequency of pathologies such as leukemia, other cancers, and birth defects. A summary of the personnel hazard from radiation is given in Table 3.

2.5 Shielding

Gamma rays are removed or annihilated as they pass through matter as discussed above. This results in a decrease in their intensity or fluence as a function of distance of penetration, x, into the material. The intensity of the radiation decreases exponentially with distance assuming that the radiation is absorbed. This results in the expression

$$I(x) = I(0) \exp [- \mu x] \tag{2-1}$$

where $I(0)$ is the initial intensity

μ is an attenuation (absorption) coefficient.

Table 3. Summary of Relationship Between Exposure and Level of Radiation Sickness*

Exposure Range	Type of Injury	Probable Mortality Rate Within 6 mos of Exposure
0 - 50 R (rad)	No observable signs or symptoms	None
50 - 200 R (rad)	Level I Sickness	Less than 5 percent
200 - 450 R (rad)	Level II Sickness	Less than 50 percent
450 - 600 R (rad)	Level III Sickness	More than 50 percent
More than 600 rad	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.

The fact that the attenuation is exponential implies that the percentage, or fraction, of photons removed from the photon stream is constant. This fraction is independent of the initial intensity I(0). Because the incident photons lose energy mainly by ionization, the losses per unit length of photon path should be proportional to the average concentration of electrons in the material, therefore proportional to the atomic number of the material. The losses are also a function of the energy of the photons. Table 4 shows the absorption coefficient (Tipton, 1960) as a function of three energy levels for several materials of interest in the shielding of long-haul, fiber optic cables.

Table 4. Gamma-Ray, Mass-Absorption Coefficients for Various Materials Used in Shielding

Material	Density, g/cm^3	Mass-Absorption Coefficient, μ, cm^{-1} 1 MeV	3 MeV	6 MeV
Air	0.001294	$7.66 \cdot 10^{-5}$	$4.3 \cdot 10^{-5}$	$3.04 \cdot 10^{-5}$
Clay	2.2	0.130	0.0801	0.0590
Concrete (1 Portland cement: 3 sand)	2.07	0.133	0.0760	0.0559
Lead	11.34	0.797	0.468	0.505
Steel (1% carbon)	7.83	0.460	0.276	0.234

The thickness of material that attenuates the intensity of radiation to 10 percent of its incident value is often specified for various shielding materials. This thickness can be calculated for the above materials.

2.6 Radiation Environment for NSEP Study

The assumption of a 2 psi overpressure limit as a boundary for NSEP restoral of communication systems provides limits on the radiation fields against which protection is required. Initial nuclear radiation, emitted within a minute of the nuclear detonation, is insignificant at the 2 psi overpressure contour (Warren et al., 1985). [Note: This statement is confirmed by Messenger and Ash (1986) in a table excerpted from Brode (1969).] Residual radiation emitted later than 1 minute from the instant of a nuclear detonation reaches the 2 psi overpressure contours in the form of fallout radiation. This radiation is predominantly gamma radiation.

2.7 Summary

The sequence of physical effects that would accompany the detonation of a nuclear weapon is thermal irradiation, blast, winds, radioactive fallout (particularly in the case of surface bursts), and fire growth and spread. In the explosion of a typical strategic nuclear warhead over a military or industrial target, the effects of initial nuclear radiation (gamma rays and fast neutrons) can generally be ignored in regions outside of the 2-psi overpressure boundary. The nuclear effects occur in more-or-less distinct time intervals (over most of the area involved) (Glasstone and Dolan, 1977). The thermal pulse is delivered in the first 1 to 10 seconds. The blast is delayed by the travel time of the shock wave, and generally follows the thermal pulse; the positive duration of the blast wave lasts for approximately 1 second. Afterward, winds blow for several minutes. The most intense and lethal radioactive fallout occurs during the first hour after a surface detonation. Although many fires would initially be ignited in the ruins, it could take several hours for mass fires to develop. In the case of surface bursts, during the latter period, dense radioactive fallout would continue in areas downwind of the blast destruction zone.

Estimates of the areas that would be subject to levels of blast overpressure and radioactive fallout exceeding specific minimum values are given in Table 5. It can be seen from this table that modern nuclear weapons (i.e., those having yields less than about 1 Mt) detonated as air bursts would create moderate to heavy blast damage over an area of approximately 500 km^2/Mt and ignite fires over a similar area. In general, smaller weapons produce greater blast and thermal effects per unit energy yield than larger weapons. The area in which blast overpressures exceed a given value (e.g., 2 psi) scales approximately as $Y^{2/3}$, where Y is the yield in megatons (Glasstone and Dolan, 1977). The areas of blast and thermal effects for surface bursts are about one-half the areas for air bursts of the same yield (Glasstone and Dolan, 1977). Surface bursts also create large local areas of potentially lethal radioactive fallout. Doses of up to 450 rad in 48 hours are possible over an area of approximately 1000 km^2/Mt in the fallout plumes. Lesser doses occur over much larger areas.

For this study, the radioactive fallout at the 2-psi overpressure contour for surface or near-surface bursts will be considered to be the primary threat to fiber optic systems. It is assumed that buildings and equipment will survive in this region and there will be need for NSEP communications. For exoatmospheric bursts, the HEMP will be the threat of concern.

3. HIGH ALTITUDE NUCLEAR EXPLOSIONS

A nuclear explosion above an altitude of 40 km can expose a large area of the Earth to an intense pulse of electromagnetic radiation. (The nuclear effects, described in Section 2, of thermal irradiation, blast, winds,

Table 5. Areal Impacts of Nuclear Weapons Effects[a]

Nuclear Weapon Yield (Mt)	Area (km^2) of Blast Overpressure[b]		Area (km^2) of 450 rad Fallout Dose[c]	
	5 psi	2 psi	48 h	50 yr
0.1	34	100		
	(14)	(40)	(100)	(200)
0.3	70	200		
	(30)	(80)	(300)	(600)
0.5	100	300		
	(42)	(115)	(500)	(1000)
1.0	140	480		
	(65)	(180)	(1000)	(2000)
5.0	415	1410		
	(190)	(525)	(5000)	(10000)
10.0	660	2240		
	(300)	(835)	(10000)	(20000)

[a] Areas are given in square kilometers for air bursts and surface bursts (in parentheses). In the case of radioactive fallout, areas are given only for surface bursts (the early fallout from air bursts is negligible, and prompt and long-term radiation effects are ignored. Within the areas quoted, the magnitudes of the nuclear effects are greater than the limiting values shown above each column. The limiting values apply at the perimeters of the circular contours centered on the explosion hypocenter which define the area of each effect.

[b] For air bursts, the optimum explosion height has been chosen to maximize the area subject to the overpressure indicated.

Areas are given only for surface bursts. No protection or shielding from fallout radiation is assumed. A fission yield fraction of 0.5 is adopted. A dose reduction factor of 0.7 is also applied for surface "roughness." The area in which an acute 48-hour whole-body dose of greater than 450 rad could be received is estimated from standard fallout patterns (Glasstone and Dolan, 1977).

[c] The area in which a long-term integrated total dose of more than 450 rad could result is also calculated from local fallout patterns. Cumulative global fallout is not included.

radioactive fallout, etc., will generally not be present at the Earth's surface for these exo-atmospheric bursts.) This electromagnetic radiation is in the form of a plane wave that can be collected by conducting media such as power lines, water pipes, electrical conduits, and, in the case of long-haul fiber optic cables, by the metallic elements needed for strength or armoring of the cable when it is directly buried. The optical waveguides, of course, are dielectric materials and, therefore, impervious to such electric fields. The complete transmission system including switches, regenerators, and electronic terminations are vulnerable to the threat of these very high electromagnetic fields. The fields are similar to those produced by lightning. Lightning produces very high fields and currents at a point on the Earth's surface. The pulse of concern here covers a very large area whereas the pulse from lightning is generally localized.

3.1 High Altitude Electromagnetic Pulse (HEMP)

The prompt gamma radiation from a burst above 40 km is absorbed in the Earth's atmosphere at heights of approximately 20 to 40 km. This deposition region for gamma rays is also the source region for HEMP (Glasstone and Dolan, 1977). Through collisions with air molecules, the gamma rays produce high energy Compton electrons. The Compton electron currents interact with the Earth's magnetic field, thereby generating electromagnetic fields that propagate (toward the surface) as a coherent pulse of electromagnetic energy. Figure 2 illustrates the physical origin of the HEMP. Because the rates of gamma ray emission and deposition are so rapid, the electromagnetic pulse has an extremely short rise time (a few nanoseconds) and brief duration (a few hundred nanoseconds). The magnitude of the HEMP is limited primarily by the enhanced electrical conductivity of the atmosphere caused by secondary electrons released in collisions of Compton electrons with air molecules. Nevertheless, HEMP field intensities can reach several tens of kilovolts per meter over the exposed areas of the Earth. The electric field strength of the pulse can therefore be 10^9 to 10^{11} times greater than typical field strengths encountered in radio reception (Wik et al., 1985). The nuclear HEMP frequency spectrum is also very broad and covers the entire radio frequency communication band.

The bulk of HEMP energy lies within the radio-frequency spectrum, ranging from a few hertz to the VHF (very high frequency) band. HEMP differs from any

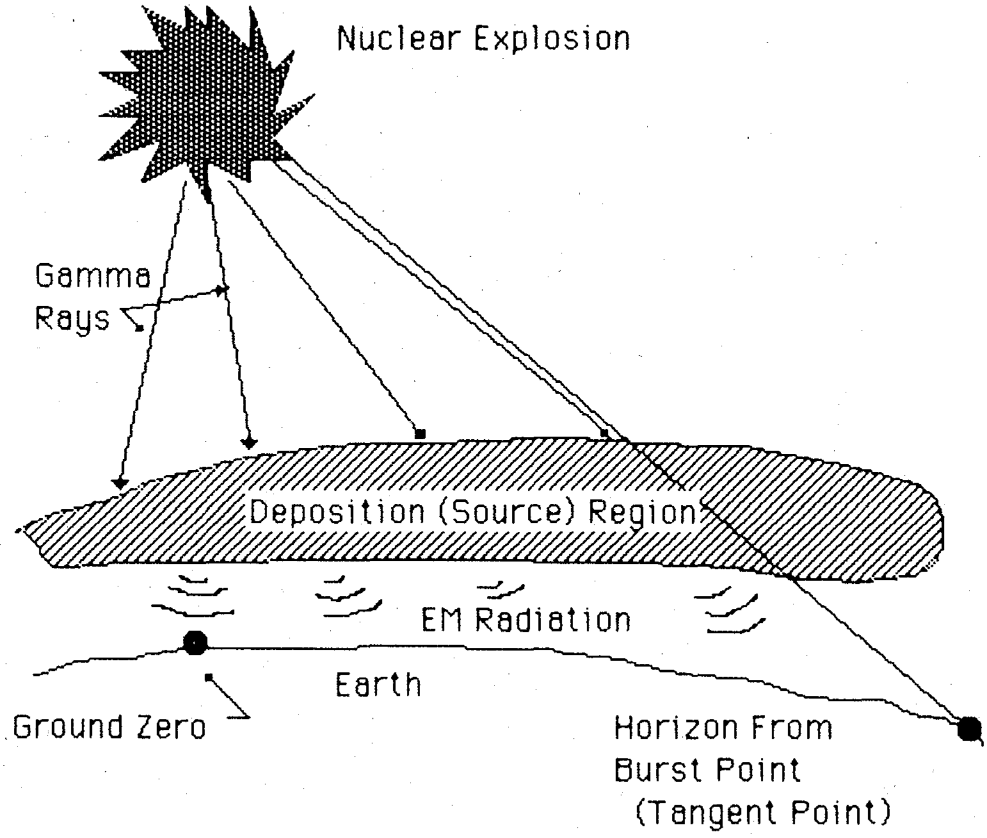

Figure 2. Origin and nature of the EMP (after Glasstone and Dolan, 1977).

other source of electromagnetic energy, whether natural (i.e., lightning) or man made (e.g., radar and broadcast radio). The HEMP's time waveform exhibits a higher amplitude and shorter rise time. These high-intensity HEMP fields can occur almost simultaneously over a large area since they propagate at the speed of light.

Figure 3 shows the coverage areas for different high-altitude bursts of nuclear devices. The circles represented here are tangents to the Earth's surface drawn from the burst point. The fields are not uniform throughout these circled areas but diminish to about 0.5 E_{max} at the boundaries. Figure 4 shows a contour map of the electric fields for the same surface zero location (Messenger and Ash, 1986). A generalized high-altitude HEMP electric and magnetic field time waveform is shown in Figure 5. A plot of high-altitude electric field spectrum and a normalized cumulative energy density spectrum for the HEMP waveform is shown in Figure 6 (BTL, 1975).

Important parameters affecting HEMP interactions with systems include peak amplitude and time behavior, particularly rise time and duration. All of these parameters vary with weapon yield, height of burst (HOB), and weapon and observer locations. The parameters described above generally apply to the early-time behavior of the HEMP. A generalized HEMP time and frequency waveform for use in system assessment and hardening activities has been developed by calculation of waveforms for several threat situations and constructing the envelope of these waveforms in the frequency domain, while ensuring consistency with important time-domain parameters (peak field and rise time) (Dittmer et al., 1986). This procedure has been followed more than once to develop a generalized HEMP waveform, with the most extensive effort conducted in the early 1980's. The resultant waveform is classified Secret-Restricted data. In a letter dated April 3, 1984, the Under Secretary of Defense for Research and Engineering directed that this waveform be used in the assessment and hardening of C^3I systems and facilities performing strategic, time-sensitive functions. The Defense Nuclear Agency (DNA) has developed a DOD Standard (DOD-STD 2169) that formalizes the waveform under the Defense Standards and Specifications Program.

For purposes of this study, an unclassified version of the recent waveform contained in the DNA EMP Course Study Guide (Dittmer et al., 1986) is shown in Figure 7. This figure shows three distinct portions of the waveform, namely: (1) early-time, (2) intermediate-time, and (3) late-time. The early-time

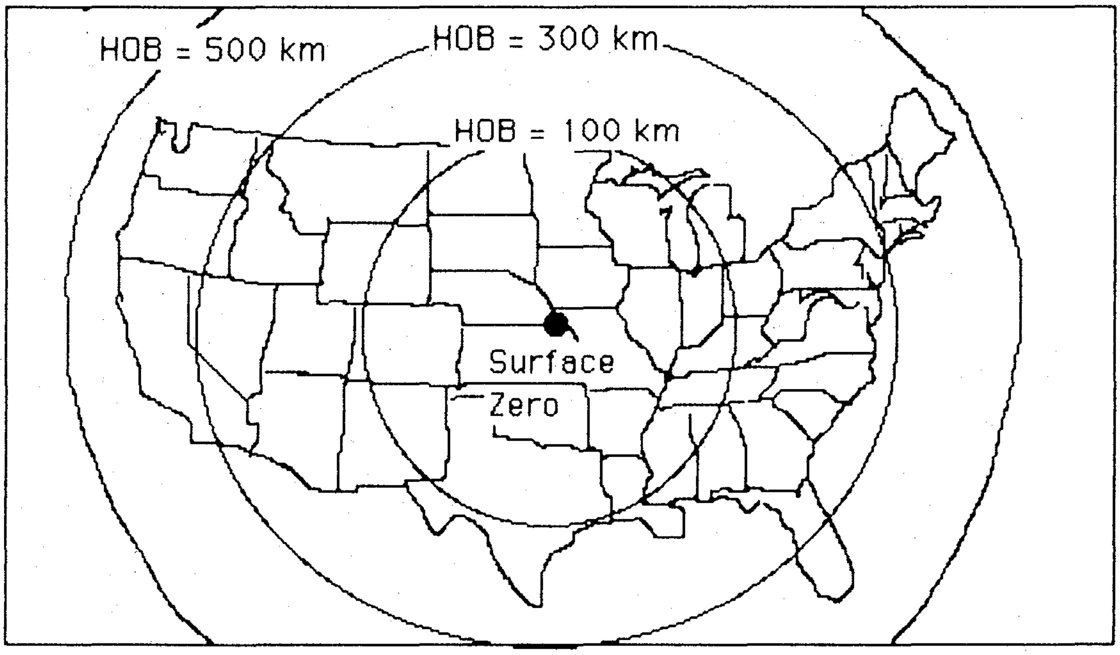

Figure 3. EMP ground coverage for high-altitude bursts at 100, 300, and 500 km.

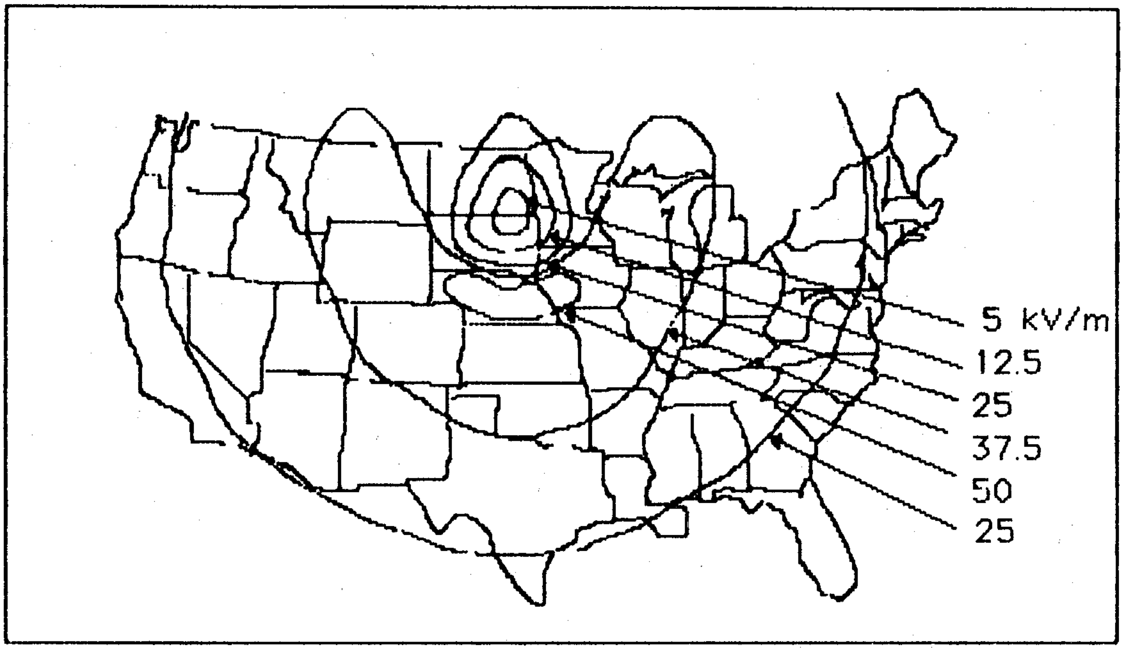

Figure 4. Electric field contours at the Earth's surface from a high-altitude nuclear detonation.

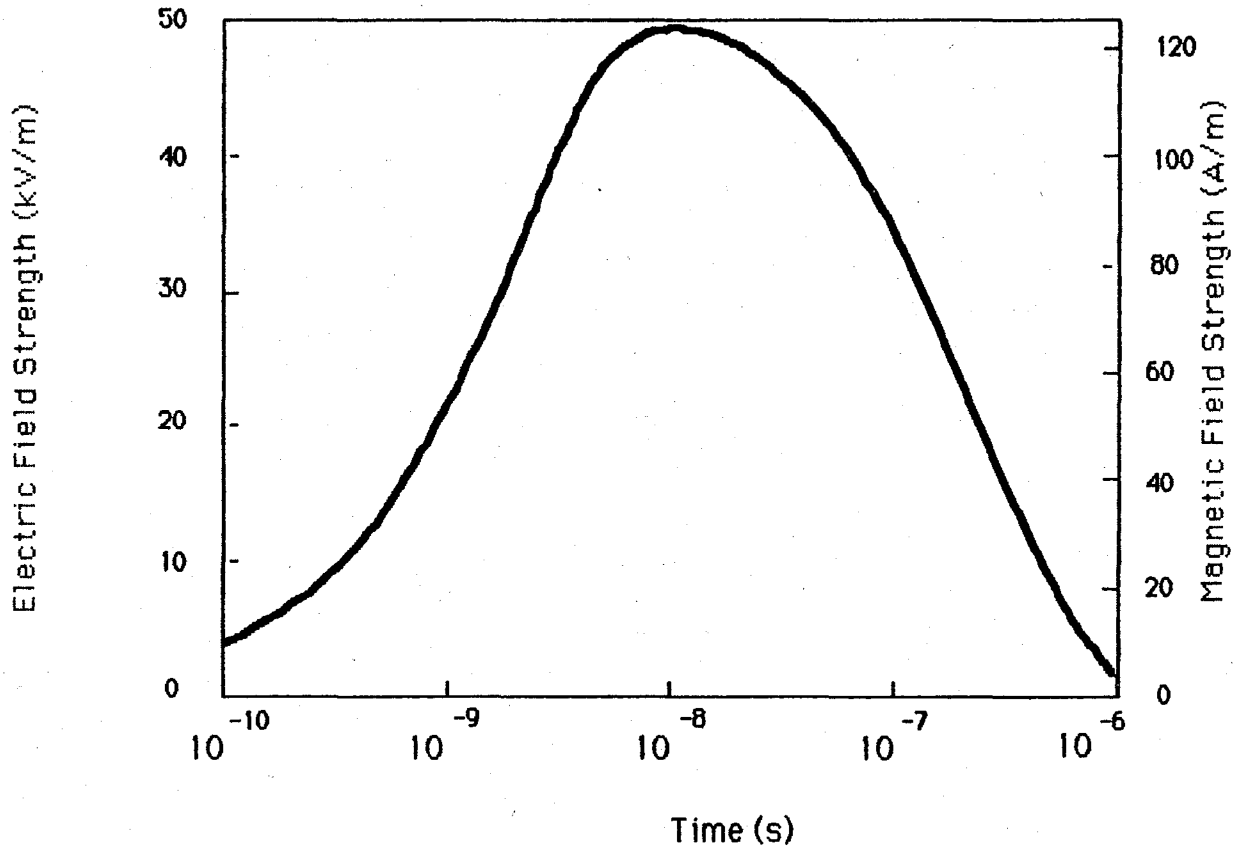

Figure 5. Generalized high-altitude EMP electric and magnetic field time waveform.

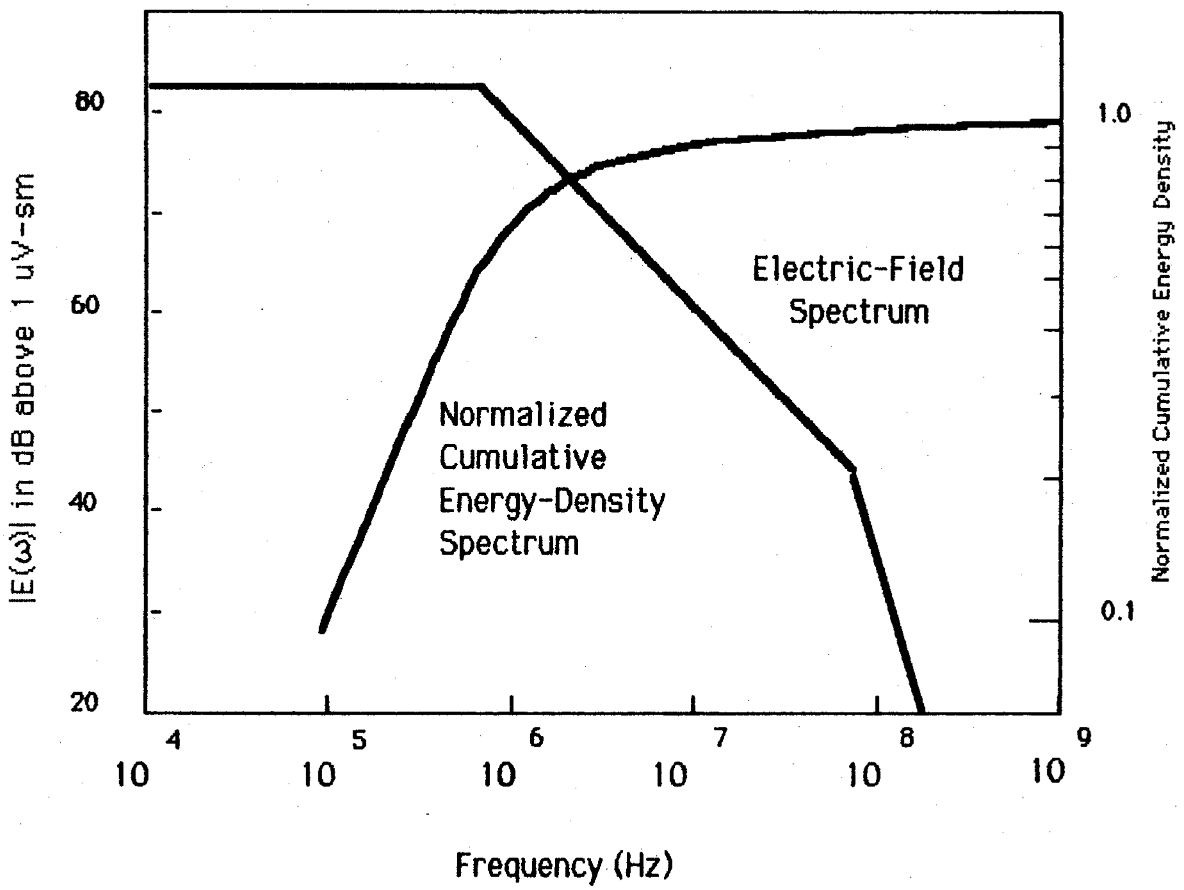

Figure 6. High-altitude EMP spectrum and normalized energy density spectrum.

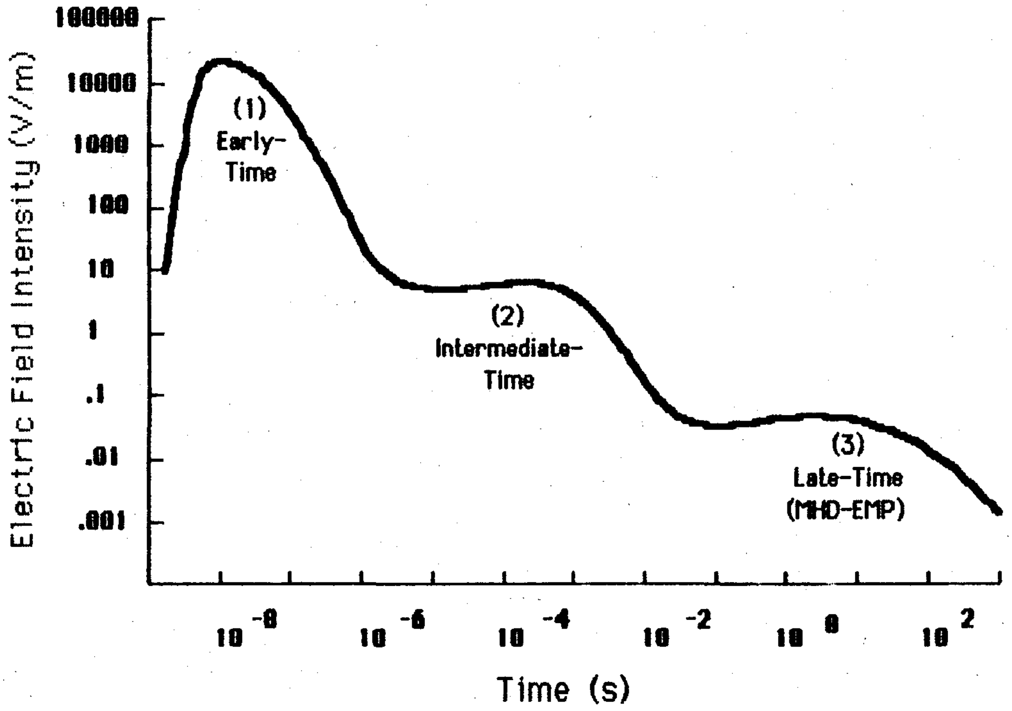

Figure 7. Current unclassified HEMP waveform (Dittmer et al., 1986).

portion is characterized by the very rapid rise time and extends out to about 1 microsecond. This is the dominant portion, and the only portion characterized in the BTL reference above. Because of the very large amplitude, short rise time, and the frequencies involved this early-time portion couples readily into telecommunication cables and antennas. Because of this dominance, this portion of the waveform has been referred to as the HEMP waveform but the term more properly applies to the total waveform. The intermediate-time portion of the waveform extends from 10^{-6} to 1 second. The late-time portion occurs after 1 second. This latter portion has been historically referred to as MHD-EMP because of the magnetohydrodynamic processes that produce it. All three portions of the waveform have wide area coverage, but the peak amplitude of the intermediate-time and late-time portions is much smaller. The MHD-EMP may be significant for long conducting cables because of the very large skin depth in Earth and sea water.

Other forms of EMP include low altitude EMP, which generates very intense fields over distances of several kilometers. These are generally of lesser importance except in specific instances such as command, control, and communication facilities that have been hardened against blast and thermal effects but might still be vulnerable to EMP.

3.2 HEMP Effects

Nuclear HEMP induces currents in all metallic objects, which by accident or design act as antennas. Aerial and buried power and telecommunication networks in particular can collect considerable amounts of energy. Even short radio antennas and other electrical lines may experience unusual induced currents and voltages. The collected HEMP energy could upset, breakdown, or burn out susceptible electrical and electronic components. Many systems contain integrated circuits and other semiconductor devices that are subject to failure at very low energy surges (down to the order of a millionth of a joule for short pulses) (Wik et al., 1985).

Apart from the difficulties inherent in designing accurate experiments of HEMP effects over large spatial volumes, there are serious difficulties in applying theoretical models and calculations to real systems, which are exceedingly complex and undergo frequent modification.

The field strength of a HEMP can approach 50,000 volts/meter (Raiford, 1979). To place this figure in perspective, consider that a radar beam of sufficient power to cause bilogical hazards has a strength less than 100 V/m. Additionally, a transmitted radio signal from a 40,000 watt commercial broadcasting station has a field strength in close proximity of the transmitting antenna of only 1-10 V/m.

The polarization of the high altitude EMP is a function of the location of the burst, the location of the observer and the direction of the Earth's magnetic field. As a rule of thumb, the polarization of the electric field is normal to both the direction of propagation (radially outward from the burst point) and the Earth's magnetic field at the location of the observer.

The polarization can vary from horizontal to vertical. For most of the United States and western Europe, the expected polarization would range from horizontal to 30-40 degrees off horizontal.

A system's vulnerability may be due to either burn-out of electronic components, or arcing between conductors, or to temporary upset of a computer memory (Carter, 1984). If the temporary upset can be corrected locally within a few minutes, it is not considered tactically vulnerable. About a microjoule of energy delivered to a single junction of an active solid-state element may burn it out. Since a threat level HEMP wave has about a joule-meter^2 energy in it, very modest coupling efficiencies can lead to permanent damage or temporary upset.

HEMP is not the only source of stress that can cause damage to sensitive circuits. A recent article summarizes the EMP stress along with other likely sources that may cause damage (Antinone, 1987). Recent success in making electronic circuits smaller, faster, and more densely packed cause these circuits to be more susceptible to damage by transient voltages or currents. When an integrated circuit is subjected to transient overstress, the failure mechanism is usually electrothermal. The power that causes the damage is delivered electrically, but the nature of failure is ultimately thermal: the dissipation of the electric power causes localized heating, to the point of melting or undesired alloying in the circuit.

The gates of Metal-Oxide-Semiconductor (MOS) transistors are especially sensitive to electrical overstress. In an MOS transistor, the maximum that the thin oxide layer can withstand is known as the dielectric standoff voltage. Beyond this limit, current punches through the oxide, forming a permanent path from the gate to the semiconductor below. Since a punch-through failure occurs very quickly, MOS gates should be handled very carefully if they lack protective networks.

Estimates of damage thresholds for various electronic components are shown in Table 6 (Sims, 1987). These devices are not hardened to military specifications. Such hardening greatly increases the cost of devices. The cost increases may be justified for some critical system or subsystem elements. For applications in common carrier, long-haul systems of interest to this study, careful attention to bonding, grounding, and shielding seems more appropriate. Electronic cabinets with specially designed conductive surfaces or overlays may actually suffice for the regenerator electronics as well as the electro-optic transceivers. Once shielding is in place, it is extremely important not to violate its integrity by carelessly inserting conducting paths such as power cords, antenna wires, or other penetrations that would negate the intended shielding.

Table 6. Typical Vulnerability of Electronic Components

Damage Threshold in Joules

	10^{0}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}
RELAYS	XXXXX	XXXXX							
VACUUM TUBES	XXXXX	XXXXX	XXXXX						
RECTIFIER + CONTROL DIODES		XXXXX	XXXXX	XXXXX					
ZENER DIODES			XXXXX	XXXXX					
AF TRANSISTORS				XXXXX	XXXXX				
RF TRANSISTORS					XXXXX	XXXXX			
INTEGRATED CIRCUITS						XXXXX			
CMOS							XXXXX		
MICROWAVE DIODES						XXXXX	XXXXX	XXXXX	

3.3 HEMP Levels

The coupling of EMP energy to exterior structures has been treated in the literature (BTL, 1975). The HEMP waveform (early-time) can be approximated analytically by the difference between two exponentials:

$$e(t) = E_o(e^{-\beta t} - e^{-\alpha t})u(t)$$

where $E_o = 5.25 \times 10^4$ volts per meter

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

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

and $u(t)$ is the unit step function.

(Note: The DNA EMP Course notes indicate that the early-time high frequency ($f > 100$ kHz) portion of this waveform is better approximated by $\beta = 3 \times 10^7 \text{ s}^{-1}$ and $u(t) = k = 1.285$.)

Starting with this expression, the coupling to a buried coaxial cable sheath was calculated in the reference (BTL, 1975). The results indicate that peak currents of 1800 amperes are generated in a 3-inch (7.6 cm) diameter sheath buried 1 meter in earth with conductivity = 10^{-2} mho per meter and permittivity = 1 (permittivity of free space). It is clear from these analyses that care must be taken in grounding metallic sheaths on fiber optic cables. Structures such as regenerator or terminal buildings may have other buried penetrations in addition to the signal cable (e.g., fuel-oil casings, drain and sewer pipes, and conduit enclosing power leads to outside lights and pumps or standby generator equipment). These external structures act as unintentional receiving antennas for EMP. Many of these structures are relatively short and induced currents of less than 1000 amperes may be expected. It is necessary to prevent such induced currents from entering the structure that houses sensitive electronic equipment. The maximum peak short-circuit current induced on semi-infinite overhead power lines or communications cables at a nominal height of 10 meters is about 10 to 15 kiloamperes for typical earth conductivity. This maximum occurs for small elevation angles of the incident EMP (between 4 and 12 degrees). (No similar calculations were found corresponding to the extended waveform, i.e., intermediate-time and MHD-portion of the waveform. The latter portion of the waveform would likely couple strongly to long lengths, e.g., 30 km, of cable. Also, the much lower frequencies contained in this waveform would make shielding by burying the cable ineffective because of the much greater skin depths at these frequencies.)

3.4 System Evaluation

The intensity of the HEMP field is so large that it does not need an antenna to collect the damaging energy (Ghose, 1984). Ghose indicates that it is not unusual for the EMP energy to reach a circuit or equipment inside a shield or enclosure by a direct penetration through the shield or through cables leading to equipment or through doors, windows and seams of shield structure. Since the early 1960's, many theories, along with their experimental verifications, have been advanced to assess quantitatively various modes of entry of EMP energy into circuits and components. The exact computation of the field or voltages or currents induced in a circuit or component of a system, by almost any mode of entry, is difficult, even when the incident, time-varying EMP field is exactly defined. This is often because of the complexities of the formulation of the electromagnetic boundary value problems for objects with irregular shapes and sizes and the simultaneous presence of multiple modes of entry of EMP energy. The direct penetration of an EMP field through a shield or an enclosure, for a given incident field at the outer surface of the shield, can be solved exactly for only a few ideal geometries, such as an infinite circular cylinder or sphere, most of which are not encountered in real-life systems. Similar difficulties arise with the analytical treatment of determining EMP-induced voltages and currents at the output of an arbitrary, but conventional, antenna, or in cables of arbitrary lengths and with arbitrary, but commonly occurring, terminations. Theories developed during the 1960's, however, do provide an insight into the damaging potential of the EMP by various modes of entry and suggest what measures are important during the design of a system to assure EMP hardness.

There appears to be a significant body of information available to those DOD contractors that build systems for aircraft or missiles that must work in an EMP environment. These "black box" units are designed to meet specified threats. Standards have been developed to allow the customer and manufacturer to agree on the degree of hardness achieved and to qualify the system or subsystem. EMP test facilities are available such as: ALECS, ARES, Small EMP Test Facility, Long-Wire Antenna Simulators, Vertical Dipole Simulator, Cable Driver, CW Tests, and Current Injection Tests (Ghose, 1984). These facilities are designed to test objects that vary in size from a component up to a large aircraft. None of these facilities can produce the very high electromagnetic fields over large areas as needed to test the fiber optic common carrier installations of interest to this program.

3.4.1 FT3C Multimode Lightwave System Evaluation

Tests have been performed (NCS, 1985) to determine the vulnerability of the FT3C Multimode Optical-Fiber Communications System by AT&T. In these tests, elements of the FT3C lightwave system such as the cable, regenerators, line repeater stations, etc., were subjected to the test conditions at the AESOP Test Facility [Harry Diamond Laboratories (HDL) Woodbridge Research Facility in Woodbridge, VA]. Bit error ratio measurements were conducted during the tests in this facility to determine the system performance degradation to be expected from an EMP event. The test program proceeded in several stages that were conducted at HDL and AT&T Bell Laboratories in Indian Hill, IL. The tests used two methods to stress the FT3C system: exposure to the Army EMP Simulator Operation (AESOP) and current injection. A communication network covers a large geographic area; hence, it can collect large amounts of energy from the nearly uniform electromagnetic field that would blanket it following a high-altitude nuclear burst. This energy is concentrated in the form of high-level currents at the termination of the long lengths of cable that connect the network.

It is not practical to simulate the full-strength EMP waveform along a cable of sufficient length that the current induced through electromagnetic coupling reaches a saturation level. Consequently, large current injectors must be used to attain representative levels in systems possessing long cables. Conversely, the nature of the electromagnetic coupling to a particular cable is best determined by direct measurement under an EMP simulator.

Testing at the AESOP facility was used to characterize the coupling of a radiated electromagnetic field to the FT3C cable (so-called Transfer Function). The currents induced by the test facility were relatively small. The data from these tests provided the input for calculations that modeled the cable current that would have resulted if the incident electromagnetic field had appeared as the waveform presented in the threat defined in a memorandum of April 3, 1984, from the Under Secretary of Defense, Research and Engineering, i.e., DOD-STD 2169. The particular lightguide cable to be tested contained metal wires to increase its strength. It also contained a metallized vapor barrier that was intended to be insulated from the metal wire strength members. Current injection tests were made while these cables were terminated (optically and electrically) as they would be in actual system installations.

A second purpose of the simulator testing was to determine the effect of HEMP on the central office equipment and the line repeater stations of the FT3C system. The most significant aspect of the EMP response of the FT3C lightwave-transmission system was the sensitivity of the over-voltage-protection circuitry in the power converters. The origin of this sensitivity was electromagnetic coupling to the leads from the output terminals of the power converters and lower-level coupling directly to the printed-circuit wiring of the converter. This disablement was not viewed as a malfunction of the system, since the protection circuits were performing the function for which they were designed and can be readily modified to eliminate this malfunction.

Other than the issue of the power converters' deactivation, the only sensitivity to EMP evinced by the FT3C system was a brief period of a few tenths of a second of signal disruption following EMP exposure. The signal persisted throughout the disruption and was compromised only to the extent that a few thousand bits of information were lost; presumably this is the price paid for a gross electromagnetic disturbance of delicate circuitry.

3.5 Conclusions

It appears from the tests reported above, that optical fiber common carrier systems can be designed to survive the impact of HEMP events without heroic measures in shielding. Clearly, emphasis on good engineering practice is required. In order to meet other NSEP requirements, it seems highly desirable to require that the transmission media, along with the regenerator electronics, be buried. It seems appropriate to analyze the added protection provided by the burial of the cable and electronics. Once a fiber optic system is in place, it is essential that a program of periodic testing be implemented to assure that the susceptibility of the system is not compromised.

4. PROPERTIES OF OPTICAL WAVEGUIDES

Fiber waveguides to be used in long-haul transmission systems where large transmission capacity is required must be single mode because of the bandwidth limitations of multimode waveguides due to modal distortion and disturbances due to intermodal interference (mode noise) (Baack, 1985).

4.1 Material Attenuation

Very pure quartz (S_iO_2) serves as the starting material for present-day, high-quality light waveguides. To vary the refractive index, the material is doped (Mahlke and Gossing, 1987) with germanium (Ge) and phosphorus (P) (to increase the refractive index) and boron (B) and flourine (F) (to decrease the refractive index). Thus, core dopants are primarily Ge and P and clad dopants are B and F. Figure 8 shows the variation with dopant levels.

Optical losses in the material arise due to scattering and absorption of the light. Impurities involved in particular transition elements such as Cu, Fe, Ni, and Cr as well as OH-ions lead to high losses in the relevant wavelength range from 0.8 to 1.6 μm. Absorption losses, which as a fundamental principle cannot be avoided, occur in the ultraviolet and infrared ranges due to absorption by the quartz material itself.

For a Ge-doped, single mode fiber, the causes of loss as a function of wavelength are demonstrated in Figure 9. In addition, the calculated resultant total loss is also shown. The limiting lower loss level in each of the windows used for telecommunications is that determined by Rayleigh scattering. (An interesting rule of thumb is that this loss is about 1 dB/km at a wavelength of 1 μm.) At wavelengths greater than about 1.6 μm, the loss increases rapidly because of the infrared absorption in this region. The silica-fiber waveguides exhibit a minimum loss at about 1.55 μm, as shown in Figure 9.

4.2 Material Dispersion

A limiting property of the waveguides for high capacity systems is the material dispersion caused by the fact that the index of refraction of the material is not constant with wavelength near the operating wavelength of the driving source. The dependence of the index of refraction, and thus the group delay time, upon the wavelength is called the material dispersion (t_g). For materials used for production of current long-haul fibers, t_g exhibits a zero-state near 1.3 μm. Figure 10 shows the dispersion of pure and doped quartz as a function of wavelength. In optical fiber technology the dispersion is specified as a change in delay time in picoseconds per nanometer wavelength change of the source and kilometers of fiber length (ps/nm-km). The zero-point of the material dispersion can be shifted to higher wavelengths by doping the quartz with Ge and to lower wavelengths by doping with B.

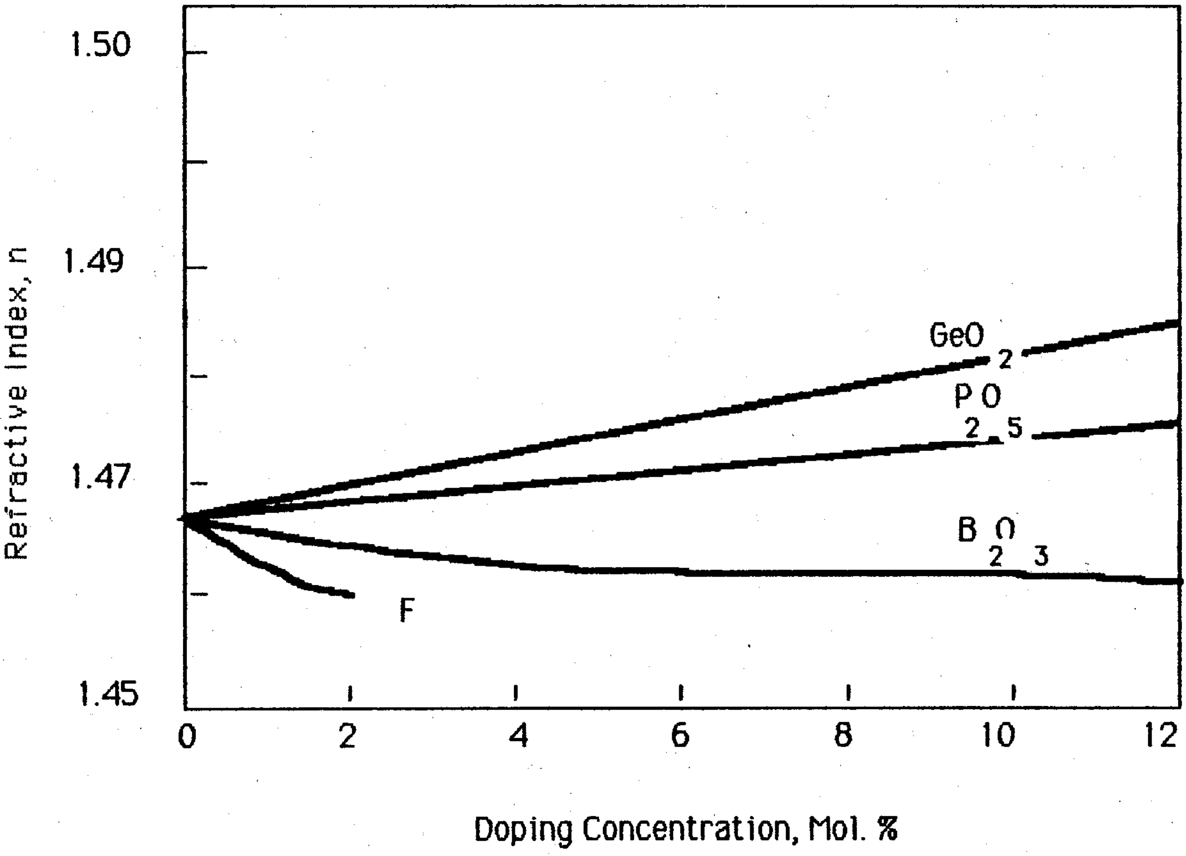

Figure 8. Refractive index of S_iO_2 with different dopants (after Mahlke and Gossing, 1987).

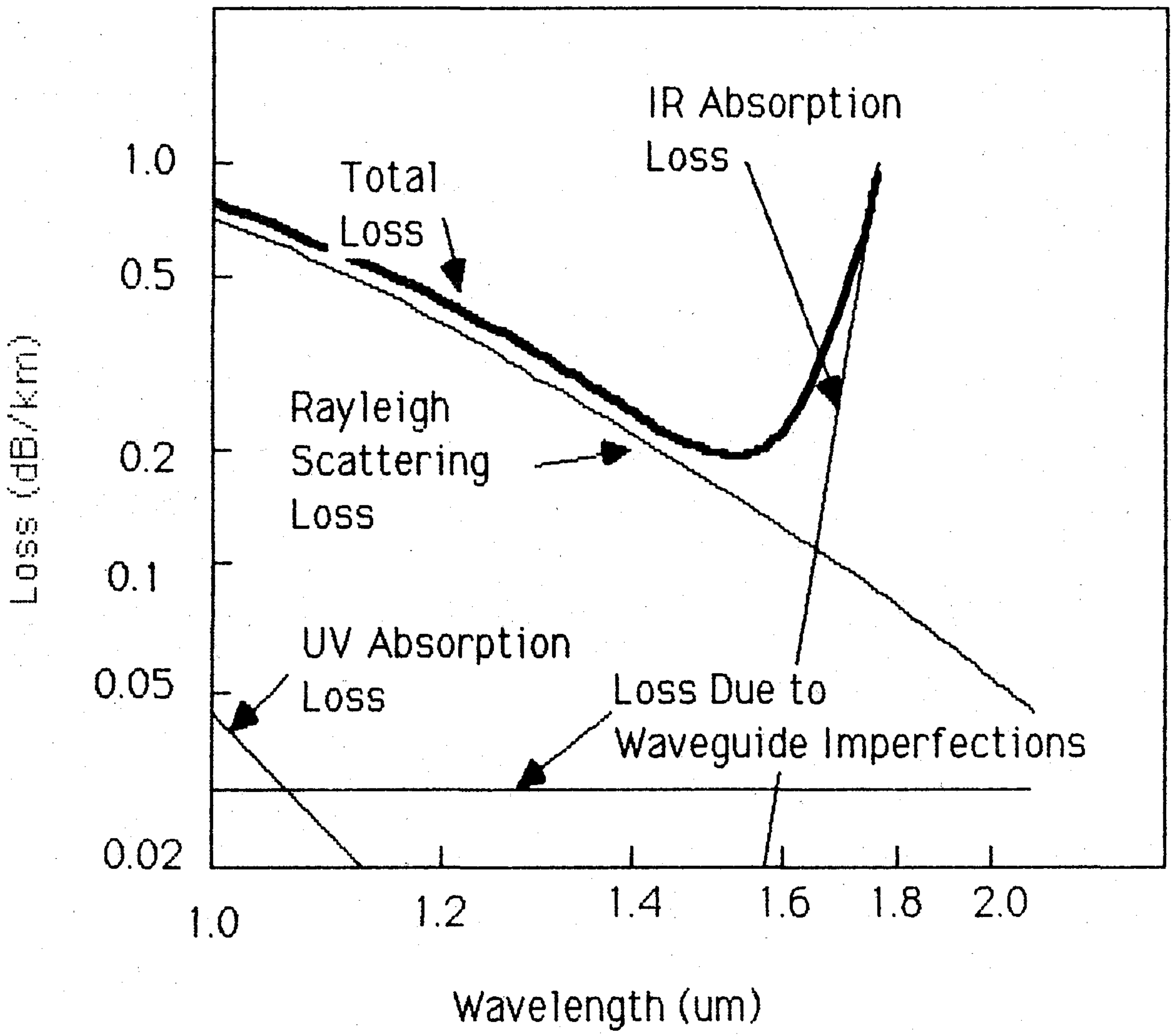

Figure 9. Representation of loss components in a Ge-doped, single-mode fiber as a function of wavelength (after Baack, 1985).

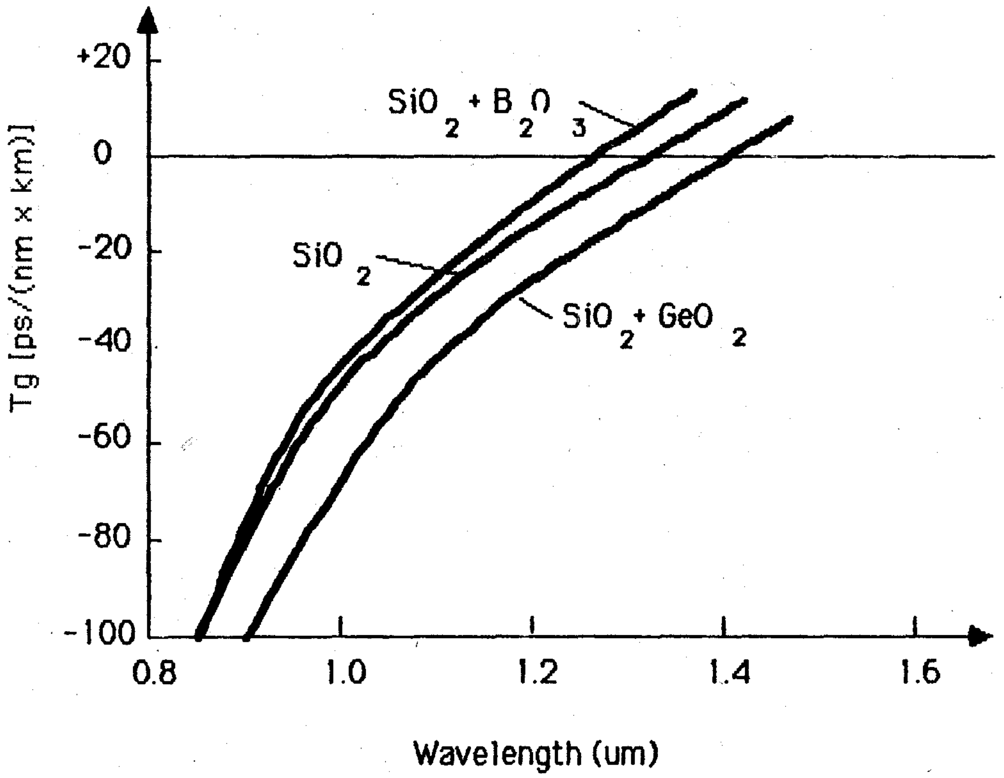

Figure 10. Material dispersion of pure and doped silica versus wavelength (after Baack, 1985).

4.3 Glass and Fiber Making

Low loss fiber waveguides are drawn from very pure quartz (S_iO_2) rods or boules that have been appropriately processed to deposit the dopants. Glass is generally considered to be the material from which windows and drinking glasses are made. Glass is technically not a particular material, but rather a state (e.g., solid, liquid, or gas) of matter. In particular, glass is a solid state of matter in which the atoms are not in a regular array (as in a crystal), but where the interatomic spacings and bond angles are irregular (Personick, 1985). Figure 11a is illustrative of the compound silicon dioxide in both its crystalline state, and the glassy state is shown in Figure 11b. If cooled down slowly, a liquid will form a crystalline solid at a temperature called the freezing temperature. This change of state as a function of temperature occurs abruptly and with an accompanying change in volume at the transition. However, if a liquid is cooled down very rapidly, then at a temperature below the freezing temperature, called the glass-forming temperature, the liquid may gradually solidify in the glassy state. For example water, which normally freezes at 273 °K, will form a glass if rapidly cooled to 140 °K from the liquid state. S_iO_2 will form a glass under similar cooling conditions at 135 °K.

4.3.1 OCVD Process

In 1970 Corning Glass Works demonstrated a method for forming low loss (< 20 dB/km) fibers from mixtures of silicon dioxide and oxides of germanium and other atoms. Their process started out with very pure silicon tetrachloride, a volatile liquid that can be purified of metallic contaminants to below 1 part per billion (ppb) with proper processing. Through this liquid they bubbled pure oxygen, which picks up some of the S_iCl_4. The mixture is burned in hydrogen to form tiny particles of very pure S_iO_2. These particles, formed in a burner, are directed at a rotating target mandrel where they are deposited in the form of soot (fine particles), see Figure 12. As the mandrel rotates and the burner translates back and forth over the mandrel, a soot "preform" is built up which is typically about a meter long and perhaps 10 centimeters in diameter. As the preform is built up, the composition of the deposited soot particles can be varied. For example, germanium tetrachloride and boron trichloride can be added to the oxygen stream to raise or lower the refractive index of the deposited material. When a sufficiently large soot

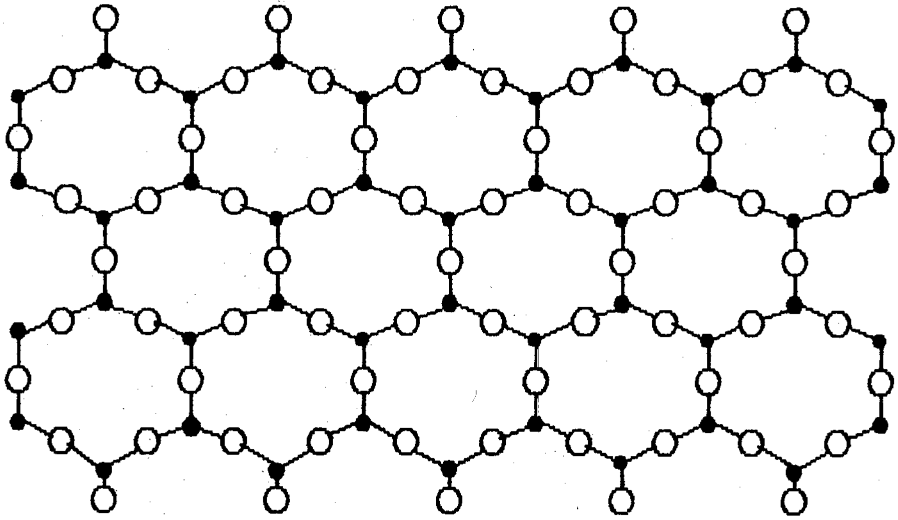

Figure 11a. Crystalline silica structure
(after Personick, 1985).

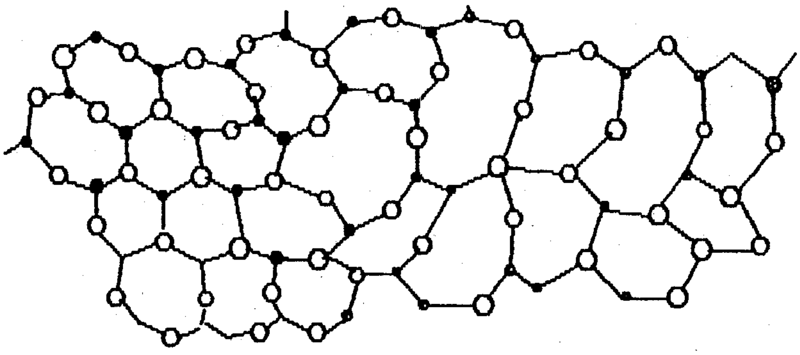

Figure 11b. Glassy silica structure.

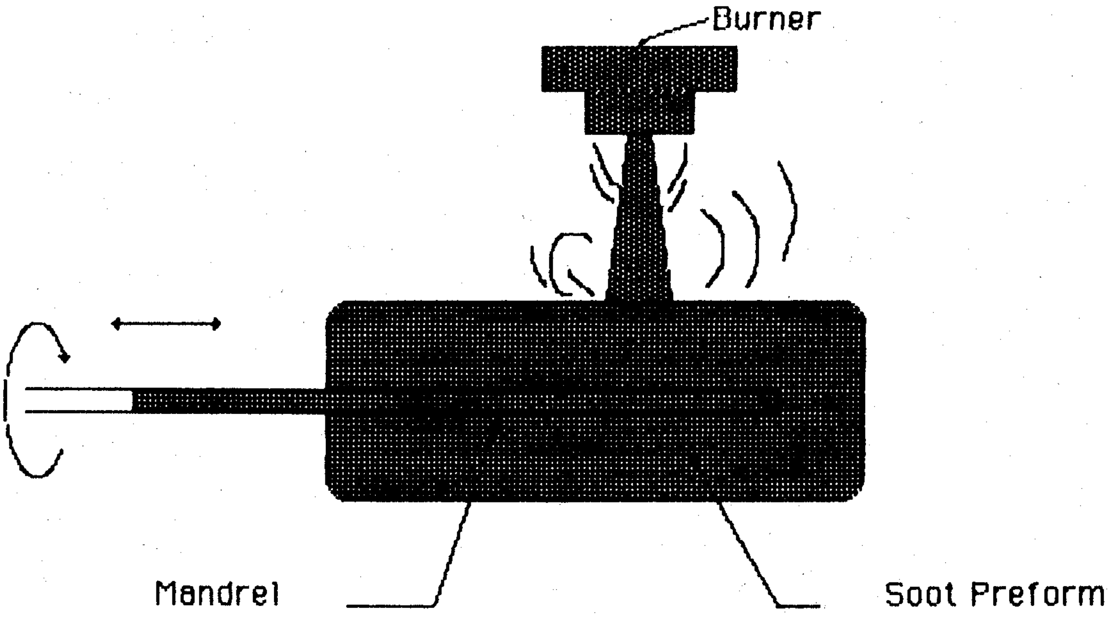

Figure 12. CVD glass preform fabrication (after Personick, 1985).

preform has been deposited, the preform is placed in a furnace, which causes the soot particles to melt together into a clear solid preform. This process is called sintering. Finally the target mandrel is removed, and the preform is again heated, causing it to collapse into a solid rod. It is from this solid rod that a fiber can be drawn. Corning called this process the outside chemical vapor deposition (OCVD) process.

4.3.2 MCVD Process

Bell Laboratories developed a modified chemical vapor deposition (MCVD) process or inside chemical vapor deposition process. This is illustrated in Figure 13. Pure oxygen is bubbled through silicon tetrachloride, germanium tetrachloride, and mixed with other materials, and allowed to flow through a starting tube of high quality silica (fabricated by some other process). The tube is held in a glass-working lathe containing two synchronous chucks. The synchronous chucks rotate the tube while allowing access to the ends. Where the cutting tool would be placed in a metal lathe, one places a torch that traverses back and forth across the rotating tube. As gases flow past the torch, they ignite to form particles of pure glass (soot particles) that deposit on the walls of the tube downstream from the flame. As the flame passes over the soot particles, it consolidates them into a solid clear glass. In this way layer upon layer (possibly of varying composition) of new glass can be deposited inside the tube. The inner cladding layers are deposited first, followed by what will become the fiber core. After sufficient new glass has been deposited inside the tube, the gases are shut off, the temperature of the torch is raised, and the tube collapses into a solid rod (preform). A typical tube is about 1 m long and 25 mm in diameter.

4.3.3 VAD Process

A third process has been developed by Nippon Telephone and Telegraph (NTT), in cooperation with Sumitomo, Furukawa, and Fujukura companies in Japan, which is referred to as the vapor axial deposition (VAD) process. In this process, illustrated in Figure 14, material is deposited on the end of a growing preform. The resultant soot preform is sintered into a solid rod, as in the outside chemical vapor deposition process.

Each of these processes is being used to make low loss, high quality, single-mode fiber waveguides. Each can provide adequate control to accurately

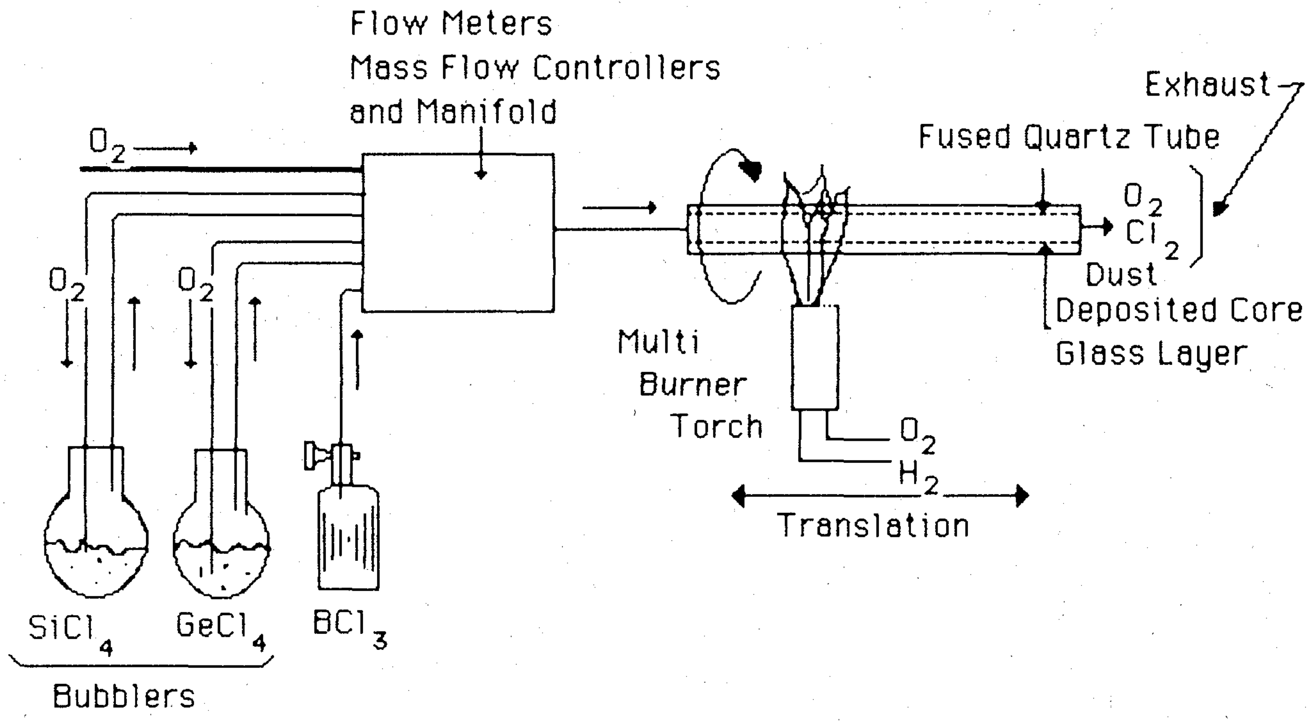

Figure 13. MCVD glass preform fabrication (after Personick, 1985).

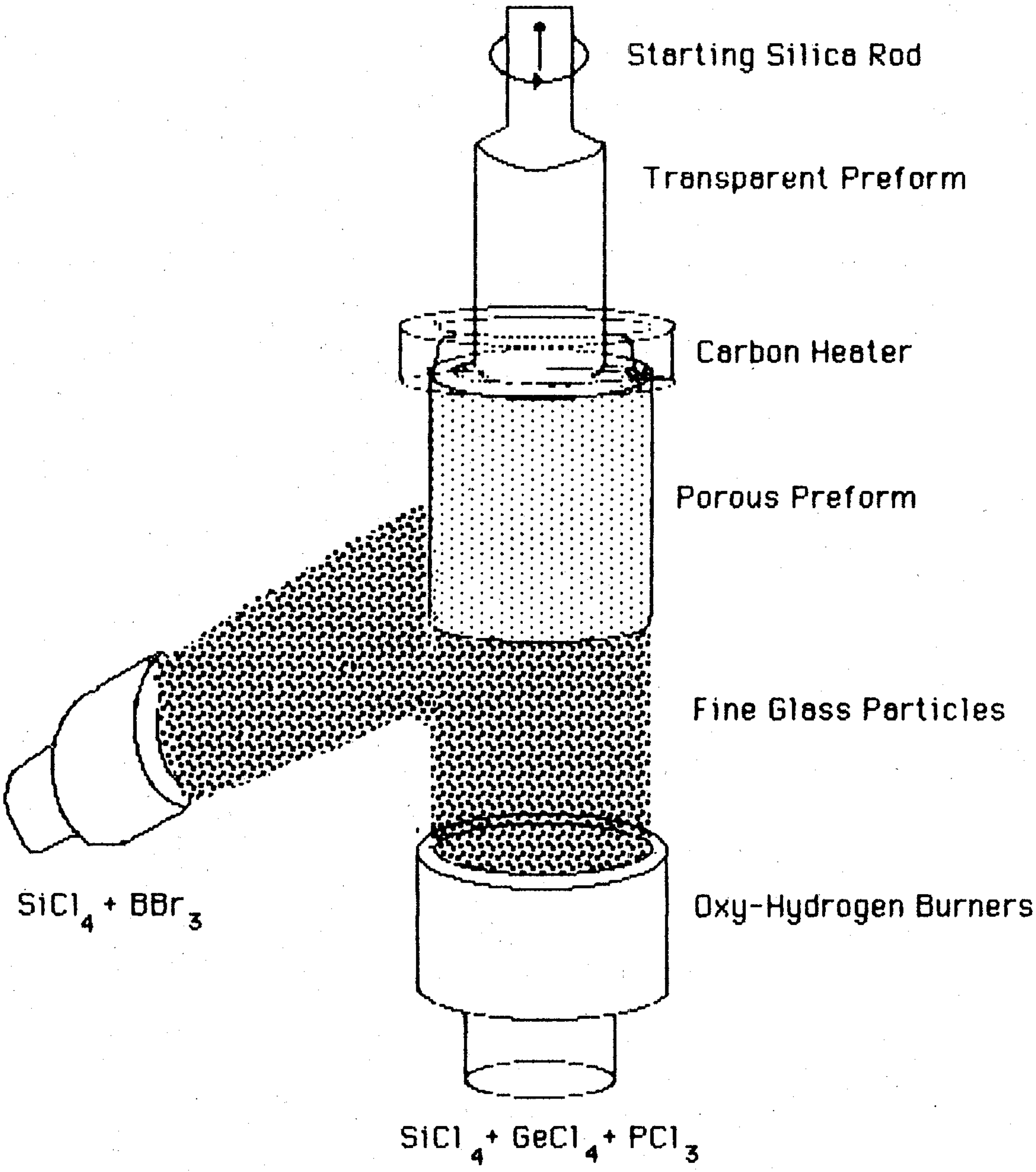

Figure 14. VAD glass preform fabrication (after Personick, 1985).

form the core and cladding regions. Each process is constantly being improved to increase the rate of deposition of materials, the efficiency of use of starting materials, and the yield of the fabricated fibers. These factors determine cost.

Having fabricated a clear glass preform by one of the methods described above, a fiber drawing machine is used to form the waveguide under accurately controlled conditions to assure uniformity of core and cladding diameter, concentricity, etc., as necessary to meet rigid internationally adopted standards so that connectors, splicing machines, and other processing can be handled by crafts personnel in the installation and maintenance of the subsequent fiber optic cables.

4.4 Single-Mode (SM) Fiber Waveguides

The condition for producing a dielectric waveguide is shown in Figure 15. The core with the refractive index n_c and the cladding with the refractive index n_{cl} are produced from correspondingly doped quartz material. To obtain a SM waveguide, specific dimensions must be adhered to for the core diameter 2a and the refractive index step $(n_c - n_{cl})$. A normalized frequency parameter is defined as follows (Baack, 1985):

$$V = k_o \cdot NA$$

where $NA = [(n_c)^2 - (n_{cl})^2]^{1/2}$

and $k_o = 2\pi a/\lambda$

a = radius of core

λ = operating wavelength.

NA is the numerical aperture of the fiber for beam optics. (The factor k_o can be remembered as the core circumference expressed in free-space wavelengths of the driving source.) For low doping percentages, $n_c \approx n_{cl}$ so that

$$NA = n_c\ (2\Delta)^{1/2}$$

where $$\Delta = \frac{(n_c)^2 - (n_{cl})^2}{2(n_c)^2} \approx \frac{n_c - n_{cl}}{n_c}\ .$$

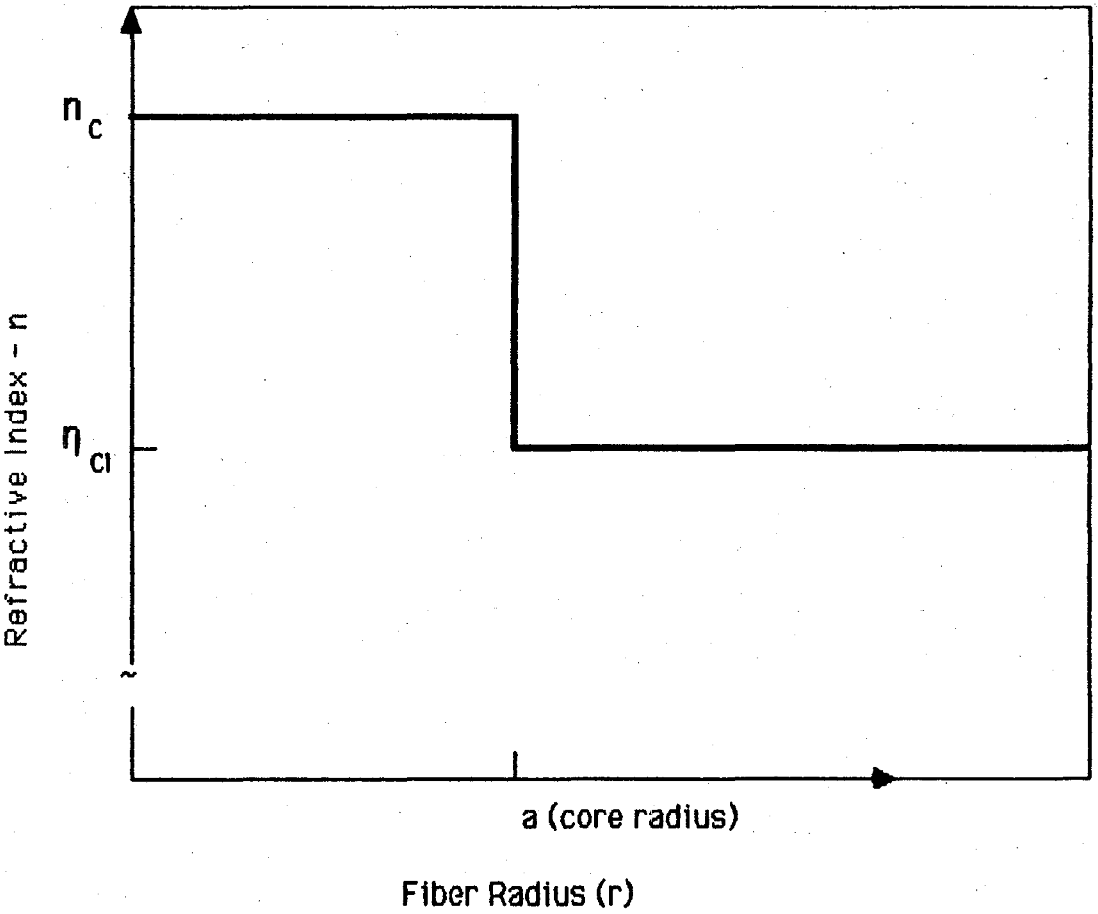

Figure 15. Schematic representation of a step-index optical waveguide (after Baack, 1985).

The radial field distribution in a SM fiber is described in the core by the Bessel function J_o and in the region of cladding by a Hankel function field which decays exponentially. At the cut-off of the HE_{21}-mode ($V = 2.4$) approximately 20 percent of the power is carried in the cladding region. For this reason, the cladding material must be low-loss similar to that of the core in order that an overall low-loss waveguide be achieved. The driving source wavelength must be chosen such that $V \leq 2.4$ as a condition for operation as a single mode waveguide.

4.4.1 Radiation Damage in Optical Fibers

The immunity of interference from electromagnetic fields is a much publicized property of optical transmission media. It is tempting to conclude that optical fiber transmission links are not subject to environmental degradation. It has been known for a considerable period of time that glass will discolor when exposed to nuclear radiation. Such discoloration represents a change in the optical properties of the glass which in general results in enhanced absorption of light passing through the glass. Thus exposure to nuclear radiation may produce significant attenuation enhancement in optical communication cables. A body of research literature is available (see Bibliography). Actual measurements on commercially available single-mode fiber representative of that which is actually being installed appears to be meager. In order to interpret that which is available, some background is required.

Various models are invoked to explain the optical properties exhibited by glasses, ranging from phenomenological treatments involving complex dielectric constants to damped harmonic oscillator models of electronic states (Englert, 1987). The models at best lend some qualitative insight into the treatment of light interaction with glass; however, no overall satisfactory quantitative theoretical descriptions at the atomic level of such phenomena have been offered.

The diagrams in Figure 11 are attempts to illustrate the difference between crystalline and glassy materials. Thus the alteration of absorption characteristics in optical fibers, after exposure to ionizing radiation, is to be expected. In simple terms a color center is an impurity or imperfection within an otherwise well-ordered system. This imperfection will generally have a set of energy levels available for electronic transitions. These energy levels then represent an absorption spectrum, so light not absorbed gives the material its characteristic color.

Color centers can be formed by exposure to ionizing radiation. The process is most likely one of bond-breaking in the solid as the high energy (e.g., x-ray or γ-ray) photon or particle energy is absorbed. This results in a local variation in the electronic energy level structure. Any rearrangement of the electronic structure at localized sites within a solid might be thought of as a defect. An electron, for example, trapped at some defect site, can participate in the absorption of incident light. At a lower temperature the electron will be bound to this site for a statistically longer period of time than if the material was at some higher temperature. The "recovery" of radiation damaged optical fiber materials at higher temperatures must be a process of thermal energy absorption resulting in the rearrangement of local defects caused by radiation. Many forms of these defects are unstable and thermal processes are sufficient to restore the material to its original state. Some processes are quite stable and thermal "healing" is not nearly so effective.

4.4.2 Scintillation

Optical fibers exposed to high dose rates of ionizing radiation have been found to show a significant increase in extraneous light during the time of exposure. The primary source of this extraneous light during irradiation is due to the Cherenkov effect. This effect occurs when a charged particle passes through a material at a speed faster than the speed of light in that material. In effect, an optical shock wave results. This process is a common way of detecting and measuring the energy of charged particles given off in nuclear or other high energy processes.

Another possible source of the scintillation observed in optical fibers is luminescence. The luminescence of materials generally arises from some form of recombination or de-excitation of atomic systems after having absorbed energy from ionizing radiation. A three-step sequence of events occurs:

1. Energy, represented by ionizing radiation or particles, is incident onto material.
2. Energy is absorbed by an atomic or molecular structure resulting in a transition to some higher energy state.

3. The atomic or molecular structure returns to its ground state and emits radiation.

The time from the first to the last step varies from material to material. For example, the afterglow of a television screen represents a rather long time (on the average) transition to the ground state. In glasses, the luminescence generally takes place very soon after the absorption of ionizing radiation.

4.4.3 Fiber Reliability Considerations

Three reliability considerations have been identified by Nagel (1986). These are mechanical strength and static fatigue, radiation-induced attenuation effects, and hydrogen induced losses. Regarding the radiation-induced attenuation effects, she states that the induced radiation effects in fibers are influenced by a large number of variables such as the nature and energy of the radiation; the dose and dose rate; the wavelength of operation; the temperature, length, and uniformity of fiber exposed; the light injection conditions and intensity; the previous radiation history of the fiber; and the time relative to exposure. Such variables further underscore the need to know very specifically not only the fiber response but the details of the environment the fiber will function in. The radiation-induced losses in fiber are composed of both a permanent and transient component. It is quite important to also specifically account for losses due to steady state exposures versus the loss at a given time after exposure. The recovery response after a fiber has been exposed to a pulsed or temporary radiation exposure can change the system response in a way to reduce the radiation effects. In some cases, photo-bleaching due to the transmission of power through the fiber or exposure to ambient light can enhance the recovery or electron-hole recombination characteristics in the glass. This can affect both characterization and performance of the fiber.

4.5 Experimental Measurements of Radiation Damage

When optical fiber waveguides are exposed to nuclear radiation, the radiolytic electrons and holes can form color centers if they are trapped on defects that either exist in the amorphous network or the glass prior to irradiation or are created by the exposure (Friebele et al., 1985). These color centers give rise to the radiation-induced optical attenuation that is commonly observed in the three infrared operational wavelength windows of 0.85, 1.3, and 1.5 μm. The optical attenuation of irradiated waveguides can be 10-1000 times greater than the intrinsic losses (e.g., 10-1000 times 0.5 dB/km at 1.3 μm).

The radiation-induced attenuation is composed of two components: (1) a permanent component, which persists years after the initial exposure or grows in during very low dose rate (< 10 rad/day) steady state irradiations, and (2) a metastable component. The latter consists of both a transient part, which evidences decay times < 1 s after a pulsed irradiation and a component which recovers in times > 10 s and is measured during and after steady state exposures of 10-10,000 rads/min. The nature and extent of the transient and steady state recovery processes depend strongly on the composition, dopants, and fabrication process of the fiber core. The radiation response of fibers is influenced by several factors such as (1) fiber structure and core and cladding composition and dopants added to minimize the radiation sensitivity; (2) system parameters such as operational wavelength, light intensity, and temperature; and (3) radiation parameters such as total dose, dose rate, time after irradiation, and the energy, nature, and history of the radiation.

4.5.1 High-Bandwidth Telecommunication Fibers

High-bandwidth telecommunication fibers typically consist of a Ge-doped silica core that may be co-doped with flourine (F) or phosphorus (P) and either a pure or doped silica cladding. In the case of multimode fibers the index of the core is graded in a near-parabolic fashion, while the cores of single mode waveguides usually have either a step or triangular profile. Extremely low optical attenuations have been achieved in these fibers (e.g., 0.12-0.16 dB/km at 1.55 μm) by removal of impurities and OH and by careful choice of dopants. These fibers have achieved the theoretical attenuation.

The transient response of pure silica core fibers following pulsed irradiation has been shown to be much less than that of any doped silica core waveguide. Thus pure silica core fibers appear to be desirable for radiation environments. The radiation response of doped silica core fibers is different from that of pure silica core. In the case of the doped silica core fibers, the concentration and nature of the dopants dictate the fiber behavior. In the case of silica core fibers, impurities and defects intrinsic to the silica network determine the radiation sensitivity.

4.5.2 Recovery of Multimode Fibers

Figure 16 shows the recovery of radiation-induced attenuation in Ge-doped (multimode) fiber following an accumulated exposure of 3,700 rads. The induced loss is the added loss following exposure. This fiber was doped with Ge in the core and flourine in the cladding layer (levels of dopant were not specified in the paper). The loss induced at 23 °C is only 2.5 dB/km, which decays to < 1 dB/km within a minute after the exposure. It is interesting to note that although the loss incurred immediately after irradiation is substantially less at 80 °C, the recovery is less at 80 °C than at 23 °C. The initial loss at -55 °C is 18 times that at 23 °C and the recovery (the slope of the curve) is substantially less (almost 5 dB/km induced loss remains 24 hours after exposure). This fiber was pulled from a preform prepared by the modified chemical vapor deposition (MCVD) process. A similar fiber pulled from a preform prepared by a plasma chemical vapor deposition (PCVD) process had identical radiation responses at 23 and 80 °C, but less than half that of the MCVD fiber at -55 °C. The MCVD process fiber contained slight F doping (< 0.2%) in the cladding layer. The PCVD process fiber contained no F in the cladding. This would suggest that flourine doping in the cladding may affect the low temperature response; however, further testing of fibers prepared by the OVD process without F-doped cladding gave identical response to the MCVD fiber. This suggests that the low temperature response of the PCVD fiber is due to the nature of the process.

Figure 17 shows the effect of adding phosphorus to the cladding. Both the level of the induced loss and the recovery time have been increased. The radiation response at -55 °C is significantly less and may approach that of the 23 °C after sufficient recovery time. This suggests that P doping may reduce the temperature effect on the radiation response provided sufficient time is allowed to permit the recovery and provided sufficient system margin can be made available to allow for the enhanced loss.

4.5.3 Single-Mode Fiber Induced Loss

Figure 18 shows the results of tests on a proprietary fiber that consists of Ge-doped silica core and silica cladding plus additional core dopants to reduce the temperature dependence of the induced loss and to enhance recovery. The loss measured at -55 and 23 °C immediately after irradiation is slightly higher than in the fiber of Figure 17. However, the recovery of this fiber is

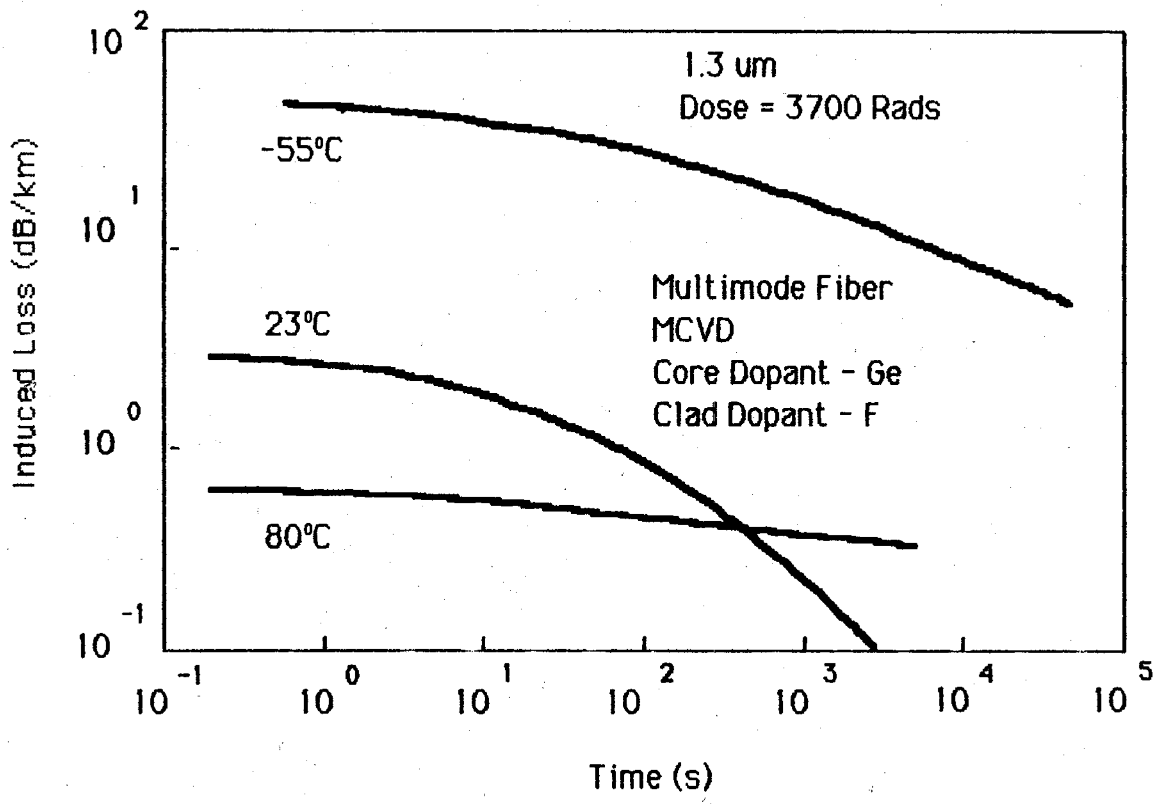

Figure 16. Recovery of the induced attenuation in Ge-doped silica core fiber.

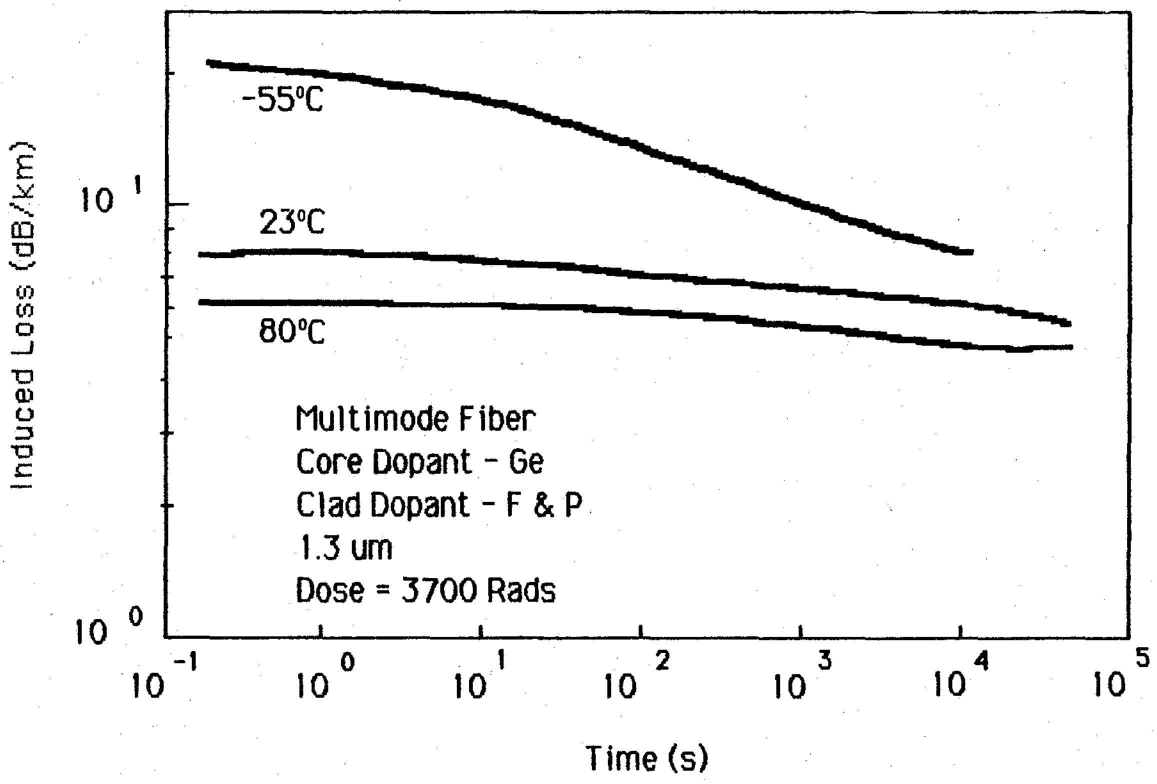

Figure 17. Recovery of the induced attenuation in Ge-doped silica core fiber with a P-F-doped cladding.

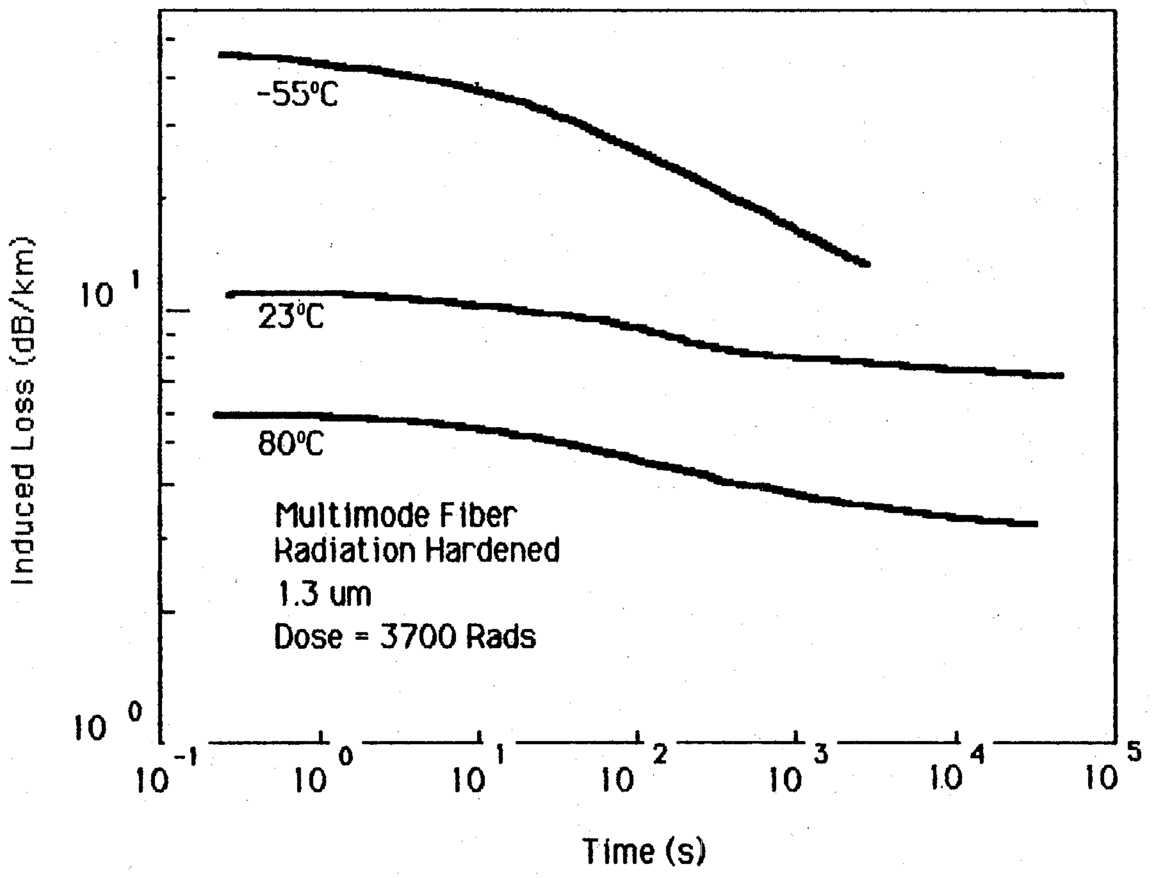

Figure 18. Recovery of the induced attenuation in Ge-doped silica core fiber (radiation hardened).

better so that the damage in the two is approximately equal to 1,000 s after the exposure; at longer times this fiber is superior. The enhanced recovery also results in less damage at 80 °C in this waveguide. The effect of core dopants to enhance recovery is especially evident in the low response of the waveguide at 80 °C.

Figures 19a and 19b show the growth of radiation-induced attenuation as a function of dose for six single mode fibers obtained from different manufacturers. Core and cladding dopant levels (weight percent) are indicated for each fiber. These measurements were made at 23 °C and the radiation source was ^{60}Co. The fibers were irradiated first at a dose of 300 rad/min to a dose of 200-2000 rad and then at 9000 rad/min to a total dose of about 10^6 rad. The preform for fiber number III was prepared by an inside vapor phase (IVP) oxidation process. The preform for fiber number IV was prepared by the VAD process. Fiber number V was drawn from a preform prepared by an outside vapor phase (OVD) oxidation process. The other preforms were prepared by an inside vapor deposition process. The induced loss after an exposure of 1000 rads varies between 0.6 and 14 dB/km. The damage at this dose level in all but the best of the fibers is at least an order of magnitude greater than the intrinsic loss. Rough approximations for the induced loss vary from about 10 mdB/km-rad for fiber number V to 0.55 mdB/km-rad for fiber number IV. Fiber IV tends to saturate (or recover) above about 10^3 rads. Note that fibers IV, V, and VI in Figure 19b contain no P-dopant and each tends to saturate compared with the fibers in Figure 19a. There were no published results regarding the temperature effects on the radiation response of these fibers.

The P-concentration in the cladding of the II-fiber is approximately twice that of the III-fiber leading to a factor of 2 higher radiation response of the II-fiber. The results of the tests on these two fibers illustrate that the cladding composition of single-mode fibers plays an important role in determining the radiation response, a conclusion that is consistent with the significant fraction of the optical power carried in the cladding of single-mode fibers. The effect of the cladding will depend on the degree of mode confinement and hence on the V-number. The core composition has a greater effect on the radiation response than that of the cladding. The damage is a factor of 5 greater in the I-fiber, which has the same P-content in the core as the III-fiber has in its cladding. (This correlates with the statement made

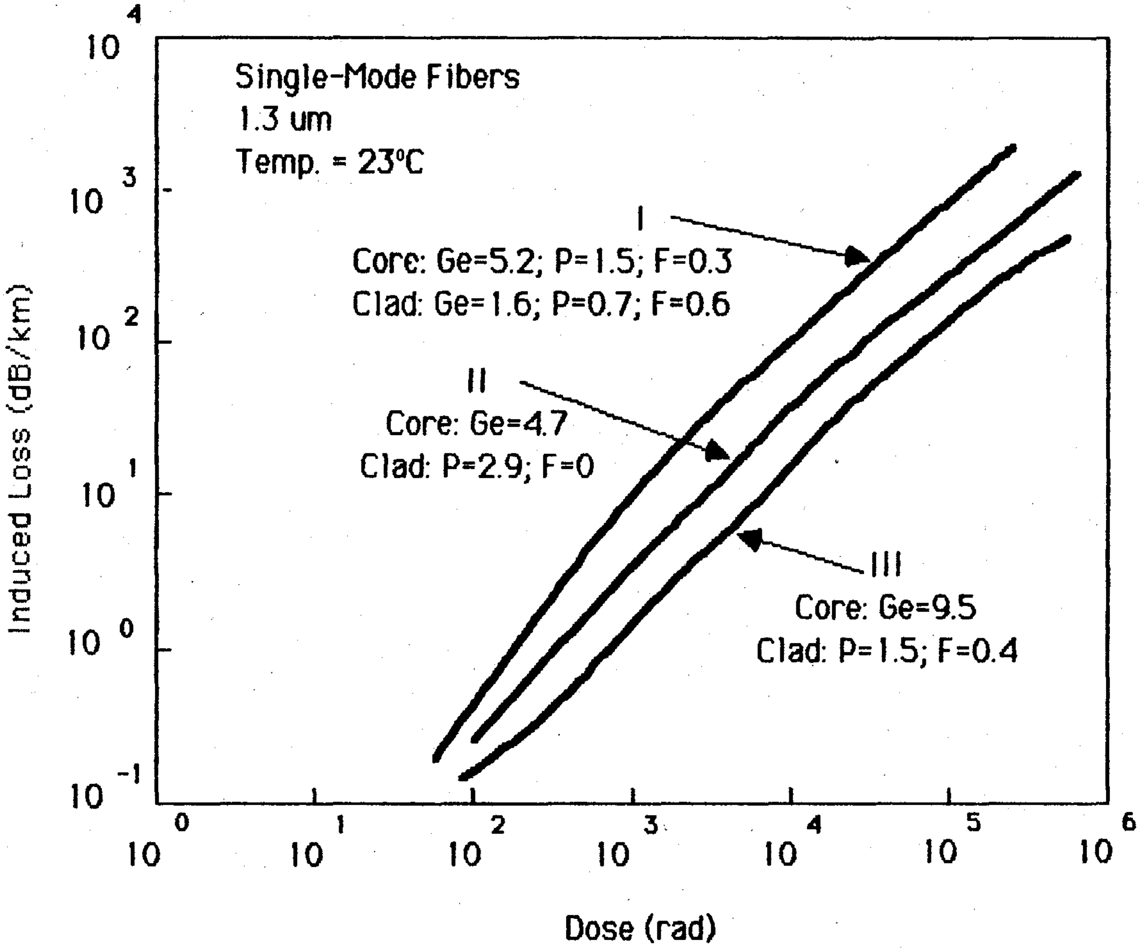

Figure 19a. Growth of radiation-induced attenuation in single-mode fibers.

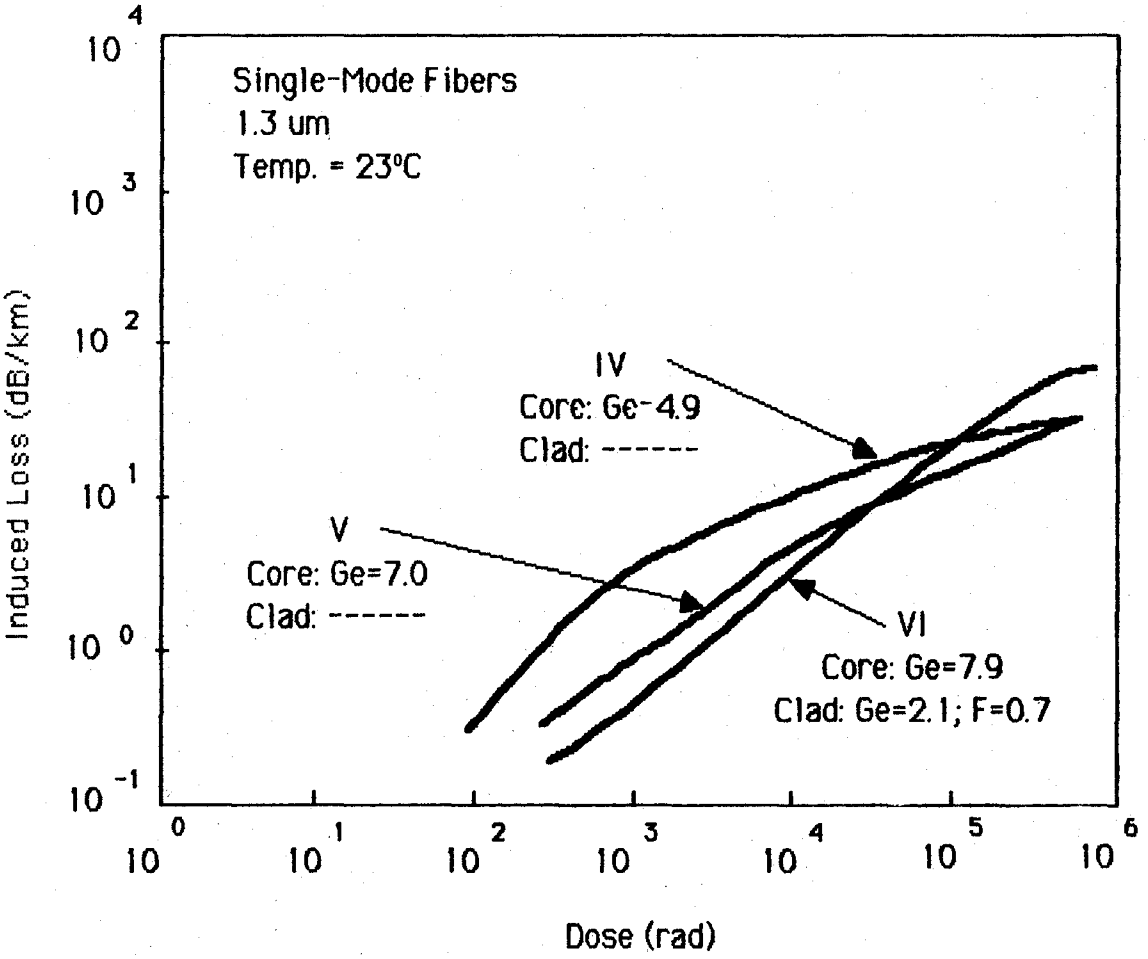

Figure 19b. Growth of radiation-induced attenuation in single-mode fibers (no P-dopants).

earlier that about 20 percent of the power is carried in the cladding in a single mode fiber.)

4.5.4 Single-Mode Fiber Recovery

Figure 20 shows the recovery of the radiation-induced attenuation in the single-mode fibers shown in Figures 19a and 19b. The fibers were exposed to a ^{60}Co source. Again the tests were run at 23 °C. Note the change in scales on this figure. The recovery data were taken after an exposure of about 24 s at a rate of 9000 rad/min, which results in a total dose of 3700 rads.

Note that there is no recovery in the fibers that contain phosphorus dopant at least up to the 24-hour period (10^5 s). The induced losses of the IV, V, and VI fibers are substantially less than those of the other fibers at short times following steady-state irradiation (due to recovery during the irradiation), and significant decreases are noted over about 1 hour. The total loss becomes $<$ 1 dB/km and approaches the intrinsic loss within this period. This behavior is not unexpected, since low initial induced loss and substantial recovery have been observed in multimode fibers doped with only Ge in the core. The losses in these fibers are similar to the induced loss on Ge content in the 7-25 weight-percent range. Large transient absorptions in these types of fiber occur following pulsed irradiations; however, it is likely that most of this loss will have decayed by 1 to 10 s.

4.6 Recent Unpublished Results

The radiation sensitivity of a series of commercially available single-mode fibers has been evaluated (Friebele, private communication 1987) and compared with experimental fibers drawn by the Naval Research Laboratory (NRL). The core and cladding compositions were determined by microprobe analysis. These fibers were subjected to a 2000-rad dose from a ^{60}Co source. The temperature at the time of exposure was -35 °C. The recovery was monitored for up to 10^5 s. A composite plot of the data representing seven of these fibers is shown in Figure 21. (The names of the suppliers have been removed except for the two experimental fibers drawn at NRL.) Fibers I and II on this figure were designated as "radiation hardened" fibers. A second set of tests is shown on Figure 22. These three fibers were all made by the same manufacturer. Fiber VI is a standard fiber representative of much of the installed fiber in commercial common carrier systems. Figure 23 shows test results on a fiber

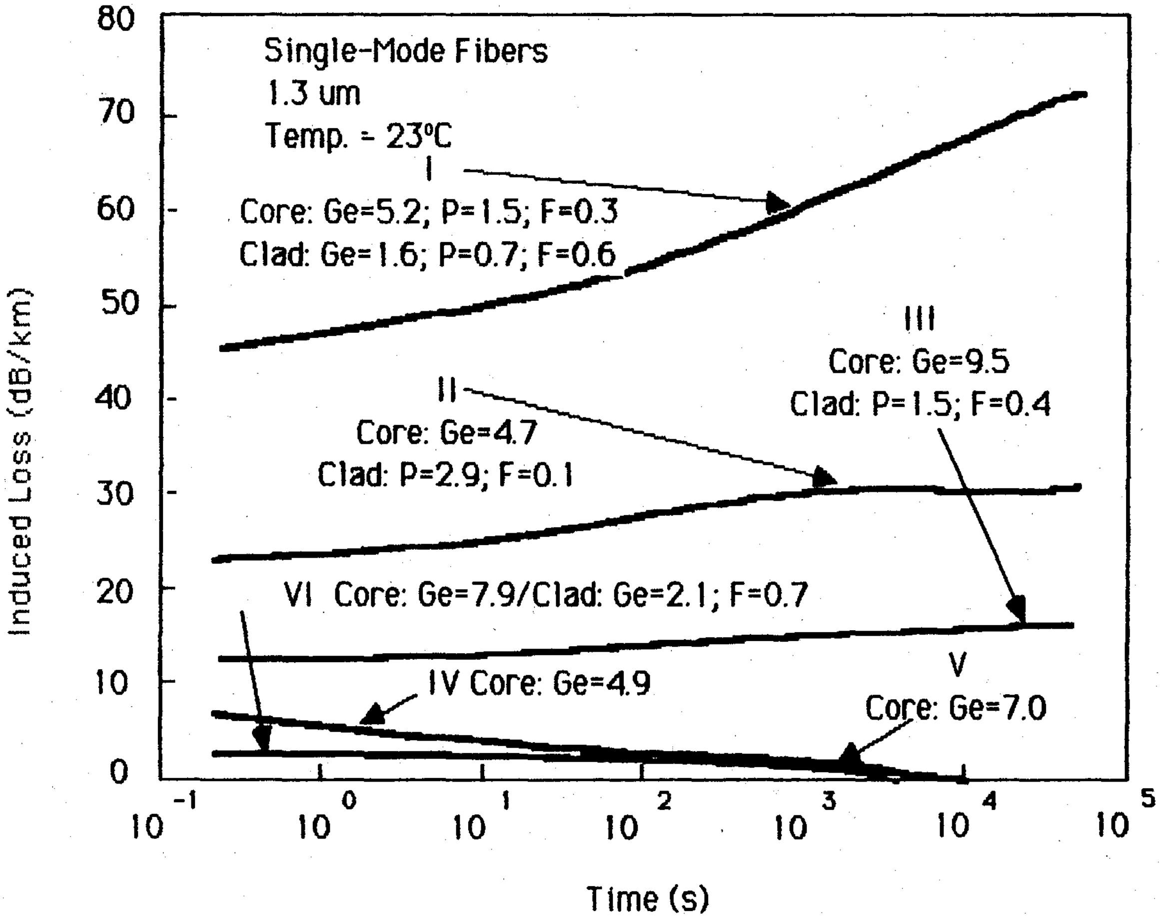

Figure 20. Recovery of radiation-induced attenuation in single-mode fibers.

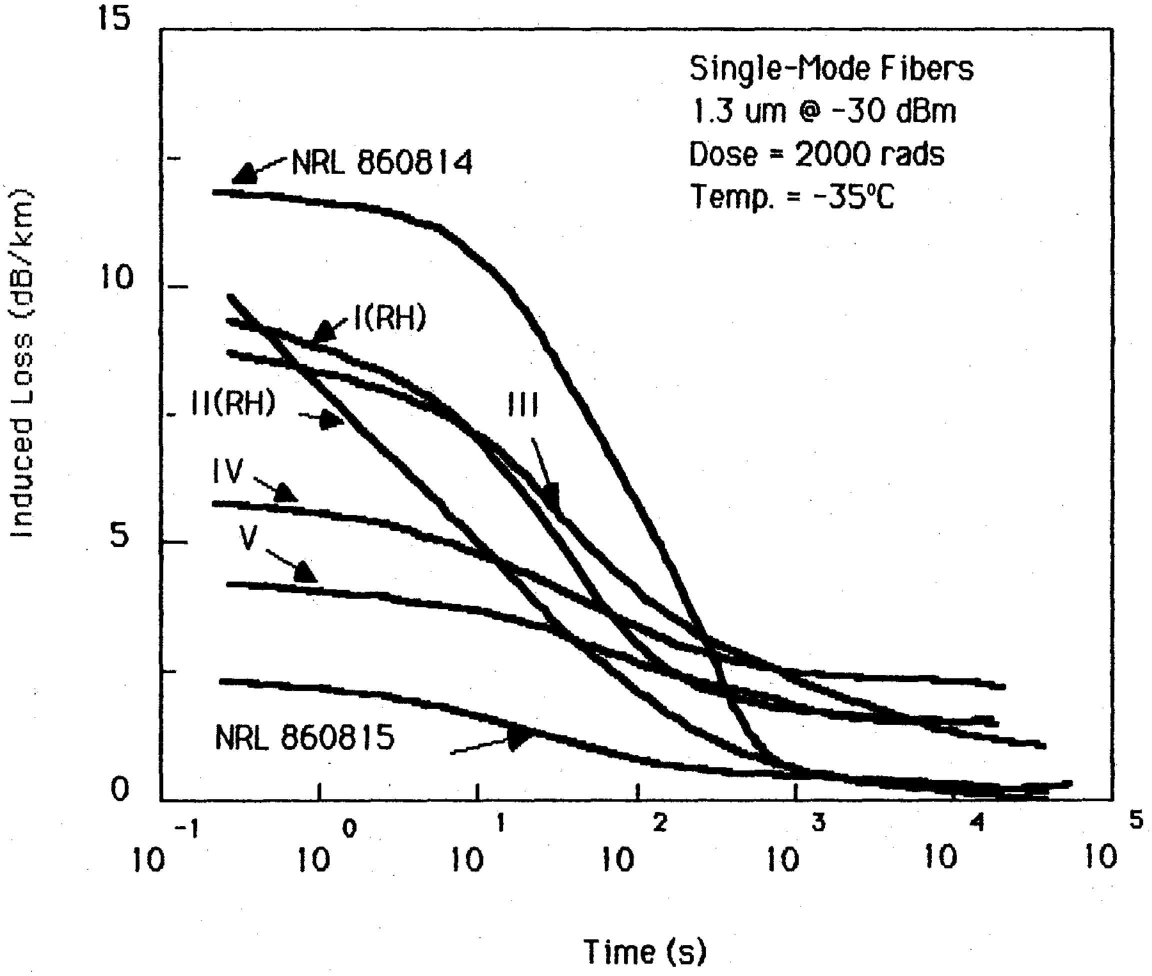

Figure 21. Recovery of single-mode optical fibers.

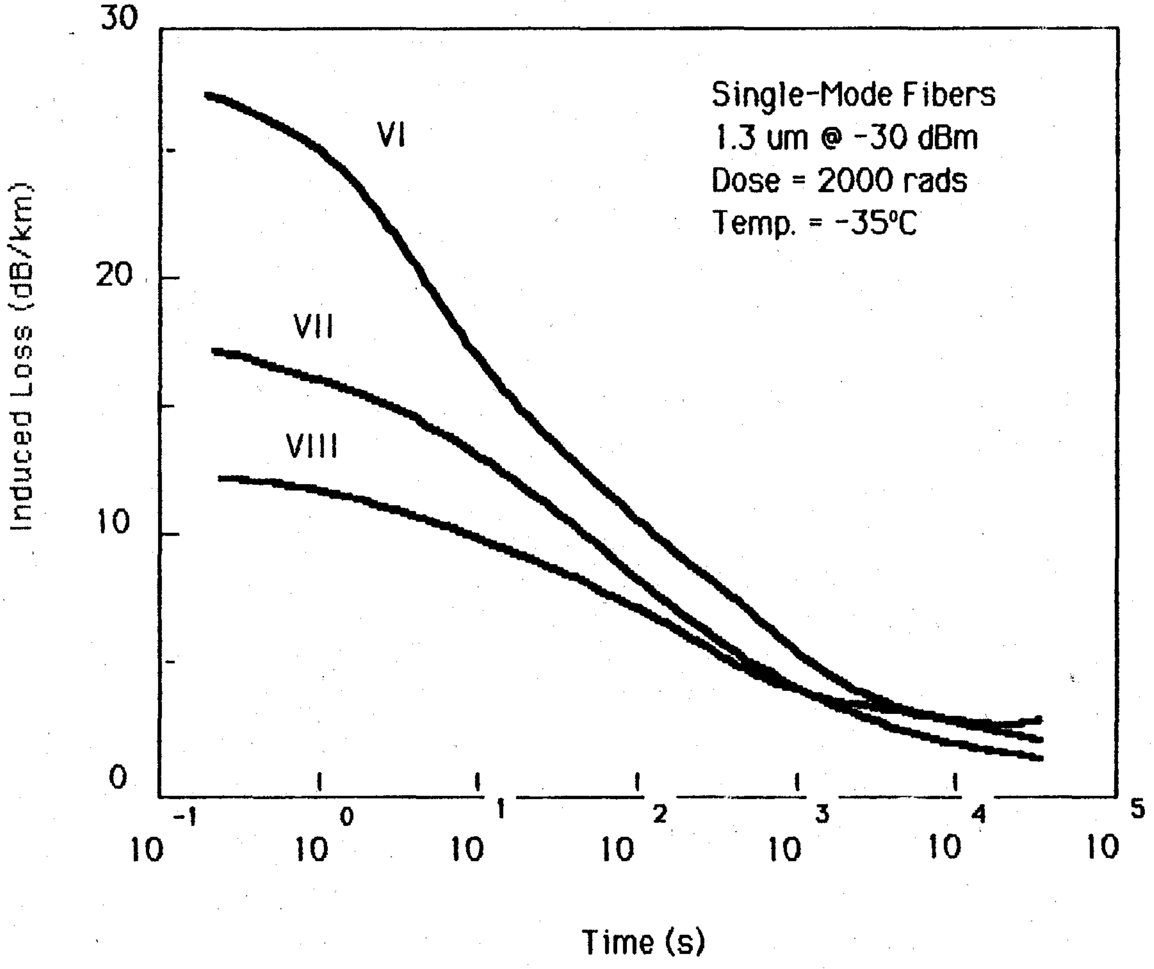

Figure 22. Recovery of single-mode optical fibers.

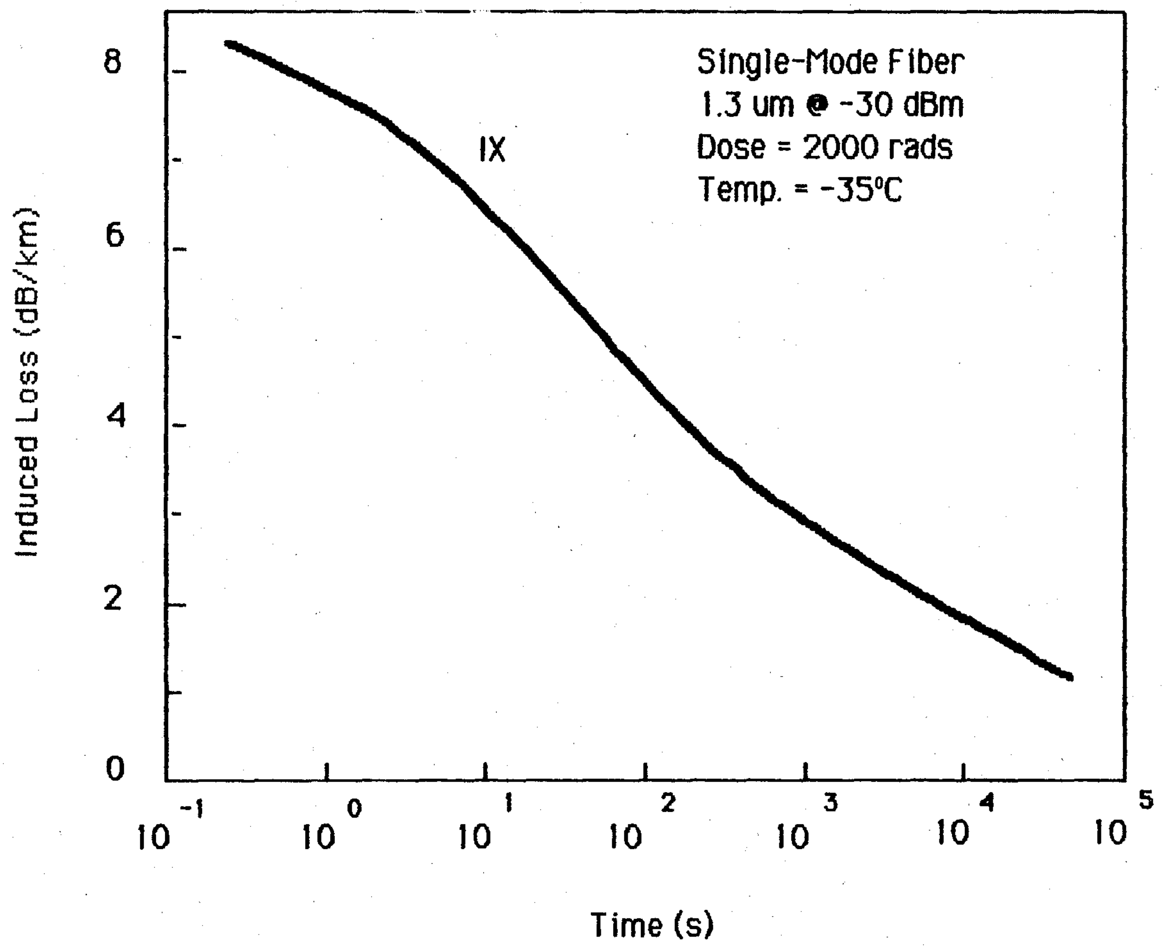

Figure 23. Recovery of single-mode optical fibers.

obtained from another large supplier. The fiber losses vary from 7.7 dB/km for the fiber VI (Figure 22) to 0.8 dB/km for fiber II-RH (Figure 21). (The intrinsic loss of these fibers is about 0.5 dB/km at 1.3 μm.) The long-term (permanent or low dose rate) response of the fibers varies between 2.3 dB/km for the IV fiber to essentially 0.0 dB/km for the II-RH fiber. The VI fiber would clearly be unacceptable for these exposure conditions. The II-RH fiber appears to respond such that sufficient system design margin could be allocated to maintain continuous operation.

The recovery response of the fibers shown in Figures 21, 22, and 23 indicate that recovery from induced attenuation can be achieved in a time frame of 10 to 15 min. The loss remaining 10 min following the radiation exposure is an indication of the system recovery following a weapons detonation. The loss (and slope) following 10^5 s is indicative of the response to low dose rate fallout exposure. The slope at 10^5 s is indicative of long-term recovery processes. It is generally true that the fibers with the higher losses have flatter slopes and would therefore experience greater damage under low dose rate fallout exposure. Note that, except for the two NRL and the II-RH fibers, all fibers have at least 1.5 dB/km permanent loss at this dose of 2000 rads. This exposure was assumed to be the maximum dose to be expected for fiber buried 36 in (1 m) for either prompt or fallout conditions as deduced from Glasstone and Dolan (1977).

Dr. Friebele has attempted to fit the recovery data observed in these tests to a general equation for n^{-th} order kinetics, where $n > 1$ (private communication). Hopefully, his work will be published soon.

In an effort to determine whether the data obtained under the 2000-rad exposure can be extrapolated to other exposure levels, the test on number II fiber was repeated at 400 rads. Within the experimental accuracy, the data for the 400 rad exposure were identical with the 2000 rad exposure divided by 5. Thus, extrapolations from the 2000 rad dose level to much lower doses are valid.

4.7 Conclusions

Radiation sensitivity of single-mode fibers doped with P in either the core or cladding can be somewhat less than that of P-doped multimode fibers due to the lower P content in the single-mode fiber. P-doping in the cladding has been found to be deleterious to the radiation resistance of single-mode fibers.

No effect on the radiation response has been found for F doping in either the core or cladding.

Single-mode fibers consisting of binary Ge-doped silica cores with pure silica claddings were found to recover quite well. This leads to low net induced loss observed during steady-state irradiation, low initial induced loss immediately following steady-state irradiation, and recovery to near intrinsic levels within a relatively short period of time. These fibers, such as the IV, V, and VI waveguides (in Figures 20 to 22), represent the best candidates for deployment in applications where slight downtimes can be tolerated. Preliminary studies of the temperature dependence of single-mode fibers have shown that extremely high losses can be induced in binary Ge-doped silica core fibers at low temperatures. P-doping tends to suppress this large temperature dependence.

From this brief summary, it can be concluded that radiation resistant fibers with reasonably short recovery times (10-100 s) are feasible. Pure silica core fibers with no P-dopant in the cladding appears to provide a fiber that will recover to near its intrinsic value in a reasonable time. The long-term (permanent or low-dose rate) induced loss response of the best fibers vary between 2.3 dB/km for a standard fiber, representative of currently installed systems, to 0 dB/km for radiation hardened fiber tested in the laboratory. Commercially available fiber cables designed specifically for radiation environments are just now becoming available. Examples are the I(RH) and II(RH) radiation hardened fibers whose radiation responses are compared in Figure 21. The II(RH) fiber appears to be the only commercially available fiber that fully recovers in the 24-hour time span.

It seems clear that measurements are needed on each of the major long-haul fiber waveguides already installed. Measurements by a government or other objective (unbiased) laboratory under uniform conditions are needed to assure the comparability of the commercially available fiber cables.

There is work in progress on an Electronic Industries Association, Fiber Optics Test Procedure (EIA FOTP-49) for radiation hardened fiber. A draft of this FOTP was presented to EIA SC FO-6.6 in June 1987. Similar work is under way in the International Electrotechnical Commission (IEC) that will be coordinated with the EIA work. There was no agreement on failure mechanisms that cause the radiation degradation as of February 1987. There is relatively little comparability of measurements made at different facilities, and considerable research may be needed before a satisfactory test procedure can be agreed upon.

5. RADIATION EFFECTS ON FIBER OPTIC SYSTEMS

NSEP radiation environments include background radiation from naturally occurring radioactive substances, potential hazards from nuclear power plants, research and testing facilities, or nuclear transport accidents, and limited exposure from nuclear attack. Since radiation effects represent one of the means by which fiber optic common carrier systems may be degraded, it is important to assess these environments.

5.1 Terrestrial Background Radiation

The rocks and soils of the Earth's upper crust contain varying concentrations of uranium (U), potassium (K), and thorium (Th), the three primary sources of nuclear radiation in the terrestrial environment (Haber, 1987). Rough estimates of average concentrations of these radioactive elements in the continental United States are 3 ppm U, 2% K, and 6 ppm Th. These were used along with estimates of contributions from cosmic radiation and radioactive fallout to calculate an average annual dose rate to a cabled fiber buried at a typical depth of 1 m. It is expected that under normal ambient conditions, the average dose rate for a buried fiber cable is about 150 mrad/yr. Haber derived an upper bound of 500 mrad/yr dose rate for such buried cables based on probability field for uranium. She has also provided locations and levels of enhanced concentrations from concentration maps and aerial measurements.

5.2 Fiber Measurements (Low Dose Rates)

Haber indicates that AT&T used low doses of gamma rays to estimate a fiber's sensitivity to nuclear radiation under the above ambient terrestrial conditions. Cobalt 60 was used as a source to irradiate the fibers at 20 °C at a rate of 2.3 rad/h for a 100-rad total dose. The 20 °C radiation sensitivities of the standard single-mode fiber are 0.45 mdB/km-rad at 1.3 μm and 0.7 mdB/km-rad at 1.5 μm. The radiation hardened design has 20 °C sensitivities of 0.25 mdB/km-rad at 1.3 μm and 0.15 mdB/km-rad at 1.5 μm.

Linear extrapolation from the above tests was used to predict long-term span losses in the average and maximum radiation environments mentioned above.

The environmental dose rate is four to five orders of magnitude smaller than the low dose rate and the total dose is roughly one order of magnitude smaller than that applied during the fiber tests. The effects of long-term recovery and photo-bleaching are not taken into account in the extrapolations. Thus it was concluded that the long-term loss calculated above should be an upper bound. Radiation loss of a fiber is a function of temperature. No attempt was made to estimate the impact of temperature on the long-term added loss calculations in the referenced paper.

Estimates of added long-term loss in both standard and radiation-hardened fiber (developed by AT&T) were presented for 30-km spans at 20 °C for the 1.3 μm and 1.5 μm windows over a 20-year life expectancy of such links (Note: This standard fiber has Ge dopant in the core and the cladding is effectively phosphorus free). The results are shown in Table 7.

Table 7. Added Span Loss for 30-km Span, 20-Year Exposure

	Standard Fiber		Radiation-Hardened Fiber	
	(A) 150 mrad/yr	(B) 500 mrad/yr	(C) 150 mrad/yr	(D) 500 mrad/yr
1.3 μm	0.04 dB	0.15 dB	0.02 dB	0.08 dB
1.5 μm	0.06 dB	0.21 dB	0.01 dB	0.05 dB

These estimates assume that a full 30-km span would be exposed to the dose rates shown. It is unlikely that even a large portion of such a span would be subjected to the dose rates shown. Therefore, it was concluded that excess loss due to terrestrial radiation exposure on AT&T single-mode fiber is negligible.

5.3 Radioactive Contamination from Nuclear Explosions

For purposes of this study, the radiation environment outside of the 2 psi overpressure level from a nuclear explosion will be considered. It was concluded in Section 2 of this report that only radiation from fallout needs to be considered. The radiological characteristics of the early fallout from a nuclear weapon are those of the fission products and any induced activity produced (Glasstone and Dolan, 1977). An air burst is by definition, a burst at such a height above the Earth that no appreciable quantities of surface materials are taken up into the fireball. By the end of 1 min after an air burst, essentially all of the weapon residues in the form of small particles will have risen to such a height that the nuclear radiations no longer reach the ground in significant amounts. Thus, gamma radiation outside the 2-psi overpressure zone appears not to be a threat for air bursts. The concern then is for the radiation effects on systems that are near to and outside of the 2-psi overpressure zone of <u>surface bursts</u>.

The fission products constitute a very complex mixture of more than 300 different forms (isotopes) of some 36 elements. The early fallout consists of particles that are contaminated mainly, but not entirely, with fission products. Glasstone indicates that the dose rate from a fixed quantity of the actual mixture decreases with time according to the following approximate rule: for every sevenfold increase in time after the explosion, the dose rate decreases by a factor of 10. For example, if the radiation dose rate at 1 hour (or other unit time) after the explosion is taken as a reference point, then at 7 hours after the explosion the dose rate will have decreased to one-tenth; at 7 X 7 = 49 hours (or roughly 2 days) it will be one-hundredth, etc. This rule indicates that after 1 week (7 days), the dose rate will be about one-tenth of that after 1 day. This dose rate, normalized by the dose rate after 1 hour, decays as shown in Figure 24a. This shows that the time dependence of dose rate decay follows the expression:

$$R(t) = \text{const} \times t^{-1.2}. \tag{5-1}$$

This dose rate decay dependence on time holds out to about 6 months (1.58×10^7 s) after which the decay rate is significantly faster (see Figure 24b). Assuming that the material remains fixed (is not blown around by winds, washed away by rain, or other mechanisms), the accumulated total dose would be the integral over time of the dose rate. This is represented by Glasstone and Dolan (1977) as shown in Figure 25. (Approximate calculations for many of the nuclear bomb effects can be made using a circular slide rule available as part of the book by Glasstone and Dolan.) The dose rate and total dose calculations made by these approximations presumably refer to the total number of disintegrations that occur. This does not address the partition of the radiation into neutrons and gamma ray energies. The residual gamma radiation

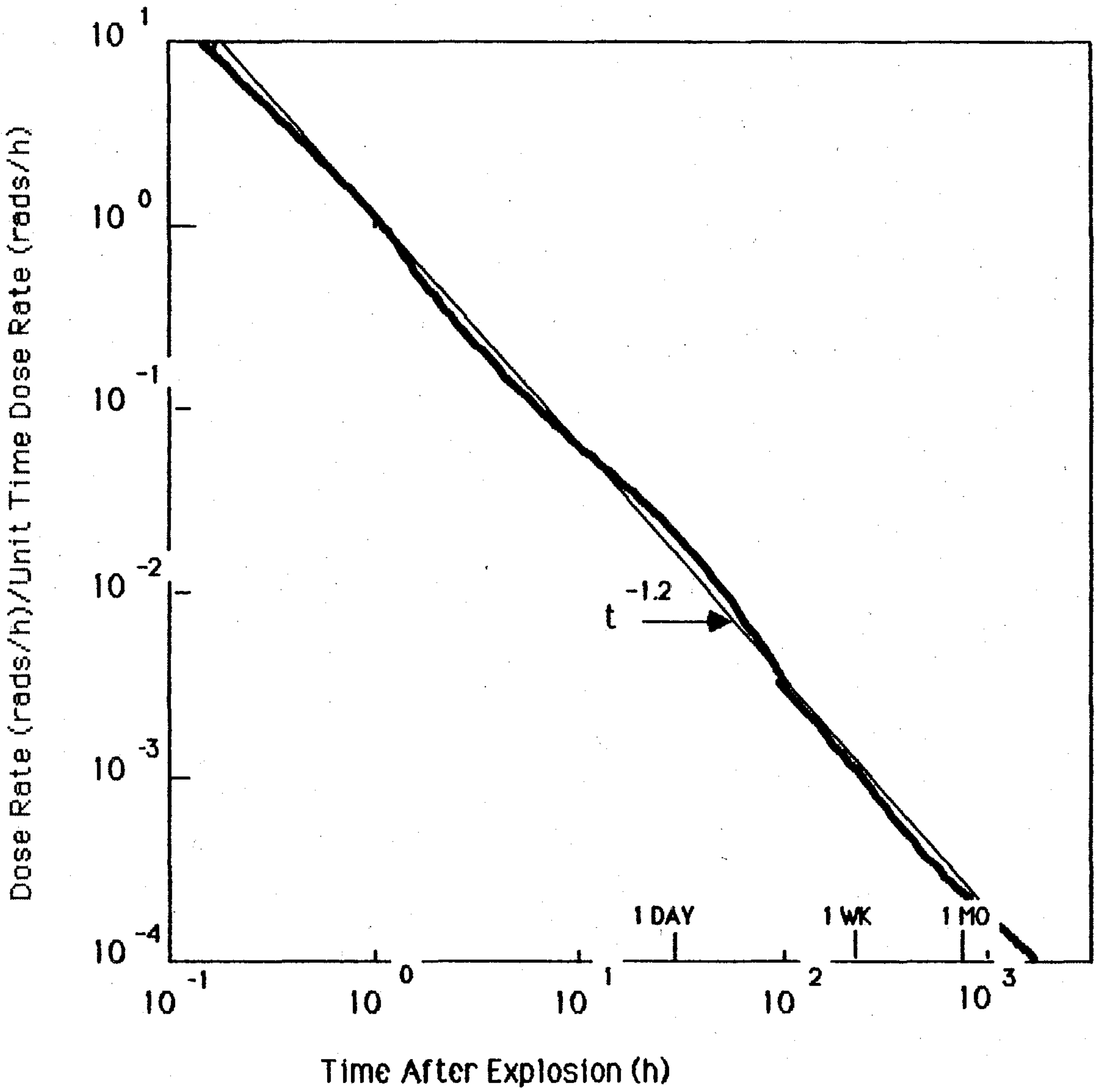

Figure 24a. Dependence of dose rate from early fallout upon time after explosion (after Glasstone and Dolan, 1977).

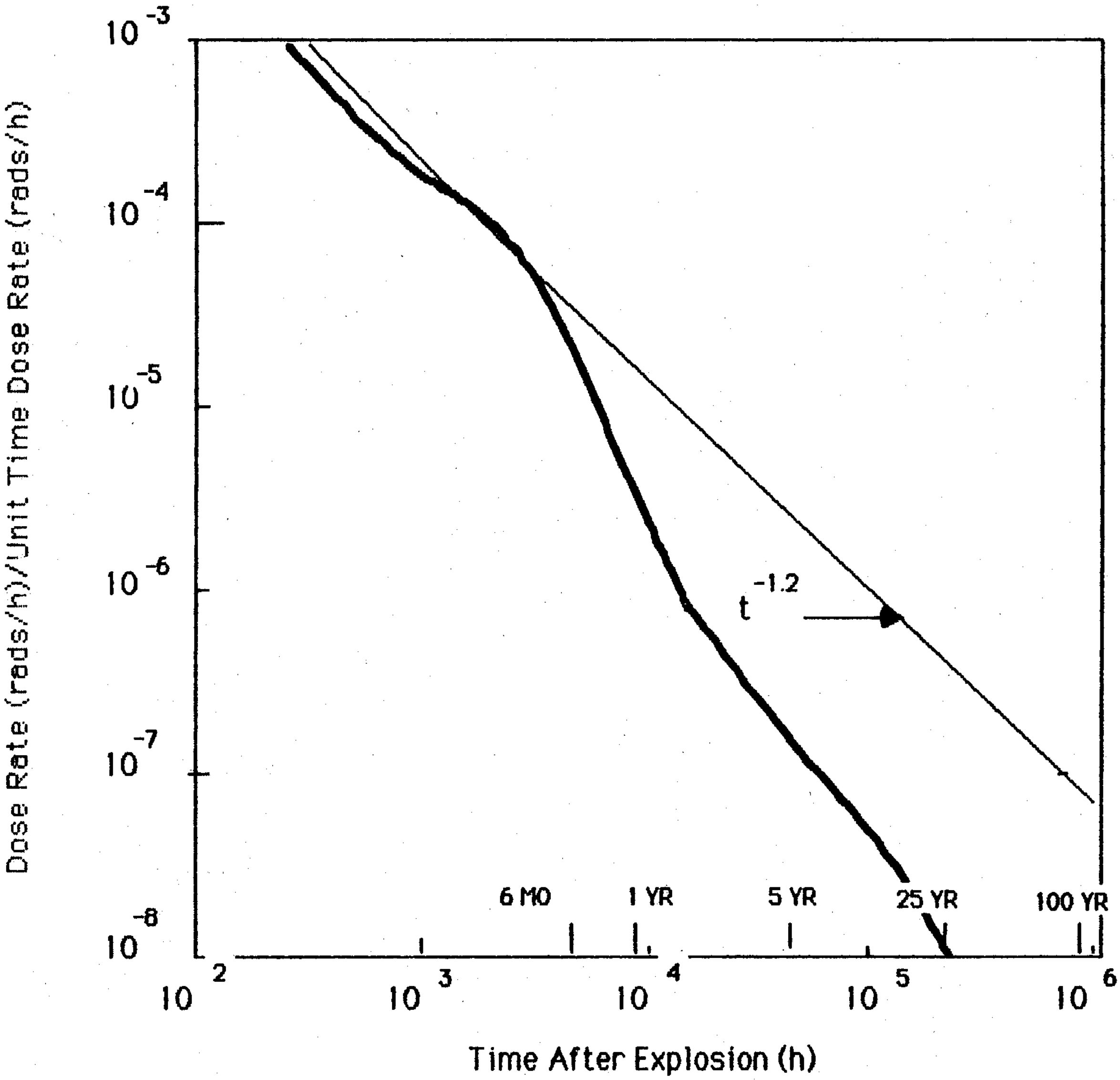

Figure 24b. Dependence of dose rate from early fallout upon time after explosion - continued (after Glasstone and Dolan, 1977).

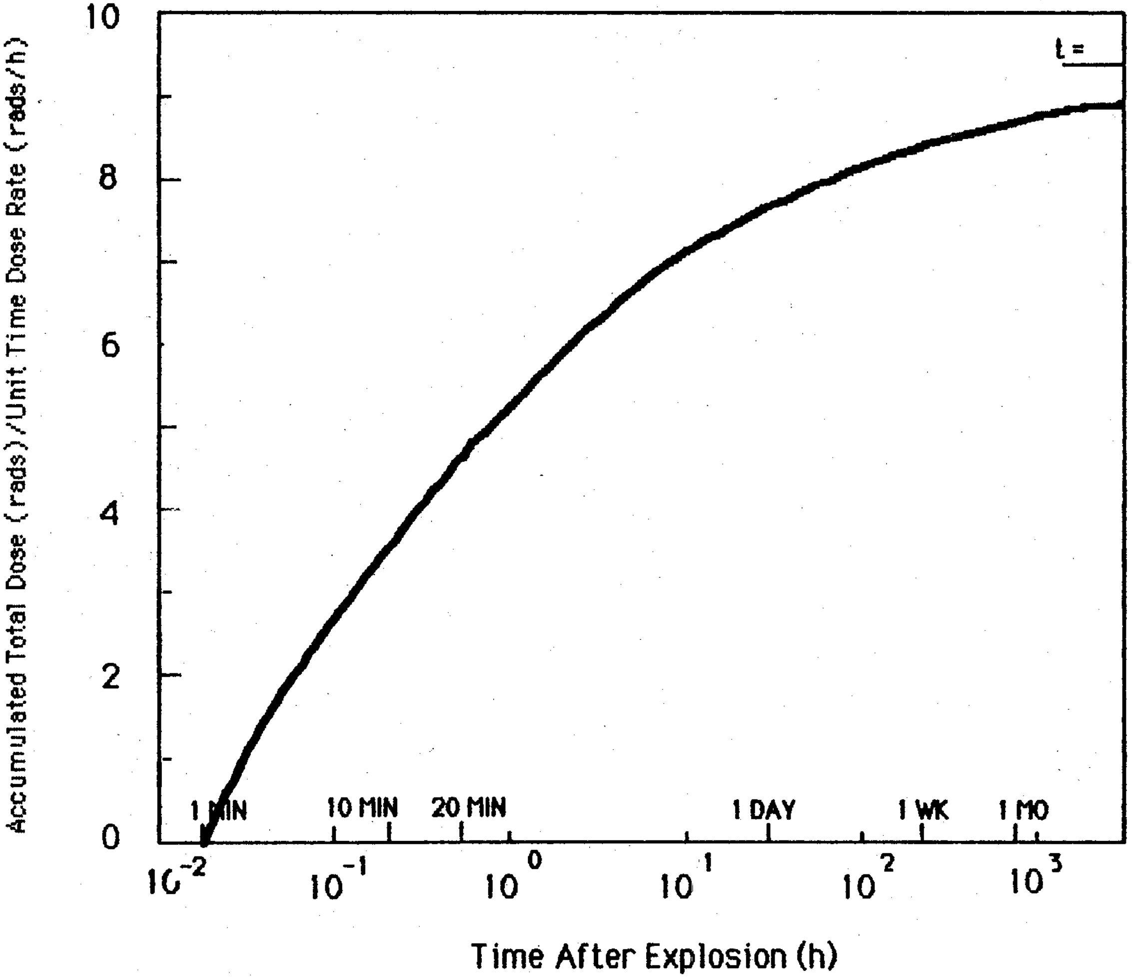

Figure 25. Curve for calculating accumulated total dose from early fallout at various times after explosion.

is of primary concern since shielding will be required in most fallout situations to reduce the radiation dose to an acceptable level.

5.4 Protection Factors from Gamma Radiation

Calculation of the attenuation of the gamma radiation from fallout is different and in some ways more complicated than for the initial radiations. The latter come from the explosion point, but the residual radiations arise from fallout particles that are widely distributed on the ground, on roofs, trees, etc. The complication stems from the fact that the effectiveness of a given thickness of material is influenced by the fallout distribution (or geometry) and hence depends on the degree of contamination and its location relative to the position where protection is desired.

The formalism for exploring the impact of the geometrical distributions of gamma radiation sources above a buried fiber optic cable has been explored by Nesenbergs as part of this study.

Estimates of the attenuation of residual gamma radiation in various structures are presented in Glasstone and Dolan (1977) and reproduced here as Table 8. These results are based partly on calculations and partly on measurements with simulated fallout. The reciprocal of the dose transmission factor in this table has been added and it is called the protection factor.

5.5 Some Estimates of Environment

Glasstone and Dolan (1977) indicate that it is possible to estimate a dose rate over contaminated surfaces (and by inference below a contaminated surface based on the above protection factors). He assumes that an area is uniformly contaminated with any radioactive material of known activity (in gamma-megacuries = 3.7×10^{16} photons per second) at a given time and that the material is uniformly distributed over an area of 1 square mile. The results of the calculations are shown in Figure 26. The gamma-ray activity from the fission products will vary depending upon the nature of the fissionable material; however, it has been calculated that a reasonable average would be about 530 gamma-megacuries per kiloton (kt) fission yield at 1 hour after the explosion. The average photon energy also depends on the fissionable material, but at 1 hour after the explosion an average energy of about 0.7 MeV is a reasonable approximation. Thus, if all the fission products from a 1-kt fission yield were spread uniformly over a smooth plane 1 square mile in area,

Table 8. Fallout Gamma-Ray Dose Transmission Factors for Various Structures (Glasstone and Dolan, 1977)

Structure	Dose Transmission Factor	Protection Factor
Three feet underground	0.0002	5,000
Frame house	0.3-0.6	3.3-1.7
Basement	0.05-0.1	20-10
Multistory building (apartment type):		
Upper stories	0.01	100
Lower stories	0.1	10
Concrete blockhouse shelter:		
9-in walls	0.007-0.09	143-11
12-in walls	0.001-0.03	1,000-33
24-in walls	0.0001-0.002	10,000-500
Shelter, partly above grade:		
With 2 ft earth cover	0.005-0.02	200-50
With 3 ft earth cover	0.001-0.005	1,000-200

the radiation dose received at a point 3 feet (1 m) above the plane can be estimated from Figure 26 as 5.3 X 530 i.e., approximately 2,800 rads/h. Other radiation activity may increase this number by 100 rads/h giving a total of 2,900 rads/h (or 0.8 rads/s for each kiloton yield). If the same residue were spread uniformly over a smooth surface of A square miles in area, the 1-h dose rate would be 2,900/A rads/h; consequently, the product of the 1-h dose rate and the area in square miles would be equal to 2,900 in units of $(\text{rads/h})(\text{mi})^2/(\text{kt fission yield})$. Measurements after several nuclear tests have given a wide range of values, but after all factors have been considered, the "observed" number is 1,300 $(\text{rads/h})(\text{mi})^2/\text{kt}$ fission. When terrain factors are taken into consideration, the smooth plane approximation would be 1,900 $(\text{rads/h})(\text{mi})^2/\text{kt}$ fission. This would indicate that about 60 percent of the total gamma-ray activity of the weapon residues is deposited in the early fallout from a land surface burst.

The factor of 2,900/A rads/h per kiloton corresponds to about 800/A rads/s per megaton. From Section 2, Table 5, the area covered by the 2-psi overpressure for a 1-megaton yield is 180 $(\text{km})^2$ or 65 $(\text{mi})^2$. The dose rate at this boundary would be 800/65 = 12.3 rads/s for this megaton yield. This intuitive derivation based on the above approximations may not be precisely correct but it does agree fairly closely with the assumed maximum dose rate (15.6 rads/s) used by Warren et al. (1985) in the FT3C Lightwave evaluation report.

Assuming that the fallout at the 2 psi boundary and beyond arrives and settles fairly rapidly (minutes), a maximum dose rate will occur at some time, t_o, after the detonation. If the fallout products are not disturbed by wind, rain, etc., the dose rate will then decay in accordance with the $t^{-1.2}$ relationship (5-1) mentioned above. A dose rate versus time plot is shown in Figure 27. The dose rate will reach a maximum at time t_o as shown on this plot. This has been described mathematically (Warren et al., 1985) in the following way:

$$\dot{\gamma}(t) = \begin{cases} 0 & t < t_o \\ \dot{\gamma}_{max}\ (t_o/t)^{1/2} & t_o \le t \le 1.58 \times 10^7 \end{cases} \qquad (5\text{-}2)$$

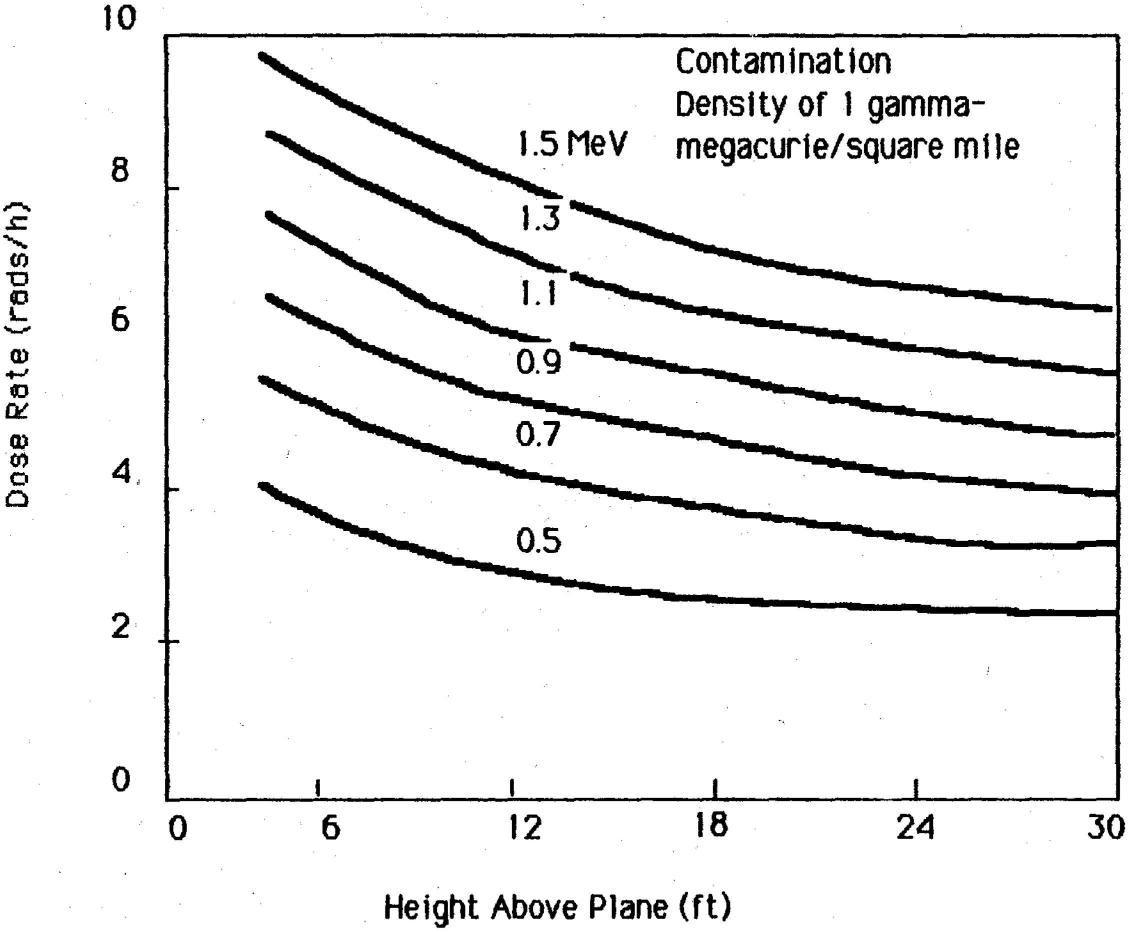

Figure 26. Dose rates above an ideal plane from gamma rays of various energies.

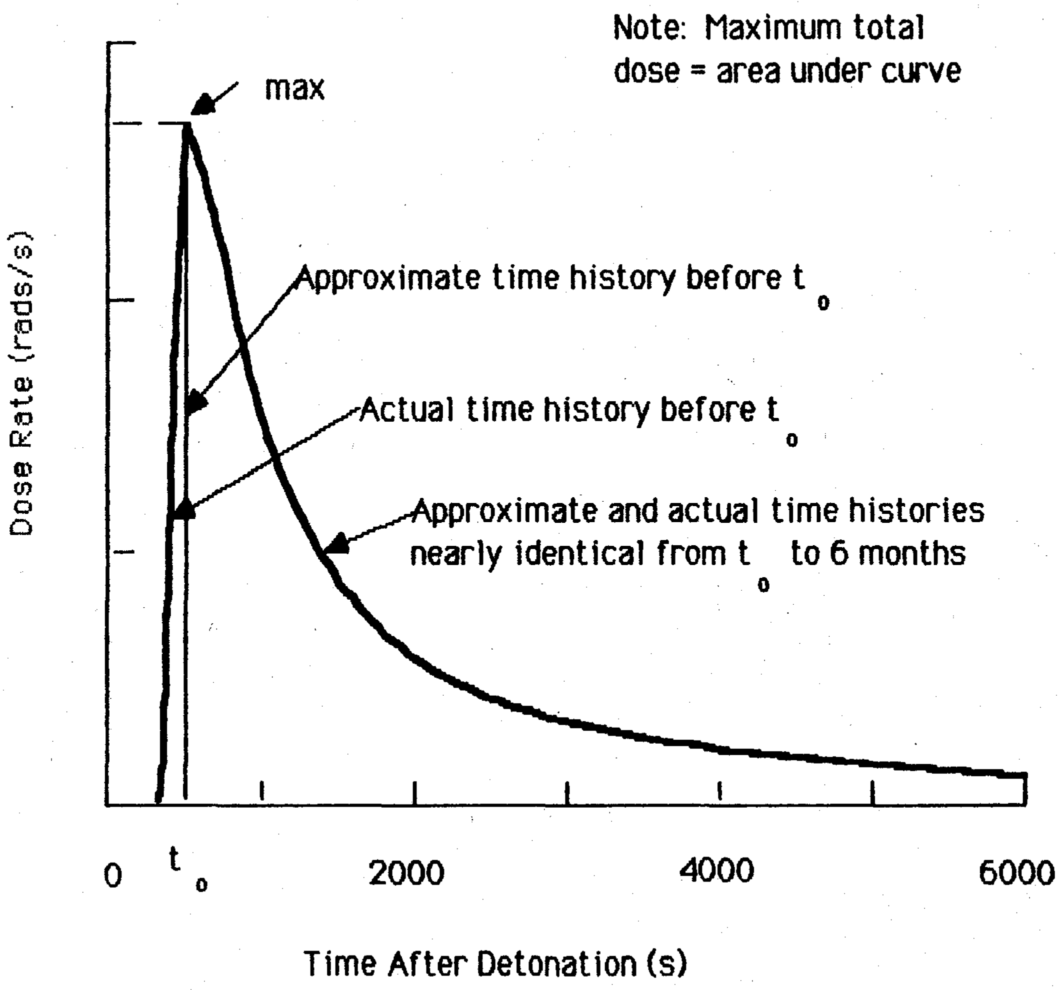

Figure 27. Typical free-field nuclear fallout radiation environment (after Warren et al., 1985).

where t = time after detonation in seconds

t_o = time in seconds when peak dose rate occurs

$\dot{\gamma}_{max}$ = peak dose rate, rads/s.

Let $t_o = 500$ s.

Then $$\dot{\gamma}(t) = 1733\ \dot{\gamma}_{max} t^{-1.2} . \qquad (5\text{-}3)$$

Total dose of the fallout radiation is the area under the curve $\gamma(t)$. Thus:

> integrating (5-3) over the range $t = 500$ to $t = 1.58 \times 10^7$ s (6 months) gives a total radiation:

$$\gamma = 2185\ \dot{\gamma}_{max}. \qquad (5\text{-}4)$$

The authors of the AT&T report indicate that the additional radiation after the 6-month time period may add about 2 percent to the total radiation accumulated during the first 6 months. The dose rate during this interval would be small and can probably be neglected since fibers to be used in this environment would have a significant recovery rate. For engineering purposes, then, the total dose to be expected from the 12.3 rad/s dose rate estimated above is:

$$\text{Total dose} = 2185\ (12.3) = 26{,}875 \text{ rads} \qquad (5\text{-}5)$$

For purposes of the multitier specification, a total dose of 30,000 rads was chosen.

5.6 System Degradation

Radiation exposure affects the transmission system in several ways. Gamma radiation produces induced transmission loss in the fiber waveguides. Section 4 of this report has dealt with this. There is extensive research literature on these effects but little quantitative characterization of commercially available fiber. Test results on commercially manufactured radiation hardened fiber is just becoming available at this writing. Radiation also affects the operation of the electronic components of the system. In the case of photodiodes, radiation interferes with the photodiode's photogeneration of electron-hole pairs. MOS and bipolar devices are also susceptible to radiation.

System assessment was performed on the FT3C Lightwave system (Warren, 1985) by assessing the vulnerability of each individual component. This approach was considered proper since the regenerator sections are arranged in tandem, making the sections mutually dependent on one another. If a critical component of one section fails, the system fails. The assessment process steps included identifying the major elements and components of the system susceptible to radiation, defining the radiation environment that the system would encounter, and conducting radiation tests for fiber darkening/recovery, photodiode susceptibility, and electronic device susceptibility.

System vulnerability was equated with the vulnerability of regenerator sections that are minimally shielded and exposed to the strongest incident radiation, operating at the lowest received signal power. If the electronic devices survive, the system degradation in terms of BER depends on operating wavelength, fiber type, bridge crossing length, and specified free-field radiation environment. The conclusion was drawn that if single-mode fibers were installed and operated at 1.3 μm, transmission would be only moderately degraded and would significantly improve after 10 hours for all bridge crossing lengths and free-field radiation environments.

The methodologies used in relating the specific device or subsystem degradation effects in the FT3C system evaluation to the BER performance as a function of time have been incorporated into a computer program (Ingram, 1987) by ITS. This program will allow the assessment of different fiber optic systems having other radiation damage profiles. Thus new fiber waveguides that have been radiation hardened can be considered for those segments of the system where adequate depth of burial is not feasible. The program should be particularly valuable in doing tradeoff studies on specific links that are required to meet specified BER performance criteria. Much more detailed descriptions of design and installation practices required to achieve the several levels of hardening proposed in the multitier specification are given in the companion report by David Peach (1987).

6. FUTURE FIBER OPTIC SYSTEMS

Commercial fiber optic, long-haul systems being installed today use single-mode fiber. The systems are designed to operate in the 1.3 μm window. The driver/receiver electronics operate at 417 or 565 Mb/s. One fiber is used to transmit and one is used to receive. A full duplex system uses a fiber pair.

One classification of systems is shown in Figure 28 (Keiser et al., 1985). Note that generations one and two utilize multimode fibers in the first and second windows, respectively. The commercial systems mentioned above utilize the second window and multifrequency lasers (typically about 2 to 4 nm spectral width). The fourth generation systems indicated here could be achieved using the multifrequency lasers and dispersion shifted fibers as described below.

6.1 Next Generation Systems

Several options exist for next-generation systems. Regenerator separation distances for the current systems is generally about 30 km and is attenuation limited (with a system margin of about 3 dB.) The fiber attenuation coefficient at the 1.3 μm window is about 0.5 to 0.4 dB/km. These same fibers have an attenuation coefficient at 1.5 μm of about 0.2 dB/km. Next-generation (fourth-generation) systems will utilize this window and will permit transmission of bit rates of 1.6 to 1.7 Gb/s over the same repeater distances. This will permit the multiplexing of four of the present operational levels onto one fiber. Only the final multiplexer and the demultiplexer plus the electro-optic modulator circuitry are required to operate at the gigabit rate. The remaining electronics can utilize the same hardware as that being installed in the current system. Another option for increasing the throughput of each fiber pair is that of wavelength-division-multiplexing (WDM). WDM can use separate windows of the fiber for transmission at different wavelengths or, ultimately, several channels can be multiplexed in one window. The rate per channel would be equivalent to the present third-generation systems. Such systems are not indicated on the chart. Recent announcements (Sanferrare, 1987) indicate that gigabit systems are about to be deployed.

6.1.1 Long-Wavelength Windows

The 1.3 μm window was selected for commercial development because of the zero dispersion window for silica based fibers. This zero dispersion occurs only at a very narrow band at 1.3 μm. It was mentioned in Section 4.2 above that the wavelength at which this crossover (change from negative to positive dispersion) occurs can be shifted by the use of suitable dopants.

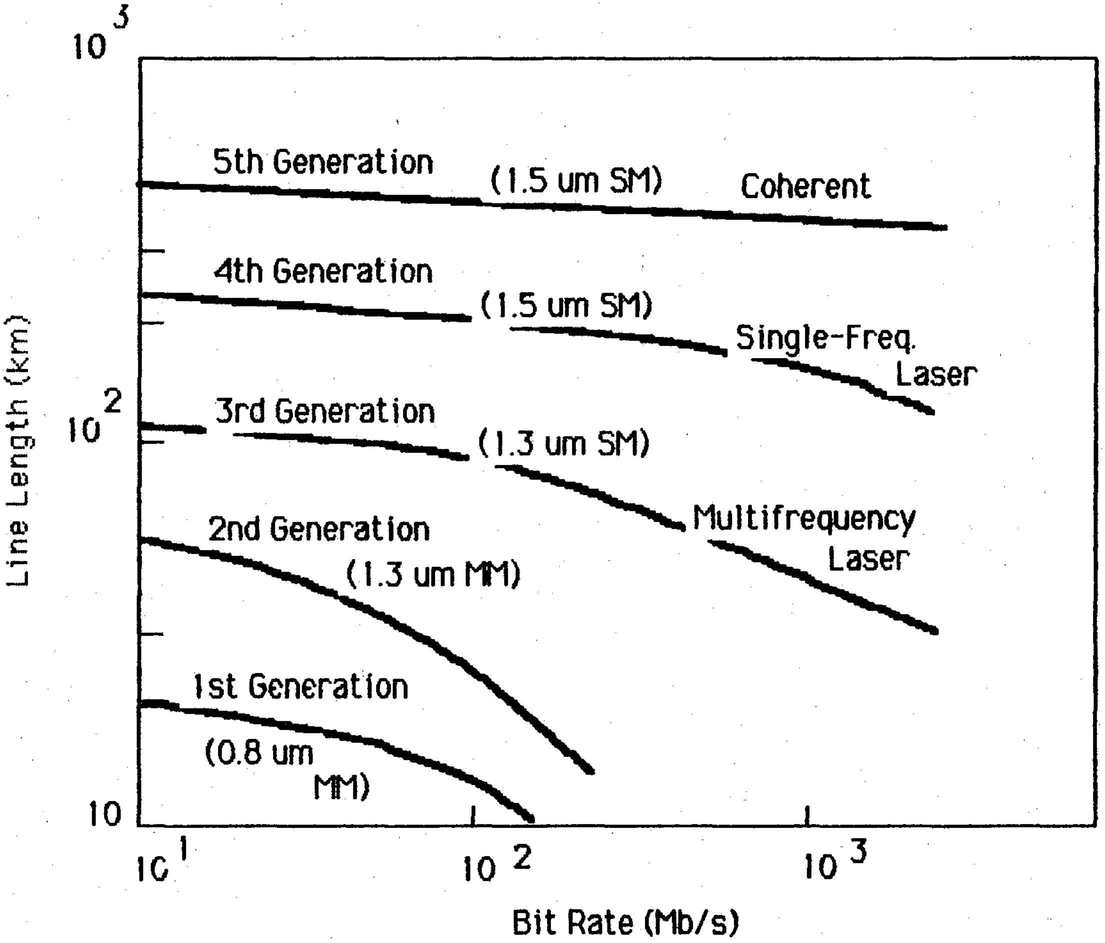

Figure 28. Five generations of fiber optic systems (after Keiser, 1985).

When these fibers are used at the 1.5 μm window, material dispersion becomes the limiting factor for the multifrequency laser driver. Two approaches are being pursued to eliminate this dispersion limit. One is to develop dispersion-shifted fibers that are optimized for least dispersion at the operating wavelength in this window. This dispersion-shifted fiber permits the use of multifrequency lasers as in the third-generation systems now in operation. The second is to develop laser sources with very narrow spectral widths (< 10 kHz) as indicated in the fourth-generation systems of Figure 29. (The latter narrow-bandwidth lasers are also required for fifth-generation coherent detection systems mentioned below.) In addition to the shifting of the zero dispersion, fiber waveguides can be dispersion flattened so that the material dispersion (picoseconds/nm-km) is low over a broad spectrum from 1.3 to 1.5 μm. The significance of shifting the low dispersion region or developing a narrow spectral width source is that gigabit bandwidths can be achieved over the distances already established for the separation of the regenerator stations.

6.1.2 Wavelength-Division Multiplexing

Commercial fiber systems are based on long-haul cables consisting of an average of about 18 fiber pairs. Devices are being developed to allow full duplex operation on each fiber. This is an optical directional coupler. If these devices do not introduce too much insertion loss, the capacity of each long-haul cable could be doubled by this technique. Another approach to extending the capacity of each fiber is to use wavelength-division-multiplexing (WDM). Separate bands, in the same or different windows, may be used to transmit information. The different channels can be separated at the receiver by optical filtering techniques.

6.1.3 Direct Versus Coherent Detection

Current fiber optic systems are based on direct detection principles, that is the detection of the presence or absence of an optical pulse. This requires about 20 photons for a high probability of detection. The system sensitivity is based on the signal to noise ratio (SNR) at the detector of the receiver. This SNR is a characteristic of the receiver. Most fiber optic systems are designed to provide bit error ratios (BERs) less than 10^{-9}.

Fifth-generation fiber optic systems that will use coherent detection are being developed. The laser source is modulated via frequency or phase modulation in a manner similar to that used in radio systems. Heterodyne detection at the receiver allows much greater sensitivity (~ 20 dB) for a given BER (Kobrinski, 1985). This allows much greater distances between regenerator stations, or much higher capacity for the same regenerator separation. For example, laboratory experiments (Li, 1987) have shown that 8 Gb/s rates over a distance of 68 km are possible. Thus in fifth-generation upgrades to commercial systems, it seems reasonable to multiplex four of the 1.7-Gb/s bit streams together and transmit 8 Gb/s over each fiber in existing installations. Perhaps a more realistic use of these systems would be to develop very long distance applications such as undersea cable with regenerator stations separated by 400 km. This would allow the placement of such stations on land for all currently required routes.

6.2 Coherent Systems

Coherent fiber optic communication is certainly a challenging technology that still requires more research and investigation. Data from experimental systems indicate that theoretical system performances can be achieved. As the trend toward higher data rates continues, coherent fiber optic techniques are the only methods that can fully exploit the long-distance and wide-bandwidth potential of fiber optic systems.

The technology for the fifth-generation systems is somewhat more advanced than that required for the current direct detection systems. A very narrow spectral bandwidth source is required. The fiber waveguides should have polarization maintaining properties. Much of the electronics required will be adaptable from existing radio communications technology.

Coherent fiber optic transmission techniques are similar to those used in microwave systems. At the transmitter, the information is placed on the carrier wave by altering the source's amplitude, frequency, or phase. The signal is then carried over the medium. At the receiver, a local oscillator locks with the incoming transmitted signal's phase. Both signals are mixed in a nonlinear device, filtered, and the information is then recovered.

Figure 29 shows a typical coherent fiber optic communication system. The highly stable laser source emits a very narrow band of optical frequencies. The optical wave of the laser source is temporally and spatially coherent.

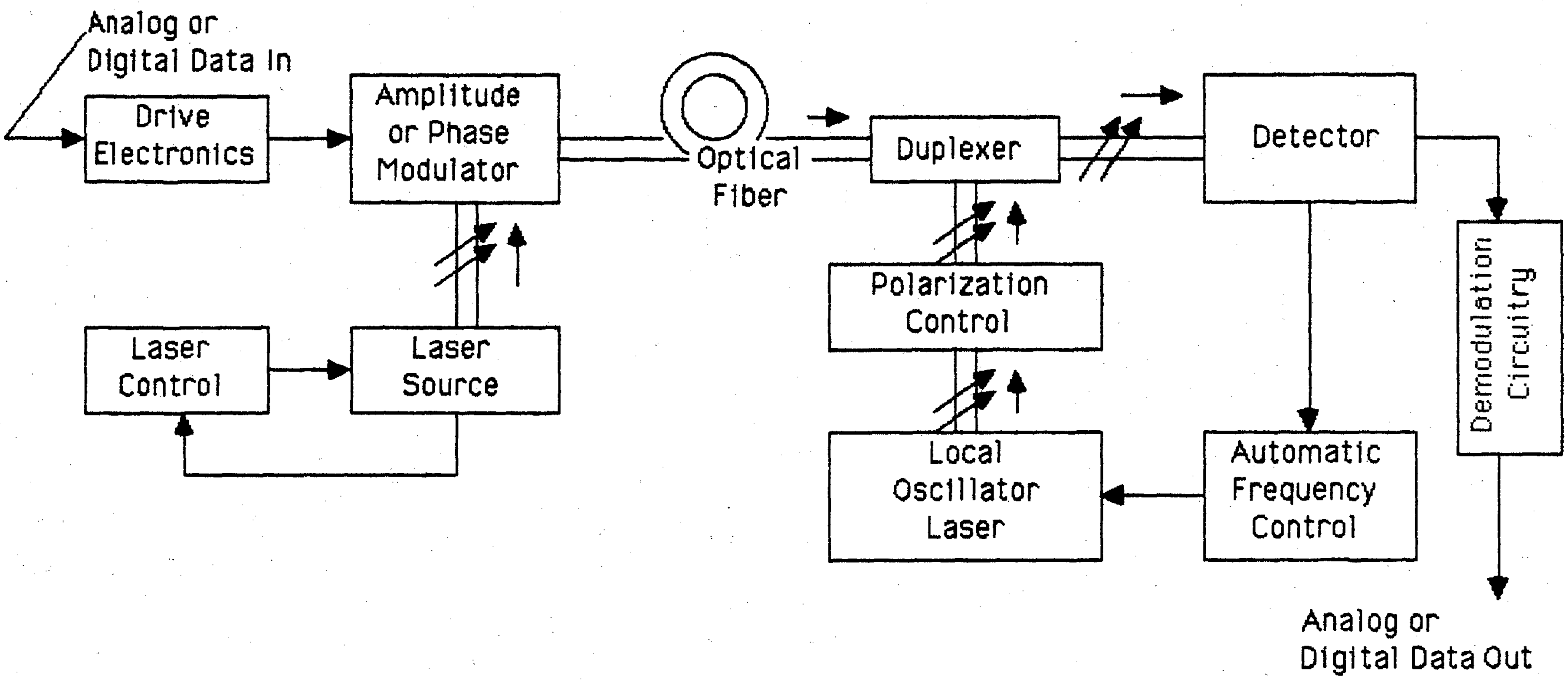

Figure 29. A coherent fiber optic communication system.

This means that at a given time at a given point in space, the laser's field will be in phase. By using the coherence properties of the laser's optical carrier wave, information may be placed on the carrier wave by modulating its amplitude, frequency, or phase. This is called coherent modulation. The optical signal is then transmitted along single-mode optical fiber.

At the receiver, the incoming carrier wave is optically mixed with a local oscillator wave emitted by a highly stable coherent laser. The nonlinear, square-law detector detects the mixed optical signals as a single optical wave, and converts it into an electrical signal. The resultant output electrical current contains the square, sum, and difference frequencies of the transmitted and local oscillator signals. Since the difference frequency is the lowest and contains the desired information, it is more easily processed than the square and sum frequencies that are filtered out. If the local oscillator and transmitted signal frequencies are equal, then the difference frequency will be zero and the information will be recovered at baseband. This process is called homodyne detection. However, if the local oscillator and transmitted signal frequencies are different, then the information must be recovered from the difference frequency (or intermediate frequency) electrically. This process is called heterodyne detection.

A coherent fiber optic system does not necessarily imply that coherent demodulation is performed in the receiver. Rather, the term "coherent" as applied to fiber optic systems generally refers to any fiber optic system that uses a laser source with a spectral linewidth considerably narrower than the linewidth of the laser sources used in traditional intensity-modulated/direct-detection fiber optic systems.

6.2.1 Operational Advantages of Coherent Systems

In addition to the advantages that fiber optic communications have over wire or microwave communications such as increased security, wide bandwidth, lightweight, immunity to electromagnetic interference, and freedom from electromagnetic pulse effects, coherent fiber optic communication systems have additional advantages over intensity-modulated/direct-detection fiber optic systems. Probably the most written-about advantage is increased receiver sensitivity. Since the detector sees the combined local oscillator and transmitted signal waves as a single wave, the signal detected at the receiver may be greatly increased by raising the local oscillator power. This means that only a very small amount of transmitted signal power has to reach the receiver in order for the information to be retrieved. If the local oscillator power is much greater than the transmitted signal power, shot-noise limited detection will be achieved.

In a coherent fiber optic communication system, the receiver sensitivity may increase by 10 to 19 dB over an intensity-modulated, direct-detection (IM/DD) system depending upon the modulation format. In theory, any modulation format used in radio can be used in coherent fiber optic systems. As shown in Figure 30, a 10 to 25 dB improvement in receiver sensitivity is expected when amplitude-shift-keying (ASK) modulation/ demodulation with heterodyne detection is used. The best performance is predicted for phase-shift-keying (PSK) modulation/demodulation with homodyne detection. The expected receiver sensitivity is 19 to 34 dB better than for an IM/DD system. Figure 31 shows the minimum detectable power required to achieve a BER of 10^{-9} versus the data rate for various coherent fiber optic systems.

As a result of the potential improvement in receiver sensitivity, the transmission distance between regenerators can be significantly increased. This is especially true at long wavelengths (1550 nm) where fiber loss is lowest.

Another potential advantage is that optical amplifiers may be easier to implement in coherent fiber optic systems. A repeater could consist of a simple optical amplifier such as a laser diode with optical fiber pigtails.

For short-distance links, the increased receiver sensitivity can be used to increase the dynamic range of the system. A greater margin of loss can be allowed in a given link.

Another advantage of coherent fiber optic systems is higher channel capacity. Due to the very narrow optical bandwidth of the laser sources and the wide bandwidth of the optical fiber itself, more channels could be transmitted on carriers that are closely spaced in frequency. A thousand-fold increase in channel capacity has been predicted when optical frequency-division-multiplexing (FDM) is used.

6.3 Coherent System Implementation

Coherent fiber optic systems are more expensive and complex to design and build than IM/DD systems. Most of the additional cost and complexity is due to the components used in the systems. For example, the lasers used as the transmitter source and the local oscillator must be spectrally pure. Not only

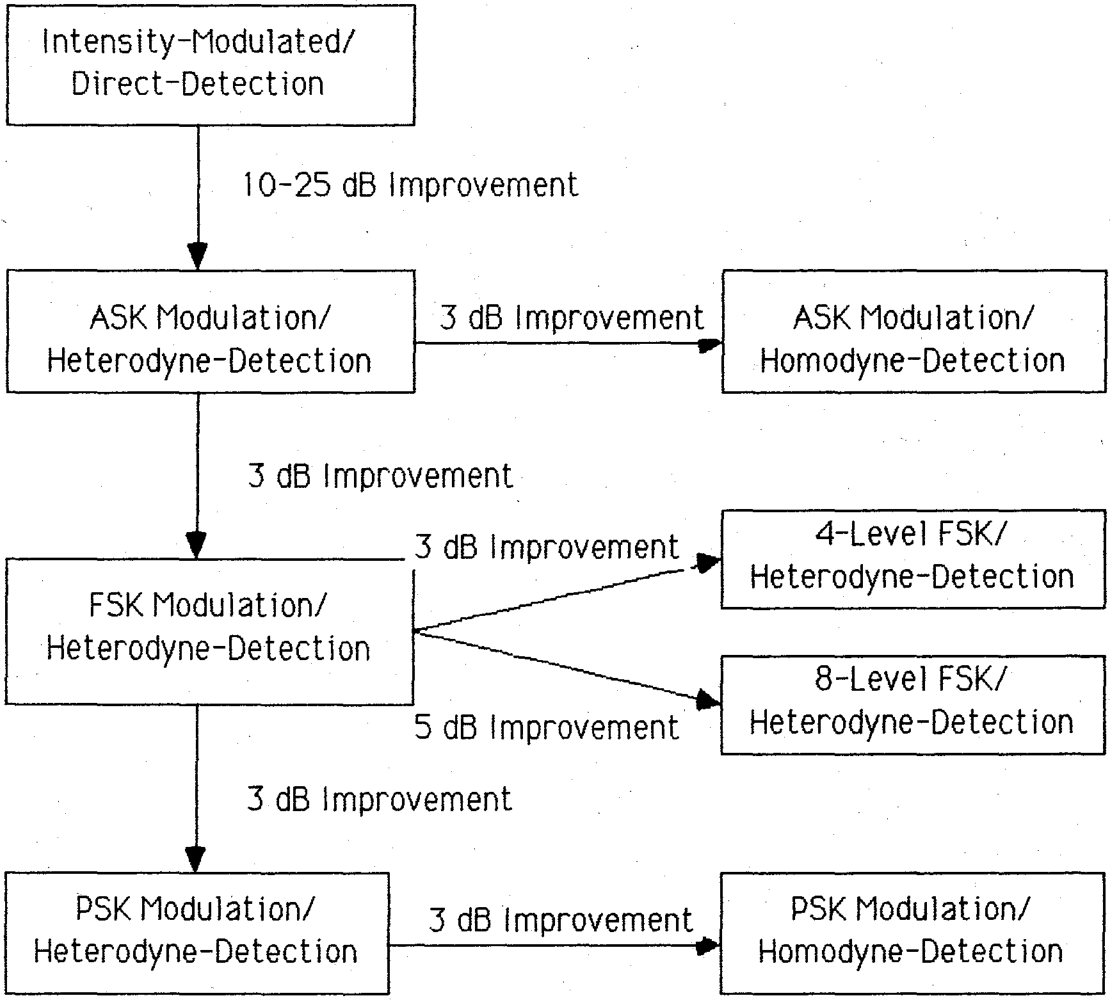

Figure 30. Improvements in receiver sensitivity for various coherent modulation/detection schemes.

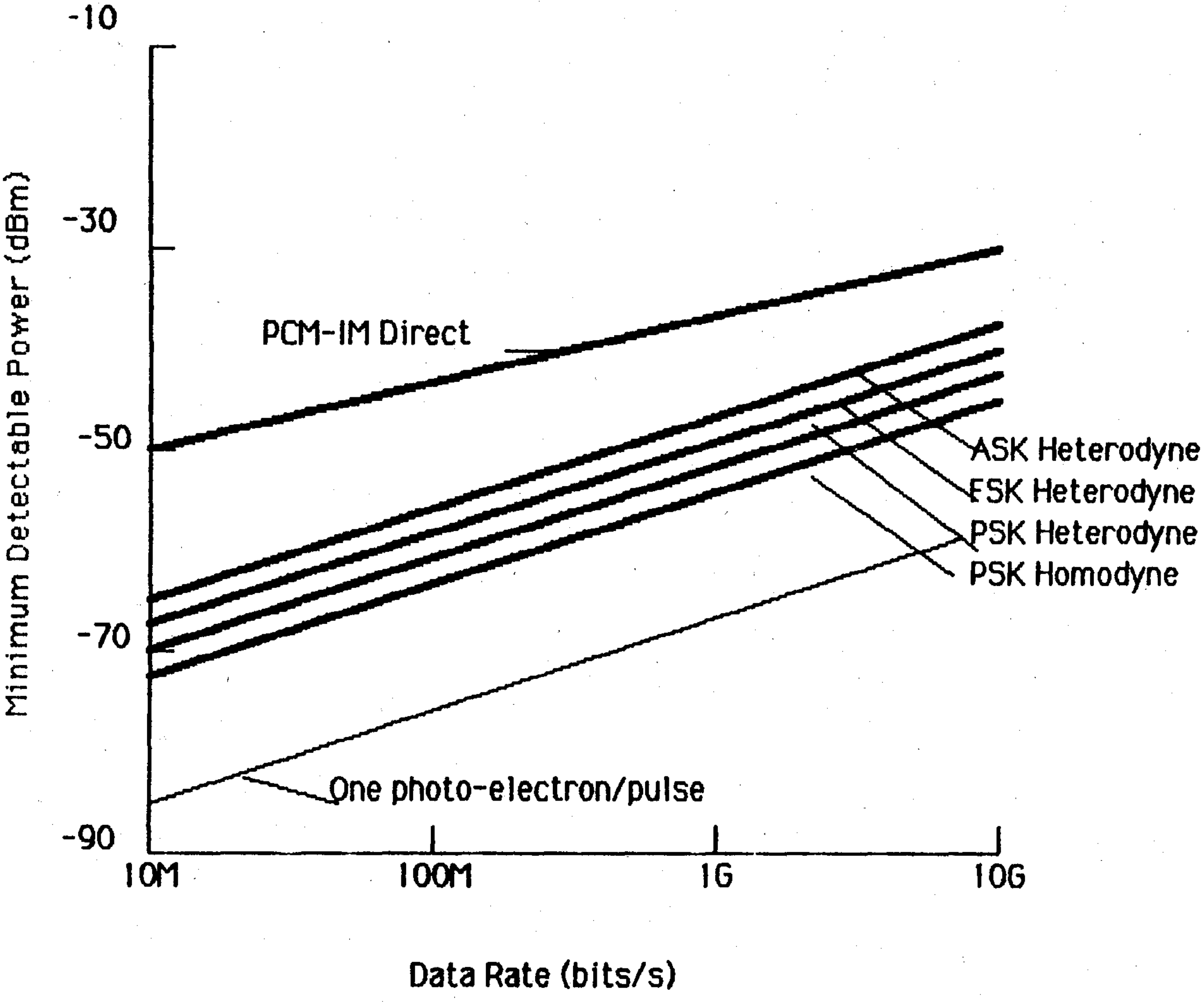

Figure 31. Minimum detectable power required to achieve a BER of 10^{-9} versus data rate.

must the lasers emit optical power over an extremely narrow band of optical frequencies, they must maintain their optical frequency stability for long periods of time and over a wide range of temperature. At the receiver, the local oscillator must lock with the incoming transmitted signal. The polarizations of the two wave fronts must match very closely in order for the system to work properly. Polarization-matching of the two waves can be difficult. The detector itself must have a wide bandwidth and high quantum efficiency for converting the low levels of received light into an electrical signal. In addition, practical techniques for performing ASK, FSK, and PSK modulation need to be developed.

The transmitter and local oscillator sources used in coherent fiber optic communication systems must have a high degree of spectral purity and optical frequency stability. A spectrally pure laser emits optical power over a very narrow band of wavelengths. This band of wavelengths is called the spectral linewidth. In IM/DD systems, the laser's emission spectrum contains several frequencies spaced approximately 1 nm apart. Each frequency may have a spectral linewidth of around 0.1 nm. In a coherent fiber optic system, the laser must be forced to emit at a single optical frequency. In addition, the natural linewidth of the laser must be reduced. Phase noise due to spontaneous emissions in the laser cavity may cause the natural linewidth to broaden. This is particularly unsuitable for systems using frequency or phase modulation. Thus, in order to use coherent modulation techniques, the unmodulated laser's optical frequency must remain very stable over long periods and wide temperature ranges while the laser is modulated. In order to achieve an optical frequency stability of 200 kHz for a 1500 nm wavelength laser a fractional stability of 1 in 10^9 is needed.

In order for a coherent fiber optic communication system to work properly, the polarization states of the transmitted and local oscillator signals must be nearly identical. If the signals are not matched, destructive interference will occur due to the different polarization states. Excessive bit errors and receiver fading may result.

There are two approaches to the polarization-matching problem. In the first approach, polarization-matching is achieved by using a polarization-tracking receiver. Standard single-mode fiber is used as the transmission medium.

In the second approach, specially fabricated single-mode fibers such as polarization-maintaining single-mode fibers or absolutely single-polarization single-mode fibers are used as the transmission medium. Polarization-maintaining single-mode fibers preserve the polarization state of the signal as it travels through the fiber. Absolutely single-polarization single-mode fibers force the optical signal to travel in only one polarization state.

6.3.1 Heterodyne/Homodyne Detection

Heterodyne or homodyne detection techniques are used in coherent fiber optic communication systems. The main advantage of heterodyne/homodyne detection is that the receiver amplifier noise and photo-detector dark current noise are effectively eliminated by optically mixing the transmitted signal with a large local oscillator signal. At 1.3 μm and 1.5 μm wavelengths, heterodyne or homodyne detection are the only methods by which shot-noise-limited detection can be achieved.

In heterodyne detection, the optical frequencies of the transmitted and local oscillator signals are different. Figure 32 shows a block diagram of a receiver using heterodyne detection. The local-oscillator optical signal is combined with the incoming optical signal in a duplexer and detected. The resultant electrical output signal contains the square, sum, and difference or intermediate frequency (IF) between the two signals. Since the IF is lowest and contains the desired information, the square and sum frequencies are filtered out. Part of the filter's output signal may be sent back to the local oscillator to stabilize the laser. The rest of the filter's output is demodulated and sent to the decision circuitry.

In heterodyne detection schemes, the carrier-to-noise density increases as the local oscillator power increases. However, a low-noise, front-end amplifier and a high-power local oscillator with minimized AM quantum noise are necessary in order to achieve an optimum carrier-to-noise ratio.

Receiver sensitivity using heterodyne detection is at least 10 to 15 dB better than IM/DD systems. As shown in Table 9, PSK/heterodyne detection is the most sensitive of the heterodyne detection schemes with only 18 photons per bit theoretically required to achieve a BER better than 10^{-9}.

Another advantage of heterodyne detection techniques over IM/DD techniques is that a better BER can be achieved for a given signal-to-noise ratio.

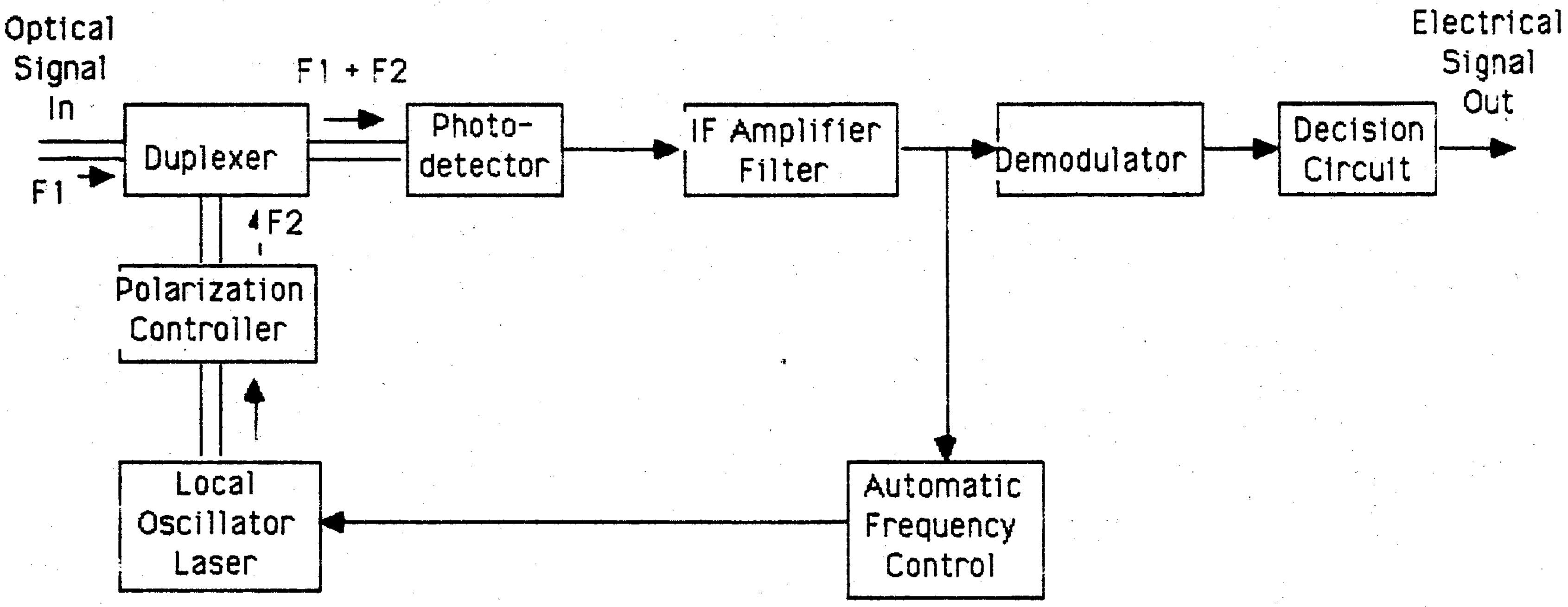

Figure 32. Optical heterodyne receiver.

Table 9. Minimum Detectable Peak Power Level in Photons per Bit for a 10^{-9} Error Rate

Receiver / Modulation	Heterodyne	Homodyne	Direct Detection
Intensity Modulation	----	----	21
Amplitude-Shift-Keying	72	36	----
Frequency-Shift-Keying	36	----	----
Phase-Shift-Keying	18	9	----

In homodyne detection, the optical frequencies of the transmitted and local oscillator signals are the same. Figure 33 shows a block diagram of a receiver using homodyne detection. The local oscillator optical signal is combined with the incoming optical signal in a duplexer and detected. The resultant IF is zero, and the electrical signal is recovered at baseband. The electrical output of the baseband amplifier filter provides phase and frequency control of the local oscillator laser.

Receiver sensitivity using homodyne detection is 3 dB better than in heterodyne detection for the same modulation format. As shown in Table 9, PSK/homodyne detection is the most sensitive detection technique with only nine photons theoretically required to achieve a BER better than 10^{-9}. Homodyne detection also has twice the data rate capability of a heterodyne detection receiver for the same receiver bandwidth.

However, there have been indications that the linewidth requirements for the laser source used in homodyne systems are much more stringent than for laser sources used in heterodyne systems.

In addition, actual synchronization of the local oscillator wave with the transmitted signal wave is difficult to achieve, particularly at low received-signal power levels.

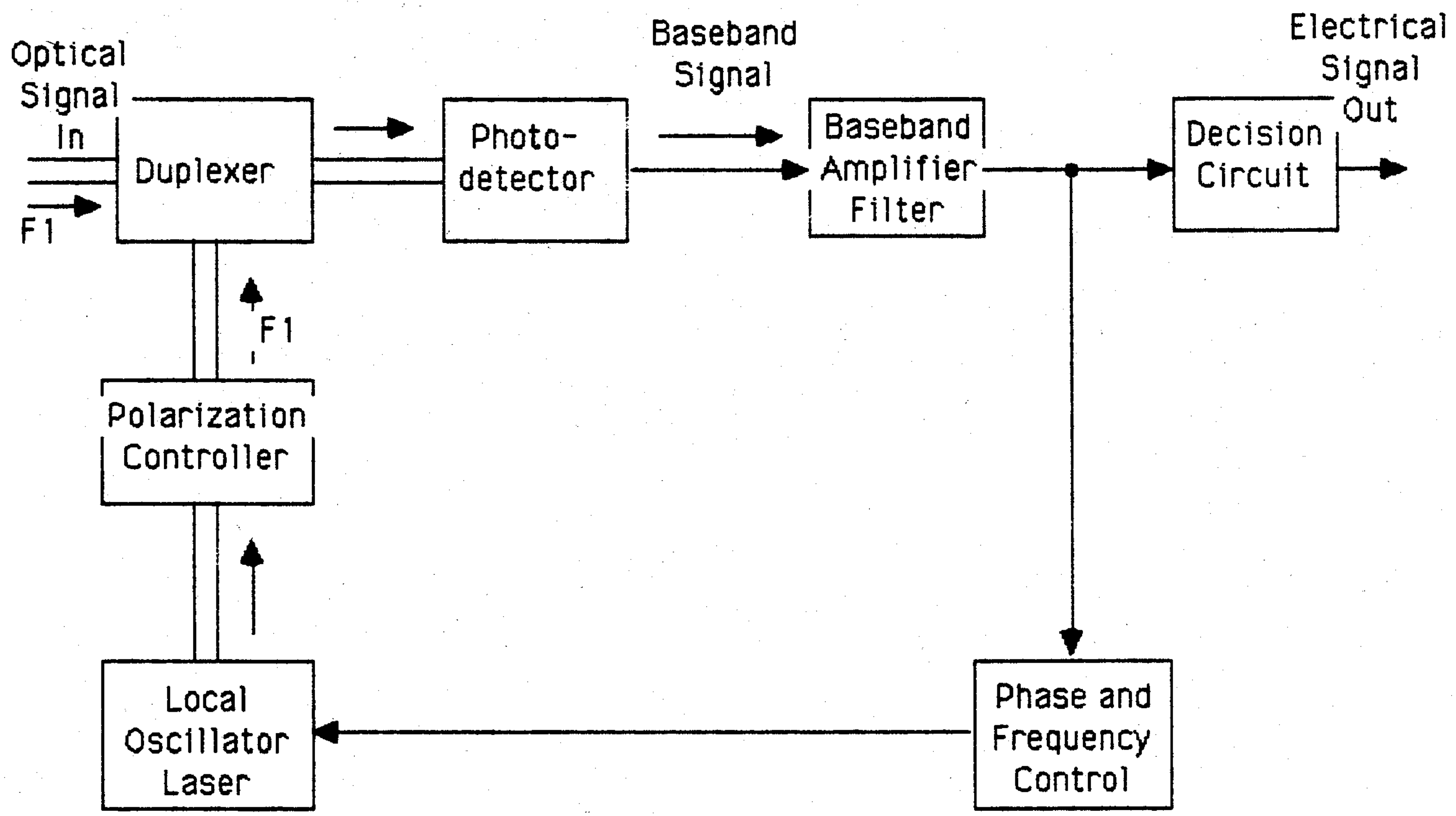

Figure 33. Optical homodyne receiver.

6.3.2 Applications

Coherent fiber communication techniques are the only methods that can exploit the potential long-distance and wide-bandwidth capabilities of optical fibers. At the present time, the longest unrepeated transmission distance can be achieved at 1550-nm wavelength. The theoretical bandwidth of single-mode fiber for wavelengths of 1550 nm to 1700 nm is 24,000 GHz.

Very long-distance, underwater, and terrestrial repeaterless links are possible using coherent fiber optic communication systems. The number of repeaters required for a transoceanic link can be substantially reduced by increasing the transmission distance of each section of the link.

Fiber optic cables less than 300 km long can be used in underwater communication links connecting either two on-shore locations or an on-shore location with a platform located at sea. In such a configuration, no repeaters are required--only the terminal equipment at the on-shore or platform locations are needed. To upgrade to a higher data rate system, the terminal equipment is simply changed.

Long-distance ground links 100 to 300 km long are another possible application of coherent fiber optic systems. In a fixed installation or in the field, this additional 15 to 24 dB link margin could be used to extend the lifetime of a fiber optic system. Thus the system would be allowed a wider margin to degrade before failure.

In a nuclear environment using a survivable fiber optic communication system, a coherent fiber optic communication system is expected to recover more quickly than an IM/DD system. After a nuclear burst, the fiber attenuation suddenly increases and then gradually decreases to a point where enough detectable power reaches the photodetector. Since the receiver in a coherent fiber optic system requires less detectable power than an IM/DD system, the coherent fiber optic system will resume operation sooner.

Coherent fiber optic communication systems are also suitable for short-distance applications. By using the wideband potential of this technology, city-wide or local networks that provide CATV, interactive viewphone, or teleconferencing facilities to many users in homes and offices are possible. More channels can be distributed to more customers.

Because of the laser launch powers and receiver sensitivities of coherent fiber optic systems, optical insertion losses of 40 dB or more can be tolerated. This feature can be used to increase the optical switching and branching capabilities of local area networks.

Coherent fiber optic techniques make possible true optical frequency division multiplexing (FDM). Large numbers of channels can be frequency-multiplexed over a single-mode fiber. A possible military application is an overlay-type system where different kinds of signals are transmitted. Such a system might include a 20 Mb/s digital channel for backbone communications, a video channel, and a 200 Mb/s digital channel for the computers in a local-area network.

A multi-level-security (MLS) communication system is another potential government application that utilizes the optical FDM capability of coherent fiber optic systems. In an MLS system, one band of frequencies would be dedicated to top-secret communications, another band of frequencies to secret communications, and a third band would be used for unclassified communications.

6.4 Long Wavelength Optical Fibers

The ultimate limit of attenuation in optical fibers is set by Rayleigh scattering losses as shown in Figure 9 of this report. This scattering loss decreases as the reciprocal of the 4th power of the wavelength of the light source. Thus, the attenuation limit at 1.5 μm is significantly less than that at 1.3 μm. There is work in progress to develop materials with high transparency at longer wavelengths, namely: 2 to 3 μm. It is conceivable to have ultralow-loss fiber that could increase repeater spacings 100 to 1,000 times what is possible today (Lay, 1986). Assuming that the engineering of such low-loss fiber can be brought to a commercial (competitive) reality, transmission loss in terrestrial systems may no longer be a factor. (Note: Private communication from J. Friebele indicates that these ultralow-loss fibers exhibit similar vulnerability to gamma radiation damage as do the silica-based fibers.)

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The National Communications System (NCS) is responsible for defining reasonable enhancements that could be applied to commercial common carrier (or carriers'-carrier) fiber optic systems that will be leased or owned by government agencies and which may be used for National Security/Emergency Preparedness (NSEP) purposes. This report provides background excerpted from many references used in the development of a multitier specification that identifies five levels of enhancement. (The multitier specification is presented in a separate report.) This report describes the nuclear environment for surface and in-atmosphere bursts outside of the blast region, where buildings and personnel would be expected to survive. In this environment, the vulnerability of optical fiber waveguides to fallout radiation is a primary concern. An assessment of fiber darkening, based on a review of unclassified literature, is presented. For exo-atmospheric nuclear bursts, the fiber optic system is exposed to High Altitude Electromagnetic Pulse (HEMP) radiation. Unclassified levels of these nuclear effects have been obtained from published literature. The characteristics of future generations of optical fiber systems, as described in current literature, are outlined.

Key words: common carrier optical fiber systems; fiber optic systems; gamma radiation darkening; National Security/Emergency Preparedness; nuclear effects

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