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EXECUTIVE SUMMARY

Carbon fibers were produced nearly a century ago in the search for an incandescent lamp filament. During the 1950's and 1960's, experimentation resulted in stronger fibers and the use of their special strength properties in new materials called composites. These materials, which are composed of carbon or graphite fibers (the difference being the temperature of pyrolysis during manufacture) embedded in a resin binder, have opened a wealth of new structural engineering and consumer product opportunities. In the next decade, composites may become as important to the United States economy as the steel and aluminum they replace. No other materials now in prospect offer equivalent advantages.

The potential benefits of composites are manifold. Higher strength, lighter weight military and commercial products portend energy savings and increased safety. Unfortunately, these benefits are not realized without risk. The carbon (or graphite) fibers used in the present generation of composite materials are finer than human hair, extremely good electrical conductors, and virtually indestructable. They are so light that millions are contained in a gram mass. If released into the air, they can easily be transported by winds or currents. In contact with electrical devices, they can create resistive loading, short circuits, and arcing, resulting in stoppages or destruction. A variety of actual incidents can be cited supporting the hazards the fibers pose to electrical equipment. Their health impact is not fully known and requires careful research and analysis before any firm conclusions can be reached. But at current manufactured diameters and lengths, based upon currently available information, they are primarily an irritant to the eyes and skin, like fiberglass, rather than carcinogenic or destructive to lung tissue.

In July 1977, the Director of the Office of Science and Technology Policy was directed by the President to conduct a study of graphite composite materials analyzing the potential problems and providing a plan for possible Federal action.

The study revealed that current uses of carbon/graphite fibers worldwide entail about 700,000 pounds of material. At least six countries are currently producing composites and fabricating them into products. Major uses today are in military and commercial aircraft, with a growing list of consumer products, e.g., skis, fishing rods, golf clubs, etc. The major anticipated use is in automobiles where weight reductions necessary to realize fuel economies can only be achieved by replacing steel and aluminum with composite materials. Worldwide use, by 1990, could reach one billion pounds.

Inadvertent fiber release, during manufacture or by destruction of the resin binder in fire, is the major hazard associated with composites. Major manufacturers are aware of the unique problems associated with these materials and have successfully applied controls to avoid the in-plant problems. With the expected rapid growth in the use of these materials in aircraft and automobiles, however, vehicle accidents followed by fire could become a substantial possible source of fiber release. Further, the uncontrolled incineration of industrial waste and of discarded consumer products could create serious problems.

In some cases, protection might be realized by seclusion of equipment through protective covering or air filtering. New generations of electrical and electronic equipment can be manufactured with added protection at relatively modest cost.

Three courses of action are open to the Federal Government: (1) do nothing at this time, (2) support further investigation of effects and solutions, or (3) impose regulatory restraints on all or parts of the life cycle of composite materials. The study supports further investigation and coordinated action by a number of Federal departments and agencies with existing relevant responsibilities.

Action Plan

Carbon Fibers

I. Introduction

This paper presents a coordinated Federal Government action plan for dealing with the potential problems arising from the increasing use of graphite-fiber-reinforced composite materials in both military and civilian applications. The plan addresses the required dissemination of declassified information and outlines near-term and continuing Government actions to minimize the social and economic consequences of proliferated composite material applications. The plan includes budget, organizational, and scheduling considerations.

II. Agency Actions and Responsibilities

A. Information Dissemination

Several goals must be met by the overall information program, without stimulating unwarranted and undesirable reactions in any part of the public. Government agencies and both operating and producing industries must be aware of the hazards and the need to develop and use protective measures; the technical community must start to work on means to cope with the problem.

The hazardous effects under consideration are insidious and, though hopefully incidents will be rare, they would affect many sectors of society. In order to reduce the likelihood of a serious incident, there must be widely disseminated information about the potential hazards and means to protect against them. While technical means for protection have been devised, they are at the laboratory stage and not yet ready for commercial development. Work is also underway on the development of alternative composite materials which will not present an electrical hazard, but this effort is now in the earliest exploratory stages. To promote further technical alternatives and to develop inexpensive and effective means of protection, the scientific community must be thoroughly informed. All possible information will be declassified by the government.

The DOC, assisted by NASA, DOE, DOS, DOT, and DOD will review and make a selection of elements of Congress, Federal agencies, state and local jurisdictions, major industrial firms, specialized constituencies (e.g., professional societies, labor organizations, environmental organizations, etc.) to receive information. DOS will determine which foreign Governments and international bodies must be informed of the technical facts and projections. Typical industries are:

Aircraft operations
Aircraft equipment
Power generation and distribution utilities
Heavy electrical equipment
Surface transportation
Consumer electrical equipment

Communications: radio, TV, telephone operations,
equipment manufacture
Computers
Electronic components.

Examples of professional societies and industrial associations are:

AIAA, IRI, EPRI, IEEE.

NASA will prepare technical information in a "technical note" form that can be used initially to lay out the pertinent facts in a low-key and authoritative manner.

NASA, assisted by other Federal agencies as required, will prepare briefing strategies and necessary material, and will help coordinate the various agency briefing terms.

The above actions will be completed within 30 days after action plan approval.

B. Near-Term Responses

The present and projected near-term use of carbon fiber composites is limited, but increasing. A USG program must be developed to deal with the possibility of incidents which might occur before long-term solutions are developed in order to limit the possible harmful side effects of the materials.

An incident created by accidental release is thought likely to occur first through aircraft crash and fire. Aircraft are a current and projected major user of composites and an aircraft crash often involves conditions favorable to fiber release. DOT, supported by NASA and DOD, shall develop a procedure for identifying and reporting all aircraft accidents which could result in carbon fiber related incidents.

For incidents arising through other applications of composite materials, it will be necessary to have a field organization that is ready to assist local government bodies, at least until the phenomenon is more widely understood. Defense Civil Preparedness Agency is well-suited in that its offices exist throughout the country, it is well-organized, it is accepted readily by local authority and it is experienced in helping with disasters. DCPA assistance would presumably be required only during the early years when use of the composite material has become more widespread than at present, but technical methods of protection are not yet widely in use. The DCPA will prepare a plan to render such assistance by March 1, 1978.

The DCPA shall maintain records and shall provide written analyses of incidents which may occur, including information on sources, damage, effectiveness of clean-up, etc. DOD and NASA shall support the DCPA with laboratory analysis as required.

C. Continuing Efforts to Minimize Material Effects

Research and Development - There are three facets of approach that must be pursued simultaneously: (1) understanding the details of damage mechanisms to equipment and personnel and what protective measures can be employed; (2) prevention of introduction of fiber into the atmosphere; and (3) modification of material so that the damaging effects can be avoided. Specific programs in each of these areas are listed below.

Commercial aircraft equipment. Studies of vulnerability of commercial grade avionics and control equipment, and other systems essential to the safety of flight, including ground-based equipment, has been started, but data are inadequate to permit assurance of protection or accurate assessment of vulnerability. Assisted by consultation with and advice from DOT (FAA), NASA has responsibility for establishing a suitable test program and design of protective measures in concert with the aircraft industry. This program will include studies of crash plus fire scenarios and will be reviewed after one year to establish a completion date.

Surface transportation equipment. Virtually no data have been generated on the vulnerability of typical civilian surface transportation equipment. DOT will take the lead with assistance from NASA. This program will include studies of surface transportation crash plus fire scenarios. The program will take two years, and will be reviewed at that time for possible continuation.

Power generation and distribution equipment. Little work has been done in this area, although DOD has a limited data base. Examination of the failure modes of typical equipment and the design of suitable protective features for new equipment and backfit measure for existing equipment is essential. DOE will take the lead in working with the power industry. The program will take at least three years. Detailed annual review for progress is required.

Other commercial and household equipment. Communication and computer equipment are particularly important. Failure modes must be studied; design standards for future equipment must be developed in conjunction with industry; and protective procedures for installed equipment must be worked out. DOC (NBS) will take the lead. The program will run for two years, with the aim of transferring the lead to industry.

Monitoring Equipment. Instruments for continuous environmental monitoring and for site surveys must be developed. EPA will take the lead, with assistance from the DOD.

Health-related Effects. There is strong clinical correlation between inhalation of certain fibrous material such as asbestos, and illness. The clinical effects of other materials, such as fibers of glass or carbon, are not equally clear. In all cases, the specific mechanism of insult is not well understood. Lacking such understanding, exposure standards can be developed only by analogy and such standards may either fail to protect or be needlessly restrictive and expensive. HEW (PHS) will undertake a three year program to elucidate the specific mechanism of damage by fibrous materials in order to improve treatment and to provide a solid base on which to establish safety standards.

DOL (OSHA) will prepare and promulgate regulations necessary for the protection of industrial workers handling carbon fiber material. These will include prescription of safe industrial practice, and will be based on a prudent extension of available clinical evidence on the deleterious effects of fibrous materials.

Environment. Uncontrolled disposal of discarded consumer goods and of industrial scrap generated during the manufacture of fiber and the fabrication of objects from the material could be a major source of release to the atmosphere. EPA, in concert with industry, will conduct a two-year study of means to control such disposal, including establishing identification of effective methods.

The most dangerous method of disposal is incineration, which may burn away the binder of the fiber material without necessarily destroying the fiber. EPA, in concert with industry will conduct a three-year study of safe methods of incineration, will develop the control technology necessary for this purpose, and will determine what methods may be suitable. At the end of that study, if required, EPA will issue regulations governing the disposal of carbon fiber material. Within the same period necessary atmospheric monitoring systems will be set up in the vicinity of major manufacturing facilities, and carbon fiber will be included in the monitoring of the effluent of major incinerators. Essentially nothing is known about the ecological effect of carbon fiber invasion of the natural water system and long-term accumulation in the environment. EPA will conduct a modest study of observation of concentrations of carbon fiber in the vicinity of manufacturing facilities, where free carbon fiber can be expected.

Alternative Materials. Since hazards arise from the high conductivity, general indestructability and ease of airborne transport of present carbon fibers, desired characteristics of alternative materials are clear: the substitute fibers should be of comparable cost and strength, but should not be able to produce the electrical effects feared unless conductivity is required for special applications. A complementary approach is to arrange that the fibers do not become airborne, or settle out so quickly that the problem is purely local. Given the desired strength and cost characteristics, investigators can look for fibers that are larger and thus settle out, are poorly conductive, or have an insulating coating. Research can seek a binder that does not burn below the ignition temperature of the present fibers, or seek a way of igniting the present fibers at temperatures characteristic of the disintegration of the present matrix. Finally, the technology program can seek a binder resin that chars and does not release fibers into the atmosphere when there is a fire. The technical history of development of composite materials indicates that between the introduction of a new fiber or a new matrix, when found, and the development of adequate engineering design data is a period of several years. Thus, an alternate material is not considered an early solution to the problem addressed here. It would seem that the earliest success is likely to appear in the form of a matrix binder material that will char rather than disintegrate.

NASA will take the lead in investigating alternative materials, with DOD assistance. Work will be aimed at larger diameter fibers, reduced conductivity, insulating coatings, and lower ignition temperatures for the fiber. Work on organic matrices will aim at non-combustible higher ignition temperatures and char characteristics. Work on charring matrices should produce results in two years; the other programs will take from three to five years. Development of engineering design data on candidate alternatives will not be complete before five years.

Composite Material Data Monitoring and Analyses. DOC shall undertake a continuing responsibility for maintaining the available data base, current industry practices, in-service protection procedures, etc., in order to assess the likelihood of incidents. The resulting analyses will provide the basis for continuing evaluation bv OSTP/NSC and OMB as to budget requirements and priorities.

Assessment of Regulatory Requirements. Methods and necessary rules are to be developed by OSHA for the protection of industrial workers exposed to carbon fiber and by EPA for the control of release into the atmosphere during the ultimate disposal of carbon fiber composite materials. If present regulatory authorities are not adequate, draft legislation will be prepared by the cognizant agency.

International Considerations. Foreign production of carbon composite materials will increase, and there will be continuing sales of material or finished products to the U.S. Attempts to exclude importation of such material are inappropriate until we are assured either of a satisfactory alternative or that regulatory controls are necessary. DOS will prepare suitable advisories to governments of other countries producing or using large amounts of carbon composite material to inform them of U.S. actions in this area.

III. Budget Issues

Lead agencies for actions are responsible for preparing reprogramming plans for FY 1978 and budget requirements for FY 1979-82 in time for the President's decisions on the FY 1979 budget. OSTP, NSC, and OMB will collaborate in reviewing and approving those plans.

IV. Organizational

The execution of the broad aspects of this plan are agency responsibilities. Coordination and central monitoring for consistency, effective dates, etc. are required. OSTP, assisted by NASA, will assume this responsibility during the early stages. Continuing lead responsibility will pass to DOC in three to five years or at a time when commercial applications have increased to the point of being the dominant source of inadvertent release. To reduce duplication and confusion in dealing with local jurisdictions, states, cities, police departments, fire departments, etc.:

- DOC will develop and coordinate all contracts with industry except for research and development projects.

- NASA will coordinate Federal research and development projects.

- EPA will develop and coordinate all contacts with local governments and their substructures.

An annual report of progress, problems, and budget recommendations is to be submitted to OSTP in August of each year. NASA will assist OSTP in the consolidation and review of the total program and in judging the progress made and the work remaining.

V. Schedule

Completion of various functions is indicated in the sections above. Key targets are as follows:

- Agency R&D plans for assigned work are to be submitted to OSTP in time for the President's budget review. Budget requirements for FY 79-82 will be shown, along with planned allocations from FY 78 appropriations.

CARBON FIBER STUDY

I. INTRODUCTION

Carbon graphite composites are a family of important, new, lightweight and high-strength materials finding very rapidly growing use in military and civil aircraft, in space systems, and in a variety of consumer products ranging from sporting goods to automobiles. Carbon graphite composites may become as important to the United States and the international economy as the steel and aluminum they replace.

In a letter to the President, the Deputy Secretary of Defense and the Administrator, National Aeronautics and Space Administration (NASA), recognized the benefits and increasing usage of composite materials. They also worried that the carbon fibers if inadvertently released into the atmosphere posed a potential hazard to electrical equipment and possibly to the health of individuals.

The President directed the Office of Science and Technology Policy (OSTP) to review these matters and recommend an action plan. To accomplish this task, an interdepartment/interagency committee was formed under OSTP aegis to prepare a report and develop the action plan. The carbon fiber study presented below is the result of the OSTP sponsored review.

II. BACKGROUND

A. History of Composite Materials

The history of carbon fibers and filaments extends back for many years. In his classic work on the incandescent lamp, Edison made carbon filaments before 1880 by carbonizing natural cellulose fibers, such as cotton and linen. A further development occurred in 1909 when Whitney patented a process for coating carbon fibers from cellulose with pyrolytic graphite by flashing at temperatures up to 4,000° C. However, after the introduction of tungsten filaments, interest in carbon for lamp applications declined.

In the 1950's, the search for new materials for structural composites generated an upsurge of interest in carbon fibers. Early work at this time on pyrolyzed viscose rayon, sponsored by the Air Force Materials Laboratory (AFML) at Wright-Patterson Air Force Base, produced relatively strong flexible fibers by stretching the fiber during carbonization at 2,000° C. Although the process for producing high strength fibers was not very reproducible, reliable low-strength carbon and graphite yarns and fabrics could be manufactured. These low-strength fibers found application in tape configurations for strategic missile re-entry vehicle heat shields and rocket nozzles in the early 1960's.

A significant breakthrough in carbon fiber technology occurred in the period 1963-1965 when it was discovered that very high strength carbon filaments could be obtained by subjecting the precursor fiber to a rigidly controlled continuous tensile stress during the high-temperature treatment. It is the high values of the specific modulus and specific strength that make these new carbon fibers attractive materials as structural reinforcing agents.

Commercial carbon and graphite fibers are made from any carbonaceous, fibrous, raw material that pyrolyzes to a char, does not melt, and leaves a high carbon residue. The physical properties of the final carbon fiber materials are extremely sensitive not only to the type of precursor material, but also to such manufacturing variables as rates of heating, maximum baking temperature, time at maximum baking temperature, the baking environment, and the strain applied to the fiber during pyrolysis. Technically, the term "carbon fiber" is applied correctly to fibers that have been pyrolyzed at temperatures of 1,100° C. to 1,200° C. and consist essentially of amorphous carbon networks. The term "graphite fiber" is applied to the carbon fibers that have been heat treated at temperatures on the order of 2,200° C. to 2,700° C, resulting in a crystalline fiber structure. (For purposes of this report, the two terms will be used interchangeably, since the hazards under consideration are generally common to both.)

The starting material, called the precursor, for carbon fibers is usually continuous and may be a single fiber or a multistrand filament. Prior to 1973, most major U. S. producers of carbon fibers preferred rayon precursors; however, by 1976, most major producers in the U. S. and abroad preferred a polyacrylonitrile (PAN) precursor. Production of carbon and graphite fibers from a low cost pitch or tar precursor has received considerable attention recently, primarily from Union Carbide Company in the United States, and Taiyo Kaken in Japan. Union Carbide has its pitch-based process well along in development and Taiyo Kaken is expected to be producing this type of fiber during the next few years. The fibers derived from pitch precursors will probably be considerably less expensive to produce than those derived from PAN.

Very high modulus (of elasticity) graphite fibers in the form of a continuous yarn have been developed through the application of stress to a carbon fiber yarn during heat treatment at temperatures exceeding 2,200° C. This procedure creates a more ordered microstructure in the fiber, leading to a 10-fold increase in the elastic modulus and a simultaneous increase in the electrical and thermal conductivity in the direction of the fiber axis.

The outstanding mechanical properties of carbon fibers only become of practical interest when they can be efficiently translated into a visible structural form, such as a carbon fiber composite. To this end, significant effort has been expended in developing compatible matrix materials (to bind the fibers together), composite manufacturing methods, and optimized design configurations. The present generation of carbon fiber composites has unique combinations of properties which result in a significant capability for reduction in structural weight of both aerospace and nonaerospace transportation systems. Moreover, these same properties make possible significant economy of certain industrial operations with accompanying increases in safety for both static and rotating machinery. Finally, carbon fiber composites provide entirely new capabilities to consumers in the areas of sporting goods, medical equipment, electronic components, etc.

Studies based on experience gained from R&D programs and production of advanced composite aerospace structures indicate that extensive utilization of carbon fiber composites in the next generation of aerospace systems will provide significant benefits in the form of either reduced weight, size, and cost or in improved performance.

(1) Improved Performance (structural and aerodynamic):

o More efficient structure/lighter weight (higher specific stiffness and strength);

o Greater ability to dynamically tailor the structure; and

o Greater ability/flexibility relative to advanced geometric shapes and structural concepts.

(2) Improved Safety and Survivability:

o Improved fatigue characteristics;

o Greater damage tolerance;

o Improved flight safety (characteristically a redundant structure) -- slow, soft failure with advanced warnings; and

o Satisfactory ballistic tolerance.

(3) Reduced Cost:

o Acquisition - fewer parts, greater automation of fabrication (less labor intensive), less scrappage of basic materials, less testing required.

o Life cycle - improved performance - improved mission effectiveness - reduced maintenance (improved repairability) inherent corrosion resistance.

Commercial aircraft have begun to use carbon fiber composites and are expected to use more significant amounts of these materials with the introduction of the next generation of new or derivative aircraft. Weight reductions made possible in commercial aircraft are expected to be realized by improved fuel economy with a full fleet fuel savings of about 200 million gallons of gasoline per year projected on the basis of the quantities of graphite composites expected to be used in commercial transports by 1990.

The Federal automobile average fuel economy standards are expected to cause automobiles to be by far the largest user of graphite fiber by 1990. In this time period, the U. S. automotive industry alone may use more than 1,000 times the volume of graphite fiber used by the nonmilitary aerospace industry. Use of graphite composites in automobiles could result in full fleet fuel savings of as much as 2 billion gallons of gasoline per year based on the projected estimates for graphite usage in the 1990 automobile. If the automotive industry does substitute even a relatively small amount (90 lb./auto) of graphite composites for structural steel in automobiles, this will sufficiently reduce the cost of graphite fibers and sufficiently enhance the technology base that the trucking industry likely will apply large amounts of composites to new trucks. This should result in an approximate 15% increase in either fuel economy or load capacity. Likewise, the rail freight industry will apply composites in an amount which is likely to result in a 7% increase in rail freight capacity.

Future projections indicate that as the price of carbon fibers decreases, there will be an increase in other industrial uses of carbon fiber composites due to weight and cost savings as well as to increased safety. Also, the reduced cost will lead to a rapid expansion of use by the general public in the form of sporting goods and other recreational articles, due to the increased performance capability that carbon fiber products will offer to the consumer.

B. Nature of the Hazard

There are two categories of potential hazards that must be recognized and dealt with in the use of carbon fibers. These are: (1) accidental interference with electrical equipment, and (2) health impacts.

(1) Accidental Interference with Electrical Equipment

The only proven hazard of working with graphite fibers lies in their effects on unprotected electrical and electronic equipment. Release into the atmosphere of even a few grams of these fibers (actually millions of fibers) may damage unprotected electrical equipment. High electrical conductivity of the carbon fibers is a prime factor in causing the electrical hazard; however, other properties such as small fiber diameter (8 μm), generally short length (6-10 mm), and low density (1.5-1.9 gm/cm^3) are also important contributing factors. These fiber characteristics permit any small movement of air to cause free fibers to become airborne. The nominal fall rate of the fibers is 1 m/min. in still air. Therefore, fibers which are accidentally released can be transported over very long distances by normal atmospheric motion. Moreover, fibers which have settled out of the atmosphere are easily resuspended by minor atmospheric turbulence or mechanical agitation. As can be seen, therefore, depending on prevailing atmospheric conditions, localized release of a small quantity of carbon fibers can lead to contamination of a very large geographical area. As an example, it has been estimated that an accident involving burning of an aircraft containing 1,300 pounds of composite material can result in atmospheric exposure levels at distances 5 km away from the accident site which are equivalent to those which have produced electrical damage.

Because of their high conductivity and their physical inertness, carbon fibers which settle on or across electrical contacts or circuits can cause one of three types of electrical effects. They can cause: (1) resistive loading; (2) temporary, but possibly damaging, shorts; or (3) electrical arcing.

Single fibers of the type used in structural composites do not normally cause resistive loading in low voltage, solid state circuits. However, two or more such fibers in parallel can provide a sufficiently low resistance to adversely affect even these circuits. This effect, which is obviously somewhat dependent on the circuit impendence and voltage as well as the terminal or circuit board surface material, can lead to malfunctions of the equipment containing the circuit. These effects are most commonly associated with low voltages.

Single carbon fibers of the type normally used can cause shorts at voltages below 30 volts. The specific voltage at which such shorts begin is somewhat dependent on contact spacing and the surface of the contacts. (The existence of a contact potential is often the largest contributor to the overall resistance of the short circuit created by the fiber. However, for carbon fibers, even this contact resistance drops to a very low level at quite low voltages.) Due to the high conductivity of the fiber, it will carry quite high currents at relatively low voltages. The fiber will, however, burn out in the manner of a fuse because of its fine diameter. Nevertheless, even the momentary short formed can blow fuses in the equipment or can cause stressing of electrical and electronic components so that they no longer operate within specification.

Single fibers can also initiate arcing (air breakdown) between contacts either by effectively narrowing the air gap between contacts or by vaporizing (or causing the conductor material to vaporize) and producing ions to initiate air breakdown. Once the arc is initiated, it will often lead to extensive destruction of the equipment through fire. Even if the arc is not self-sustaining, the initial arcing can lead to vaporization of the carbon fiber which may recondense as a "carbon streak" on associated insulating surfaces. This highly conductive carbon deposit will then maintain the short circuit even in the absence of the arc.

Research has been conducted on various types of carbon fibers possessing a range of mechanical properties. In general, the electrical conductance increases with increasing modulus of the fibers. Therefore, the present commercial trend to higher modulus (and higher strength) fibers will, if anything, make the electrical hazards more severe. However, it should be noted that the carbon and graphite fibers presently being used for structural applications all have such high conductances that, except for very low voltage effects, all carbon and graphite fibers should be considered to cause nearly equivalent hazards.

The specific effect of fiber length in determining hazard severity has not been completely identified. Neither has the distribution of lengths which is likely to be produced in a typical accidental release scenario. Short fiber lengths favor easy distribution and penetration while long fiber lengths might be expected to cause more incidents by bridging wider gaps. However, it is not necessary for an individual fiber to bridge a gap in order to cause an incident since the fibers are polarizable in strong electrical fields, and the dipoles created can link up to bridge a gap which is wider than an individual fiber length. Whether or not this will actually occur in any particular case is dependent on the competition between electrostatic force and other external forces (e.g. wind).

As will be discussed later, protection methods are available; these include insulating circuits and/or contacts with a variety of insulating materials. However, preliminary research indicates that electrostatically charged carbon fibers may, in some cases, actually penetrate polymeric or resin type insulations leading to an electrical incident in a supposedly "protected" circuit.

The electrical hazard is a poorly correlated and an unpredictable phenomenon. However, the research done to date and the limited number of documented incidents are sufficient to prove that the hazards are real. Limited test data indicate that electrical equipment tolerance to free carbon/graphite fiber interference can be characterized in terms of exposure, or (fibers/m^3) x sec; electrical interference seems to begin in the exposure range of 10^4 - 10^7 (fibers/m^3) x sec.

(2) Health Implications

The carbon fibers of concern are often approximately 8 micrometers (μm) in diameter and typically 6-10 mm. in length. Tests conducted by the U. S. Army Environmental Hygiene Agency did not show a significant number of fibers with diameters of less than 6μm, but it is known that exposure to fibers of smaller diameter (such as asbestos) can produce severe respiratory problems.

While at the present time available information does not provide a basis to conclude whether man-made fibers (as opposed to asbestos) are or are not carcinogenic in man, smaller fibers can penetrate more deeply into the lungs than larger fibers. Until more definite information is available, the possibility of potentially hazardous effects warrants special consideration.

The fiber itself (not the carbon from which it is made) would appear to create the principle health significance, based on an extrapolation from other fiber materials, namely, asbestos, fiberglass, etc. The maximum permissible occupational exposure levels for carbon fibers is comparable to that for other fibers. For example, the Department of Labor, Occupational Safety and Health Administration (OSHA), has a current asbestos permissible exposure limit of 2.0 x 10^6 fibers/m^3 for an 8-hour time weighted average and has proposed to lower that level to 0.5 x 10^6 fibers/m^3 for an 8-hour time weighted average for asbestos fibers greater than 5μm in length because of the known human carcinogen risk associated with asbestos fibers. The National Institute for Occupational Safety and Health, DHEW, has recommended a level for asbestos of 0.1 fibers greater than 5 μm in length per m^3 on an 8-hour time weighted average with peak concentrations not exceeding 0.5 fibers greater than 5 μm in length per m^3 based on a 15-minute sampling period.

NIOSH recently recommended a maximum occupational exposure level of 3.0 x 10^6 fibers/m^3 for up to a 10-hour workshift in a 40-hour workweek for fibrous glass, as well as other man-made mineral fibers, having a diameter equal to or less than 3.5 μm and a length equal to or greater than 10 μm.

The discussion of asbestos fibers is only to provide general background data and should not be extrapolated to apply to carbon fibers on the basis of any existing toxicologic or epidemiologic data.

The potential health hazards associated with exposure to small diameter fibers may include:

(a) Acute skin and eye irritation;
(b) Skin sensitization;
(c) Chronic lung disease;
(d) Carcinoma of the lung; and/or
(e) Pulmonary and abdominal mesothelioma.

Of principle health concern are possible human exposures resulting from the manufacture, formulation, and rework (cutting, grinding, etc.) of such fibrous material, particularly as increased production occurs and as new commercial applications are developed. Another concern, although not yet observed, is the potential degradation or breakdown of the existing 8 μm diameter fibers thus resulting in a significant respiratory hazard, or a change in current manufacturing processes which would allow greater use of smaller diameter (less than 3.5 μm) fibers.

Acute human exposures from accidental release of carbon fibers into the environment will be less than occupational exposure during manufacture of various carbon fiber-containing products when considered as a time-weighted average exposure. It is unlikely that a significant risk to human health would occur from an acute exposure following an environmental incident.

(3) Biological Studies

An extensive literature review and evaluation of the biological effects of exposure to fibrous glass was recently completed by the U. S. Public Health Service, National Institute for Occuptational Safety and Health, in its "Criteria for a Recommended Standards --- Occupational Exposure to Fibrous Glass," DHEW (NIOSH) Publication No. 77-152. These recommendations also relate to all man-made fibers and, therefore, by analogy are important to this project.

Carbon fibers like other fibers (including man-made and mineral) would appear to have carcinogenic potential if smaller fibers (both diameter and length) were produced, or if currently produced fibers were to break up into smaller units. At the present time, no carbon fiber is reportedly being produced with diameters less than 5 μm. Smaller diameter carbon fibers would have less desirable structural and electrical properties. Therefore, production of smaller diameter carbon fibers seems unlikely at this time. Industrial hygiene evaluations conducted to date have failed to demonstrate any significant breakup into smaller diameter fibers, even though breakup into shorter lengths occurs in both occupational settings and following environmental release. Additional studies of possible breakup of different types of carbon fibers under various occupational and environmental conditions appears to be highly desirable. However, considering the lack of demonstrated breakdown into smaller diameter fibers in occupational and environmental settings, and the relatively small amount that would be released into the environment following an incident, any potential carcinogenic risk to man from fibers of currently produced diameters seems exceedingly small.

Human exposures to man-made fibers have indicated few reported health changes except those related to skin and respiratory tract irritation. The absence of such reports may be due to the short time that small diameter man-made fibers have been in commercial production, along with the short duration of exposure of adequate study groups. (Effects from asbestos exposures often are not indicated for 20-30 years after exposure.)

Large diameter fibers have been demonstrated to exhibit different effects in biological systems than small diameter fibers. Studies indicate that 3.5 µm approximates the diameter of the thickest long fibers observed in lungs of rats following inhalation exposure and that 90% of the fibers in lungs of deceased fibrous glass workers were less than 3.5µm in diameter.

Previous exposures to humans have been mostly to large diameter fibrous glass and the health effects that have been observed include skin, eye, and upper respiratory tract irritation; a relatively low frequency of fibrotic changes, and a very slight indication of an excess mortality risk due to nonmalignant respiratory diseases.

An epidemiologic study of the mortality experience of 12,000 workers, sponsored by the Thermal Insulation Manufactures Association (TIMA), is now in progress on occupational exposures to manufactured (man-made) mineral fibers. The study, consisting of 3 groups of workers, is scheduled to be completed in phases between June 1977 and May 1978. Another current study, also sponsored by TIMA, will provide additional information on environmental concentrations, fiber characterizations, and durations of exposure.

(4) Industrial Environmental Data

In 1974, the U. S. Public Health Service reported on investigations of airborne particulates in 10 fibrous glass production facilities. The study consisted of four facilities producing fibers used in standard home insulation (designated as large diameter fibers) and six facilities producing or using fibers measuring less than 1 m in diameter (designed as small fibers).

In facilities where large diameter fibers were produced or used, mean airborne fiber counts ranged from 60,000 to 130,000 fibers/m^3 (0.06 to 0.13 fiber/cm^3). The highest single concentration was 830,000 fibers/m^3 (0.83 fiber/cm^3). Mean total dust concentrations ranged from 0.34 to 2.73 mg/m^3. The highest concentration was 14.5 mg/m^3. The median diameter of the fibers found in the various plants ranged from 1.1 to 4.3 µm. In most operations sampled, over 50% of the fibers were less than 3.5 µm in diameter.

In facilities where small diameter fibers were present, fiber diameters ranged from less than 0.1 to 2.0 µm with the majority being less than 1.0 µm and 40% to 85% less than 0.5µm. Mean airborne fiber counts for these facilities ranged from 1,000,000 to 21,900,000 fibers/m^3. (1.0 to 21.9 fibers/cm^3);

the single highest concentration was 44,100,000 fibers/m^3 (44.1 fibers/cm^3). In bulk handling operations, four of six facilities had a mean concentration in excess of 5,000,000 fibers/m^3. (5.0 fibers/cm^3). All operations studied had mean gravimetric concentrations less than 1.0 mg/m^3 with the single highest observed concentration being 2.0 mg/m^3.

C. Fiber Release

Waste disposal by incineration of either industrial scrap or discarded composite products represents a source of carbon fibers capable of causing hazardous effects. Those who have responsibility for disposal are generally unaware of the hazardous potential of the fibers, thereby increasing the probability of inadvertent occurrence of a fiber releasing event.

Another possible fire-related accident which could cause fiber release is a crash plus associated fire of either an aircraft or surface transportation vehicle containing carbon fiber composites. Since the major near term use of carbon fiber composites for structural application is expected to be in military and civilian aircraft, the possible crash and burning of composite containing aircraft represents one of the immediate threats for release of carbon fibers. Most crashes of military aircraft involve fire followed by an explosion, and preliminary test data indicate that up to 15% of the carbon fibers contained in a composite undergoing this sequence of events may be released in a hazardous form; i.e., as single fibers or lint.

D. History of Incidents

The discovery of the damaging effects of the impingement of carbon fibers on electrical equipment came about quite accidentally. In 1968, the Air Force was conducting electronic interference experiments. Test personnel noted that electronic equipment exposed to the carbon fibers malfunctioned. Laboratory tests substantiated the effects of carbon fibers on electrical equipment.

On May 12, 1972, during a clean-up of an area in the Union Carbide's Carbon Fiber Production building at Fostoria, Ohio, a cardboard carton containing untwisted filaments of fine strands or carbon fibers 6 to 42 inches long was inadvertently placed in the plant incinerator rather than going to land fill. Subsequently, fibers were emitted from the stack, and conveyed by air over the plant and surrounding areas. The loose fibers were experimental material from development work; carbon fiber composite material was not involved. The electrically conductive strands settled on several electrical substations at the plant, causing short-circuits and power outages in three of the substations. The carton of fibers was placed on a burning pile of wood in the incinerator with a stack about 125 feet high and five feet in diameter at the top. The incineration occurred at 9:00-9:15 a.m., on May 12, 1972, a Friday. Within minutes, fiber strands were being discharged from the stack top. Strands (both single and in tumble-weed like clumps) were observed floating around in the air, settling on wires, roofs, and in the yard area. Some unburnt fibers were pulled from the fire and the fire was extinguished. The fibers were probably in the incinerator for 20 to 40 minutes.

Between 9:25 a.m. and 10:00 a.m., the 4000-volt circuits in two substations at the Union Carbide plant about a half mile downwind from the stack were shorted out. Power was restored in these substations by 2:00 p.m. A third substation nearby shorted out at 5:15 p.m. on the same afternoon. Startup of this substation was delayed until the following day pending an inspection of temporary repairs. Eight other open air substations and a metering station at the plant which were downwind from the stack did not short out. A newspaper account in the Fostoria Review Times on May 12, 1972, reported the Union Carbide power failure and also quoted a spokesman for the Ohio Power Company as indicating that three or four power outages were reported in the city at 9:10 a.m. The Ohio Power Company spokesman also said failures occurred within 15 minutes of each other at Ohio Power's east end substation, which is adjacent to the Union Carbide plant, and its west end substation which is some 3 miles to the west (downwind) of the plant. A power outage was also reported on Saturday, May 13, 1972, from 1:25 p.m. to 3:17 p.m. which darkened most of the downtown area of the city east of Main Street. Ohio Power's east end substation adjacent to the Union Carbide plant was reported as losing six 4000-volt line insulators.

E. Interests of the United States Government

There is a considerable range of Federal interest in the widespread use of graphite composite materials and potential hazards therefrom. Composites may offer the transportation industry the only economically viable means of meeting the automotive fuel consumption standards established for the 1980's. Composites are now integral to a number of key aeronautical and space systems being developed and procured by the military and civil agencies of the Government; in certain cases (F-18, Space Telescope), the mission objectives cannot be met without its use.

Composite materials are of growing importance to the entire national industrial economy as they find use in many different applications; they offer an improvement in performance and weight in comparison to the metals they replace. The Federal responsibilities for the public welfare encompass the full range of the possible threats posed by graphite fiber release, including environmental protection, human health, public safety, and degradation of such basic services as power and communications. Federal responsibilities for informing the public as to the positive and negative implications of new developments may not be explicit in every case but are nonetheless real, especially in light of the Government's dual promotional and protective interests. Considerable foreign use is being made of graphite composites and a significant amount, both as raw material and in finished consumer products, is being imported by the United States.

Federal R&D programs, notably within NASA, have focused on expanding the use of composites in the civil aviation field; Federal procurement programs, notably within the military, have specified these high-performance, lightweight materials; and Federal automotive fuel consumption standards virtually require conversion from present metals to new lighter materials. The role of the Federal Government, therefore, has included both the promotion of economically and socially beneficial new materials and the protection of the society from deleterious side effects.

III. PRESENT PRODUCTION AND APPLICATION

A. Production

Worldwide production capacity of carbon fibers was over 900 tons in 1976, and will probably be more than 1,500 tons in 1977. The industry as a whole, however, was operating at only about 40% of full capacity in 1976 with total sales of about 300 tons. Six of the leading carbon fiber producers accounted for about 80% of the world capacity and about 85% of the total carbon fiber sales in 1976. Producers of significant quantities of carbon fibers are listed in Table 1, along with estimated production capacity and some sales statistics. Marketing experts are currently predicting more than a 400% increase in the worldwide carbon fiber demand and production by 1980. Such increases will depend, in part, on further development of lower cost continuous, high-modulus, pitch-based graphite fibers; the utilization of carbon fiber technology in the automotive industry; the availability of Government aerospace and defense contracts; and the ability of producers to reduce the price of PAN-based graphite fibers below $10/lb.

B. Applications

The consumption of carbon and graphite fibers in the free world, by the general industrial and sporting goods industries, accounted for over 75% of the total output in 1976, with the remainder being consumed primarily by military and aerospace applications. By 1985, all sectors of the industry will be consuming larger volumes of carbon fibers with the automotive industry expected to consume a sizeable fraction of the total. Applications of carbon fibers in the aircraft and aerospace industries will continue to increase, especially in the area of structural load-bearing applications. Significant carbon fiber applications are listed in Table 2. There are over 250 fabricators using carbon fiber materials in the United States alone and probably as many more in the rest of the world. Hundreds more may be attracted to the field in the next 10 years as the market expands.

IV. POTENTIAL USAGE

A. Projected Military Usage

Of materials technologies which have emerged during the past ten years, the graphite composite technology appears to have the most significant across-the-board impact on future military systems. For this reason, the military is projecting the use of graphite fiber composites in virtually all new aircraft being considered. Table 3 lists these aircraft along with the anticipated weight and location of the graphite fiber components. Of the aircraft listed, two are worthy of special note.

The Navy F-18 aircraft is being designed for extensive use of graphite fiber composites. The use of this relatively large amount of graphite fiber composites will enable this aircraft to achieve mission and performance capability that could not presently be obtained with any other carrier-based aircraft designed without the extensive use of composites. Similarly, the VTOL aircraft, AV8B, is dependent on the use of large amounts of graphite fiber composites to provide this aircraft with adequate range and payload.

Table I

CARBON FIBER MANUFACTURERS AND ESTIMATED PRODUCTION CAPABILITIES
(Metric Tons)

Country	Company	Trade Name	Total Capacity 1976	Total Capacity 1977	Sales 1976
United States	Union Carbide	Thornel			
	Hercules	Magnamite			
	Stackpole	Panex			
	Morganite	MODMOR			
	Great Lakes Carbon	Fortafil			
	Celanese	Celion			
		Total United States	282	170[1]	126
United Kingdom	Courtaulds	GRAFIL			
	Hyfil (BCM)	HYFIL			
	Morganite-Modmor	MODMOR			
		Total United Kingdom	112	172	21
Japan	Toray	Torayca			
	Taiyo Kaken	Kureha			
	Toho Rayon	Beslon			
	Nippon Carbon	Carbolon			
	Mitsubishi Rayon	N/A			
	Nitto Boeski	Wonderfil			
		Total Japan	372	912	164
France	Le Carbone Lorraine (Serofim)	RIGALOR			
	GEPEM (SEP and Fibre-Mica)	N/A			
		Total France	22	22	N/A[2]
Federal Republic of Germany	Sigri Elektrographite	SIGRAFIL			
		Total F.R. of Germany	4-10	4-10	4

[1] Firms that reported 1976 capacity did not report in 1977

[2] N/A = Not Available

Table 2

APPLICATIONS OF CARBON AND GRAPHITE FIBERS

Structural components for commercial airlines

Antenna for Jupiter flyby satellite

Equipment section for third stage of TRIDENT missile

Space Shuttle cargo doors

Rocket motor combustion chambers and nozzle components

Access doors, empennage parts and speed brakes for fighter aircraft

Helicopter tail boom

Sporting goods, such as: fishing rods, shafts for golf clubs, CB antennas, tennis racket frames, javelins, bats, hockey sticks, etc.

Experimental automotive parts, such as: drive shafts, spring leaves, side intrusion beam, bumper parts, frame rails, valve trrain pushrods, gears, bearings, brake linings

Lightweight oil field derrick

Textile equipment

TABLE 3

GRAPHITE FIBER COMPOSITE USE ON MILITARY AIRCRAFT

A/C	Location	Weight (lbs)
F-18	Tail, Slats, and Fairings	1300
AV8B	Wings	900
CH-46	Rotor Blades	30
S-3	Spoilers	6
A-7	Wing Tips	50
YF-17	Tail, Slats/Flaps	1000
F-15	Speed Brakes	165
F-111	Fairing over Doubler	20
CH-47 Mod	Rotor Blade	150
UTTAS	Tail Drive Shaft Rotor	50

B. Projected Civilian Aerospace Usage

As for all other segments of the nonmilitary marketplace, the projected use of graphite composites cannot be determined with a high degree of certainty since the anticipated volume of use is dependent on price, which is likewise dependent on volume. However, since the benefits of lightweight structures to aerospace applications are so great, this segment of the market will likely continue to grow quite rapidly even if the optimistic estimates of price reductions are not realized. The relatively wide ranges given below, of projected weights of graphite fiber to be used, are due primarily to price uncertainties. Since the aerospace industry is expected to be a relatively minor user of graphite composites as compared to the ground transportation industry in the time period beyond 1985, decisions of the aerospace industry, in this time period, should not have a significant impact on price.

The major use of graphite fibers, in the commercial aerospace market, will be in airframe structures. A significant fraction, however, will be in engines and miscellaneous commercial aerospace components including civilian rockets and spacecraft, aircraft brakes, interior components, etc.

The Aircraft Energy Efficiency (ACEE) Program estimate for volume of graphite fiber usage in 1990 is plotted on Figure 1. As can be seen, volume of nonmilitary aerospace use is expected to increase by about a factor of 5 each 5 years until at least 1990.

C. Potential Usage in Surface Vehicles

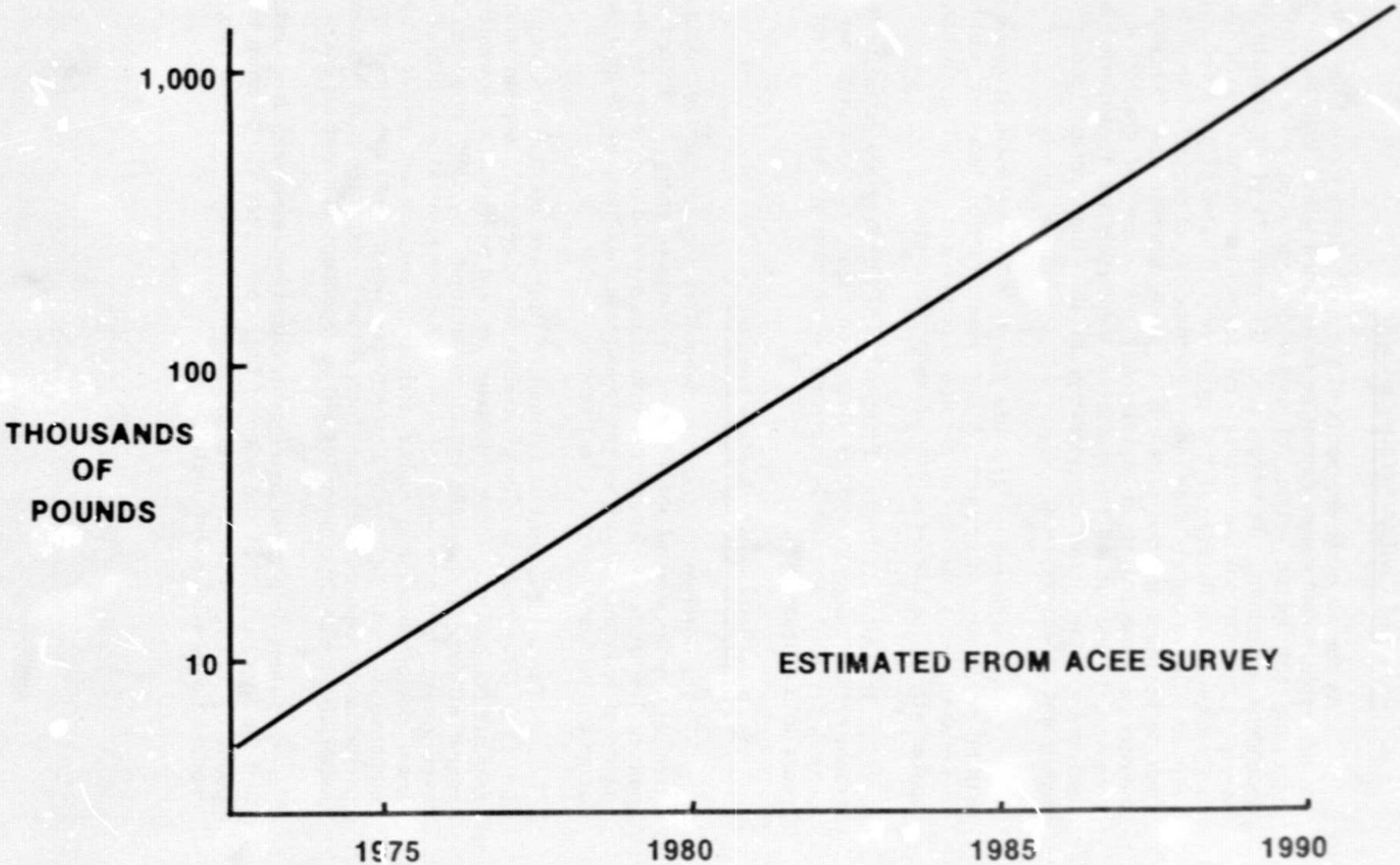
The interest in graphite composites for automotive manufacturing has risen largely because of the pressure to conserve energy in accord with national policy. The truck and freight car industries are also motivated by their interest in means of reducing vehicle weight to increase maximum useful load carried. Their usage will be based on cost effectiveness.

The achievement of automotive fleet average fuel economy standards set for 1985 (27.5 mpg) by Congress does not necessarily depend upon the use of graphite composites. These objectives are now being met by downsizing, improved engine efficiency, and light metal substitution. By 1990, however, the need for even greater fuel economy will require further alternatives such as smaller cars, lower performance, and higher efficiency engines and power trains, or more emphasis on exotic lightweight structures. Government specifications provide only performance requirements; therefore, it can be expected that decisions to use new materials such as CF composites will be dependent on materials costs.

There is general agreement, based on references from industry sources and the literature, that the price of fiber composites will be down to $5 - $10 per pound by 1985. At these lower prices, they would move into a range where they would be competitive with metals.

FIGURE I

ESTIMATED USE OF GRAPHITE FIBER FOR NON-MILITARY AEROSPACE APPLICATIONS



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Several automotive components made from graphite fiber composites are currently found in test vehicles: leaf springs, drive shafts, car-door intrusion beams, truck frame elements, and wheels. Future application potentials are for: push and connecting rods, rocker arms, oil pan, etc., in the engine area; shafts, axle and axle housing, yoke, and transmission-housing in the drive train area; leaf springs, frame components, brake linings, wheels in the chassis and suspension area; and secondary body components including the air condi ioning, transmission and radiator supports and brackets, bumper beams, and whole bumper systems.

Estimates of around five pounds of graphite composites per average car in 1985 and possibly 90 pounds per average car in 1990 are reasonable, based upon a technical review by the Department of Transportation (DOT). At an estimated 10 million car production rate in 1990, the projected consumption of composites would be 450,000 tons per year in 1990 or about half that number in fibers, which constitute roughly 50% of the composite weight.

References on applications to the truck and railroad industries are sketchy as to the market potential. However, one can expect the market for graphite composite components in trucks to be second only to the automotive in significance. The freight car usage will be a small fraction of the passenger car usage based on the considerably fewer number of units manufactured annually. Other surface transportation applications, in buses and light rail vehicles, will also share in the development but the market share of these vehicles is dwarfed by the automotive industry.

D. Other Uses

The major current use of graphite fiber is in consumer products such as sailboat masts and spar structures, golf clubs, tennis rackets, fishing rods, oars, and lightweight, high-performance bicycles. In addition to these consumer applications, carbon fiber composites are being used in selected industrial applications for such products as gears, flywheels, and structural members. While it is extremely difficult to get hard data on current and projected use of carbon fiber composites in this wide range of applications, it is estimated that 50,000 pounds are currently in commercial use; this will possibly increase to 100,000-150,000 pounds by 1980. There are no market surveys in existence covering commercial utilization of these materials which could provide a further breakdown on uses. Also, manufacturers seem particularly reluctant to discuss their plans for use of these materials which may be indicative of ongoing research and development programs for new market applications.

V. CONSIDERATIONS FOR THE FUTURE

A. Projected Rate of Electrical/Electronic Incidents

Given the relative scarcity of data on inadvertent release of graphite fibers from composite materials, on their dissemination in the atmosphere, on their persistence after release, on the ways in which fibers in the atmosphere reach electronic or electrical components likely to be affected, and on the severity of damage likely to be produced, it is nearly impossible to currently project the rate of future graphite fiber induced electrical incidents. Both NASA and DOD are currently involved in experimental test programs and risk analyses to improve the capability to make such assessments. Nevertheless, in order to provide some quantification of the near-term and far-term risks involved in the civilian use of graphite composites, NASA has carried out two very preliminary calculations to provide a basis for discussion. The first deals with the near-term risk due to the use of small amounts of graphite composites in commercial transport aircraft, and the second deals with the projected far-term risk due to their use in automobiles.

Commercial aircraft applications were selected for assessment since they are expected to be the second largest nonmilitary use of graphite composites in the near time frame, and since the small amount of data available for the risk assessment calculation are most suitable for this application. (The largest nonmilitary user in the near time frame will be consumer products such as sporting goods, but assessment of incidence rate for this application cannot be done now due to a complete lack of data on disposal by incineration which is the only significant fiber releasing scenario applicable to these products. Moreover, since these products are currently quite costly and durable, substantial disposal of them does not appear to be likely for the next several years. Automobiles, of course, present an entirely different situation, but their disposal will not involve a carbon fiber issue in the near term.)

In the context of the following discussion, a graphite fiber induced electrical incident refers to a single electrical anomaly. This would include any small or large electrical short or component failure which would cause the malfunction of an electrical instrument or appliance. An incident is then clearly differentiated from a graphite releasing accident which could cause either many incidents or none at all depending on the various factors to be discussed below. At present, the incident rate can be discussed only in statistical terms with very little account given to the possible consequences of a particular incident. Some attempt will be made, however, to illustrate examples of consequences of the two examples used below.

In general, the way in which the incidence of graphite fiber induced electrical hazard can be evaluated is to determine: the number of fiber releasing accidents which are likely to occur; the number of fibers released in each accident; the integrated exposure of all areas due to the accident; the density of equipment in the affected area; the site; and the probability that the exposure at the damage site will cause damage. Based on the available data base, assumptions or statistics can be used to place a value on each of these factors. However, a high to very high degree of uncertainty must be placed on each of these values because of the very limited amount of data currently available. Table 4 lists the assumptions used to assess the incidence rate due to near term commercial aircraft use of graphite composites and provides judgmental remarks concerning their certainty. Table 5 shows some factors which were not evaluated.

The following calculations are included for illustrative purposes only and only relative significance can be attached to the actual numbers develcped. In most cases, the values assigned to the various factors represent highly conservative

Table 4

KEY FACTORS IN AIRCRAFT INCIDENCE CALCULATIONS

Factors	Valued Used	Remarks
Exposure	$10^4 - 10^7$ (fibers/m^3) seconds	See NASA Technical Memorandum 78652
Accident Rate (AC)	0.004 fire related commercial accidents for 10^6 miles	Accident statistics from NTSF and unpublished NASA study. (Average over lifetime.)
Flight Miles/AC/Yr.	1.2×10^6 miles/yr.	Average for narrow bodied jet.
Population Density	3,340/km^2	U. S. Census, Norfolk, Virginia. Assume one electronic device/person.
Fiber Fraction Released from Fire and Explosion	15%	Limited data, chamber tests. Probably worst case. Need full scale tests.
Fiber Exposures	$10^1 - 10^5$ (fibers/m^3)x(seconds)	Integrated exposures calculated downwind for worst case release heights and atmospheric conditions.
Transfer Coefficient	1.0	Transmission factors for buildings, filters ducts vary from 1.0 to 0. worst case.
Probability of Damage	$P = 1 - e^{-E/\bar{E}}$	E is the actual exposure and $\bar{E}$ is the critical exposure.

Table 5

FACTORS NOT EVALUATED

Factor	Remarks
Turbulence, Additional Energy Sources	Mechanisms which keep fibers airborne increase risk. Washout mechanisms decrease risk.
Equipment Concentration	
Major Power Generating and Transmission Equipment	
Washout, Fog, and Rain	
Material Life and Redeposition	
Material Length Distribution	Effects of material length, life, and redistribution are unknown.

(worst case) conditions. No account was taken of natural protection offered by buildings, containers, filters, etc. (This will be discussed more extensively below.) Accidents were assumed to occur exclusively in populated areas and only worst case atmospheric conditions were considered. No account was taken of actual fire failure modes as opposed to "worst-case" fire plus explosion.

A calculation of possible near-term incidence rate was made for the case of a fleet of 40 narrow bodied (Boeing 737) aircraft each containing 10 lbs. of graphite fiber in a composite form. This scenario closely approximates the actual use of graphite composites in NASA-sponsored flight demonstration projects at present. The results of the calculation show that this usage produces the possibility of between 35 and 50 incidents of graphite fiber induced electrical failure per year, arising from one expected aircraft accident involving fire every five years in a fleet size of 40 aircraft. This value is undoubtedly very conservative (high, perhaps by several orders of magnitude) because of the assumptions discussed earlier and because of the assumption that each fire related accident would involve and consume all the composite material. This same statement cannot necessarily be made for aircraft use of graphite composites in the future. The quantities of material per aircraft may increase by a hundredfold and the number of aircraft involved may also increase by the same factor.

A similar calculation can be made for the case of incidents caused by graphite composites used in the 1990 automobiles. For this calculation, many of the same factors can be used. It should be cautioned, however, that for this case, the values assigned to the various factors are even less certain because of a total lack of test data directly applicable to automotive crash scenarios. However, for purposes of illustration, such a calculation was done.

Statistics from the National Highway Safety Council provide a "best estimate" that 0.1% of the 17 million automotive accidents occur each year involve fire in various degrees of severity. Using a value of 10,000 fire accidents per year to account for the severity, it is possible to show that if the average automobile in 1990 contained 90 pounds of graphite fiber, the rate of fiber induced electrical incidents might be very high based on the factors of population, transfer coefficient, etc., in Table 4.

An additional factor which should be considered in a more extensive risk assessment, but one which is difficult to quantify at this time, is related to the possible consequences of a given incident. Two electrical incidents which may cause approximately equal damage to a given piece of equipment may have vastly different consequences. Using the two examples given above, it is easy to imagine that an accident at a commercial airport which caused temporary or permanent failure of a critical communications component could have a much more severe impact in terms of both safety and costs than would equivalent damage to a personal radio or television set. The failure of the communications link could result in the requirement to close the airport entirely resulting in a large economic loss, or, in the worst case, could result in the crash of other aircraft. The auto accident, however, would be more likely to result in "nuisance failure" of consumer products which would result in inconvenience to individuals and businesses accompanied only by minor economic loss unless major structural fires resulted. These sorts of factors must be evaluated in future studies when more source and vulnerability data are available.

As indicated in Table 4, the transfer coefficient describing the ratio between fiber exposure levels in the free atmosphere to those at site of electrical hazard can vary from 1 to 0. The value used for the above calculations was 1. However, relatively simple protection methods such as providing well sealed cabinets and consoles for electronic assemblies, using fitted filters with all chassis ventilation fans, conformally coating all circuit boards, and either increasing the spacings between terminal strips or covering the terminals themselves have been shown to decrease the transfer coefficient and thereby decrease the incidence rate. Reductions in the coefficient of one or two orders of magnitude should not be difficult to achieve with equipment for which it is possible and practical to provide sealed cabinets and filter protection.

B. Future Health Implications

Future health implications relate to three primary areas of consideration:

(1) Lack of definition of size and shape and other factors related to carbon fibers.

(2) The implications of controlled and uncontrolled incineration, from occupational considerations as well as general waste disposal, related to air, water, and soil contamination.

(3) Future increases in production and distribution as related to manufacturing, commercial products, and other composite matrixes.

If total composite material recycling could be developed and inititated now, many of the occupational and environmental health implications could be significantly reduced. In addition, this would enhance conservation of resources and provide for increased energy savings through utilization of lighter and stronger materials for secondary structural applications.

Overall health implications of the carbon fiber can also be reduced when the fibers are incorporated into a stable composite matrix. Other steps, such as coating of the fibers, may reduce possible health implications.

Care must be taken during the development of any alternate materials so that a more significant health risk is not developed.

In summary, we need to know more about carbon fibers, including their interaction with the human body, industrial hygiene and environmental considerations, and future implications of an expanded commercial usage. The U.S. Public Health Service may inititate efforts to better determine sampling and analytical methods, fiber size and shape determinations, fiber transport mechanisms, control technologies, and toxicological and epidemiological studies to better define the nature of any associated health risks to both workers and the general public.

C. Protective and Remedial Measures

The electrical hazards created by carbon fibers could be protected against or remedied by a number of methods. Obviously, one method would be to regulate or terminate the manufacture and sale of the fibers, the composite material, or certain end-products. The following discussion assumes that the anticipated benefits to the U. S. of continued use of composite materials preclude consideration of such action at this time.

(1) Protective

A partial list of possible methods of protecting against electrical incidents is given in Table 6. These fall into three broad classifications: (1) protection of equipment; (2) limiting dissemination of hazardous fibers; and (3) modification of the hazard causing material. Limited test data suggest that all of the listed methods of equipment protection can be very effective. However, more research of the type to be discussed later in this section is needed to quantify the potential of each method. The added cost of protecting equipment will depend very significantly on the degree to which the electronics industry has already begun to move in a direction which will provide some measure of protection to electronic circuit boards and terminal strips. They have, for some time, been conformally coating circuit boards for aerospace applications which might be subject to contamination from debris in either short- or long-term weightless conditions. Some companies now indicate that they are applying similar coatings to boards for consumer applications to increase reliability. The cost of such coatings is apparently small compared to other production costs. This would probably hold true for production of protected or redesigned terminal strips for new equipment. Improved sealing and filtered ventilation for consoles and chassis could probably be used on new equipment at only a small fraction of the overall product manufacturing cost.

(2) Remedial

Existing electrical and electronic equipment would be much more difficult and costly to protect than would new equipment. Such costs cannot be reasonably estimated at this time. However, based on the number of years before the use of graphite composites reaches the large volume projected for 1990, it is likely that most of the equipment now being produced will be obsolete and out of service before a significant problem exists. Therefore, if manufacturers were made aware of the potential problem now and if they introduced improvements in new product lines, it is likely that only a small fraction of equipment existing in the 1990's would have to be retrofitted with protective materials and devices.

One area of uncertainty regarding costs of hazard prevention in the future is tied to the unknown persistence and redistribution of graphite fibers in the environment. If liberated graphite fibers retain their high conductivity and persist as individual particles for long periods of time, it is possible that they could represent a continually increasing background capable of electrical contamination and hazard throughout the country. If this occurred, it is conceivable that it would be necessary to use "clean room" procedures whenever producing or repairing any

Table 6

METHODS OF PROTECTION

Protection of Equipment:

- Conformal Coating
- Filters
- Sealed Cases
- Clean Rooms

Limiting Dissemination:

- Safety Regulations for Transport, Storage, and Use
- Warning Labels Against Burning and about Storage, and Use
- Safety Regulations for Handling During Manufacturing
- Firefighting Techniques
- Disposal Techniques
- Precipitators on Incinerators
- Burial of Waste

Modification of Material:

- Changes in Conductivity, Fall Rate, Fiber Length, Clumping Characteristics
- Improved Matrix Materials
- Containment of Residue

equipment containing open electrical circuitry. The costs for establishing this much higher degree of cleanliness for the electronics industry and for society in general would undoubtedly be enormous.

(3) Material Modification

Of the three classes of protective methods shown in Table 6, only material modification holds the promise of elimination of the electrical hazard entirely. Modifications which could dramatically reduce the conductivity of the fibers or could drastically reduce the potential for atmospheric dissemination could reduce the risks sufficiently that the hazard would be effectively eliminated. However, while some approaches which might lead to such amelioration have been identified and will be discussed later in this section, there are no proven technical means currently existing.

(4) Repair and Cleanup

Very little is known concerning the cost and complexity of repair and cleanup of either accident sites or affected electrical equipment. A joint NASA/Navy full scale test program is to develop methods to neutralize or minimize the release of graphite fibers in the case of an aircraft crash and fire. It will include studies of the best ways to fight crash-related aircraft fires, the containment of graphite fibers and lint, decontamination of the affected area, and disposal of debris.

The cost of cleanup and repair of electrical equipment which has been contaminated by fibers is also under investigation by both NASA and DOD. Preliminary DOD data indicate a wide variation in both time required and effectiveness of known decontamination procedures. Standard cleanup procedures involve vacuum cleaning the affected equipment, washing with a detergent solution which is harmless to electronics, and air drying. The estimated time for cleanup of specific equipment has been reported to be as little as one-half a manhour to many manhours. Sometimes the cleanup procedure has been reported as being very effective; in other cases, a new failure has been noted immediately after the equipment is re-energized. Considerably more data must be acquired before the cost and effectiveness of cleanup procedures can be determined.

Similarly, the cost of repair of affected equipment is widely variable depending on the specific component or circuitry involved. Incidents which involve shorts across low voltage circuits or on the "load" side of a power supply may be repaired by either decontaminating the equipment alone or by replacing a minor circuit component after decontamination. Incidents which are caused by fiber induced shorts on the high voltage or power generating portion of the equipment may lead to massive destruction of the electronic circuitry and may require replacement of the equipment. Due to the random nature of the specific events which can occur within any particular piece of electrical equipment, a conservative estimate of the cost of repair of affected equipment would be equal to the cost of replacement of the equipment.

D. Good Work Practices and Protective Measures to Safeguard Human Health

(1) Users of carbon fiber materials should be made aware of the potential health hazards.

(2) Engineering controls should be installed in work areas to minimize exposure to the fibers.

(3) Properly designed local exhaust systems should be used in manufacturing processes where possible to prevent the dispersion of airborne fibers. Where exposures may occur, proper protective clothing, gloves, respirators, etc., may be advisable, depending on fiber size and degree of exposure.

(4) Appropiate protective equipment (coveralls, gloves, eye shields, and respirators where necessary) should be made available to workers as well as adequate wash and shower facilities.

(5) Hand wash and shower facilities should be available to exposed persons. General good housekeeping procedures such as vacuum cleaning, washdown procedures, and wet sweeping should be followed. More extensive recommendations are provided in Appendix A.

E. Research and Technology Development Needs

Many of the characteristics and effects associated with carbon fibers are incompletely known. The relative newness of the problem, and the limited resources thus far devoted to addressing the problem all have led to the relative scarcity of data related to: understanding the details of damage mechanisms to equipment and people, and what protective measures can be employed; prevention of introduction of carbon fibers into the atmosphere; and modification of material so that the damaging effects can be avoided.

Further research is needed in the following areas:

(1) Sources of Free Fibers - How they are released or disseminated from the material in question:

(a) Aircraft/Spacecraft

Small scale and large scale tests are currently underway to determine release rates, dispersion characteristics, etc., in the case of aircraft crashes accompanied by explosion. Testing involving aircraft accidents involving large pool fires (not involving explosion) and in-flight fire plus explosion is needed. The possibility of accidental release from graphite fiber composites on spacecraft which might suffer an explosion and/or fire on the launch pad or might undergo burn-up as a result of an unplanned reentry also needs investigating.

(b) Surface Transportation

Small scale and full scale tests are needed on graphite/polyester composite automotive components under a wide range of conditions to simulate the various accident scenarios representative of automobiles, trucks, and freight cars. The tests should provide data on both chopped fiber composites and continuous fiber composites of the types expected to find application.

(c) Handling/Disposal

Tests are needed to determine proper handling and disposal procedures for both carbon-fiber-containing scrap and discarded products containing carbon fibers. The effectiveness of current filters/precipitation of commercial incinerators requires assessment. Economical methods for separating carbon fibers from other scrap materials need to be investigated.

(d) Persistence

The likelihood of previously dispersed fibers being a source for continuing incidents at future times requires study. Data are needed on the degradation of fibers, their tendency to cluster into less hazardous forms, possibilities of transport on water, etc. Such data, and data on the cumulative buildup of released fibers will permit assessment of the statistical incidence of threat due to this background as a source.

(2) Vulnerability - The degree of susceptibility of electronic and electrical equipment to damage by the graphite fibers.

(a) Airport/Aircraft

Tests are currently underway to develop an understanding of vulnerability (i.e., critical exposure levels, transfer functions, etc.) for both critical airport navigation and communication equipment as well as essential aircraft electronics.

(b) Consumer/Business

The vulnerability of a wide range of civilian consumer and business equipment requires study: home and building electrical circuits, home appliances, business machines, computers.

(c) High-Power Generation and Distribution Systems

A test program to determine the statistical vulnerability of utility power generation and distribution equipment is needed to identify the susceptibility of power turbines, power substations, high voltage transmission lines and insulations, etc., to fibers of various lengths and from various sources, and to assess the consequences of various types of incidents.

(3) Protection and Alleviation - Procedures designed to protect equipment from damage by exposure to the fibers, as well as possible modification of composite materials to minimize the damaging effect:

(a) Firefighting, Cleanup, and Disposal

Large scale tests, under a variety of conditions, are needed to develop methods to minimize the release of carbon fibers in the case of various accident scenarios. Because of the different equipment available and various degrees of control possible, many different accident scenarios need attention. These are listed below:

- Aircraft crash at airport
- Non-airport aircraft crash
- Automobile crash plus fire
- Incinerator release

Such tests should identify optimum firefighting techniques, containment of residue, decontamination of the affected area, and disposal of residue.

(b) Equipment/Building Protection

The possibility of devising economical techniques for protecting specific electrical equipment and for "hardening" entire buildings from intrusion by carbon fibers needs investigation. These might include: packaging techniques, filters, conformal coating of components, component redesign, improved ventilation filtering systems, and building (door and window) sealing techniques.

(c) Safety Regulations

Methods for reducing the threat from accidental release by defining safety regulations and containers for transport, storage, and use of graphite fiber containing material, using warning labels on products containing graphite fibers, and by promoting user education require consideration.

(d) Material Modification

A substantial national effort is required to develop modified materials which eliminate or reduce the threat of graphite-induced electrical incidents. Approaches to material modification which have been identified to date fall into the following three categories:

- Fiber modification to reduce the conductivity or to modify the dispersement characteristics of released fibers. Approaches to modifying the conductivity include "doping" the precursor fiber in some way which reduces the conductivity without affecting the mechanical properties, developing surface treatments which reduce the conductivity, or developing alternative fibers. Methods of modifying the dispersement characteristics include developing "fatter" fibers, bundling fibers together, etc.

- Matrix modification to provide a much greater degree of containment of the fibers in the case of a fire related accident. Methods for accomplishment of this include development of more resistant matrices, development of matrices which degrade to a stable char rather than melt or vaporize etc.

- Containment of the entire composite residue by wrapping the laminate with a single ply of stable, fire resistant material such as a thin, metallic coating or a layer of ceramic fibers.

Many other materials modification techniques may be identified in addition to those listed above when a broader spectrum of the scientific community is made aware of the problem.

(4) Risk Assessment - To enable trade-off decisions between anticipated benefits of and risks inherent in extensive use of graphite composite materials:

(a) Near-term Risk

Analytical risk analyses are currently underway to assess the immediate threat to airport environs and urban population centers from the crash of both military and civilian aircraft containing graphite composites. These analyses are being developed from available data on sources of graphite fiber applicable to the crash plus fire scenario, measured vulnerability of representative equipment and from atmospheric dispersion models developed in related studies. These studies do not yet deal with spacecraft accidents and other fiber release scenarios, with methods of disposal of consumer products (including industrial scrap), with characteristics of commercial incinerators, or with product "wear-out" rates.

(b) Future Risk

Continuing studies to redefine the overall risk associated with the widespread future use of graphite composites in all projected commercial applications would guide the direction of, and the need for, future research activities and budget requirements.

(5) Health Hazards

(a) Fiber Effects

Although preliminary test data show graphite fibers to not pose a significant health hazard, this is an area of obvious public concern which requires much fuller understanding.

(b) Resin Toxicity

Laboratory tests and statistical analyses are needed to determine the additional risk to humans from toxic products formed by burning of composite matrix materials, including both conventional resins and modified resins which might be developed under a materials modification program.

VI. COURSES OF ACTION FOR UNITED STATES GOVERNMENT CONSIDERATION

The spectrum of responses to the graphite fiber situation open to the Federal establishment, at this time, appears to range from taking limited actions to immediate recognition of the potential threat through regulation of composite material producers and users. A key factor in selecting a course of action appears to be the amount of factual information available at the moment.

A. To take no action at this time would presuppose that the data in hand support a position that no present or future risks of any magnitude exist at either current or estimated usage levels of graphite fibers. The current state of knowledge, as noted in Sections IV and V, does not offer a sufficiently categorical assurance that the public welfare might not suffer from governmental inaction at this time.

B. A number of intermediate or preliminary steps are open to the Government in response to the perceived problem of minimizing the social and economic impacts of useful graphite fiber materials. These include:

(1) Informing potentially affected sectors of society (importers, manufacturers, processors, users, disposers, and the general public at large) of the potential hazards.

(2) Encouraging private sector solutions to questions of vulnerability, alternative materials, and disposal techniques.

(3) Developing a broad data base on material sources and usage, on fiber effects across a full range of facilities and equipments, and on incidents related to carbon fibers and their analogues.

(4) Focusing Federal R&D on defensive measures, alternate and modified materials, and disposal techniques.

C. Regulatory measures up to and including a ban on the manufacturing, fabrication, or end-use of carbon/graphite composites in the United States require careful consideration of technical data and legal authority. In the absence of evidenced health effects, unilaterai regulatory actions by the United States Government could be challenged as restraint of commerce; legislation might be required. The paucity of analogous precedents dealing largely with hazards to property and equipment, but of uncertain or second order public health impact, warrants further development of information before regulation can be contemplated. It is not clear that existing legal authorities would permit a substantial ban on a structural material which is not hazardous in its fabricated form, but which may become so if released through accidents which are beyond Governmental control.

Nevertheless, various Federal agencies do have existing authorities to regulate the use of certain hazardous materials. Specific controls over clearly dangerous (e.g., toxic) materials and products governing their production, fabrication, waste disposal and product disposal has been effected by rule making.

To date, some "self-regulation" over graphite composites has been realized as a result of information disseminated to some material producers and fabricators: (1) earlier processing techniques which put plants at risk and posed potential liabilities to their operators are being corrected; (2) manufacturing waste is being disposed of voluntarily by burial rather than incineration. However, because of the Government's inability to prevent accidents or effectively control actions of individual consumers, regulation short of a ban would seem of little value in coping with the fully developed array of composite material applications foreseen for the future. Regulation, therefore, should be looked to, if needed, to insure compliance in the highest risk activities of the material life cycle, e.g., production, fabrication, and disposal.

At the moment, the hazards to neither equipment nor human health and safety appear to support a total ban on graphite composites. The potential energy savings, safety, and other benefits are sufficient to warrant continued exploration of positive approaches to minimizing adverse effects. There is no evidence of restraints abroad against use of the material, and their general advantages make it unlikely that other governments would follow suit domestically if a U.S. ban on import or manufacturing were imposed. However, if safe fiber manufacturing techniques, safe composite applications, post-accident controls, and nonhazardous disposal methods cannot be developed, nor nonhazardous alternative materials developed, selective (use-oriented) or total bans remain possible Federal courses of action for the future.

APPENDIX A

Protective Measures to Minimize Exposure to Mineral Fibers

The areas of the body most susceptible to hazards from fibers are the skin, eyes, and respiratory system. Prevention of contact with these areas can be accomplished by the interposition of protective equipment and protective clothing.

Respiratory protection is necessary in those operations where high volumes of dust are generated and where adherence to environmental exposure limits cannot be achieved by engineering controls. While the primary concern is for fibers having diameters of 3.5 μm or less, larger diameter fibers are also potentially deleterious to the nasopharngeal region. Fibers capable of causing laceration in the nasopharnx can be prevented from entering the nose by disposable respirators.

Respirators are recommended where engineering controls cannot be applied in operations involving fibers 1 μm or less in diameter, because of the extreme respirability of such fibers. To insure that very small fibers (those less than 1 μm in diameter) will not penetrate the lungs, respirators should be used even if engineering controls are present.

The observance of good personal hygiene is of primary importance if dermatologic problems are to be avoided or minimized. Conveniently located hand washing facilities should be provided and persons should be instructed as to the importance of their proper use. In addition, exposed people should shower at the end of the exposure period.

Special consideration should be given to the laundering of contaminated clothing. Contamination of other clothes that came in contact with these clothes in laundry machines has been observed. In operations where clothes are laundered under contract, it is important to inform contractors of the hazards of laundering clothes contaminated with fibers.

Most skin problems arise from direct contact with fibers through handling rather than from airborne fibers or dust. Decisions on whether to use gloves or other protective clothing will depend on the nature of the work as well as the nature of the materials involved. Where the exposure is limited to fibers, experience has generally demonstrated that the use of gloves is not always indicated. Some people regularly exposed seem to become toughened to the fibers and may not need to wear gloves. Those with only intermittent exposures may not become "hardened" to the fibers.

Good housekeeping practices are essential for minimizing exposures. Vacuum cleaning, washdown procedures, and wet sweeping should be used where practical to control or reduce airborne concentrations of fibrous glass dust. Dry sweeping or the use of compressed air to remove dust should be prohibited. Scrap materials should be placed in suitable, covered storage containers located as close as possible to the point of origin of the waste. Disposal should be by methods which will ensure that fibers will not disperse into the atmosphere.

The feasibility of engineering control methods such as dilution or exhaust ventilation and enclosure will vary, depending on whether operations are being performed at fixed locations or in the field, including construction sites.

Respiratory protective devices are generally not needed for fiber exposures below recommended environmental limits. For situations where airborne concentrations may exceed the limits recommended, respirators could be used but not as a substitute for feasible engineering controls. When feasible, exhaust ventilation of the enclosure should be used to provide general room air changes and limit the need for wearing respirators. The air should not be exhausted into other work areas. Respirators are not recommended to be used as primary control measures in lieu of appropriate environmental engineering controls during routine, ongoing operations.

Eye protection, consisting of safety goggles or face shields and goggles are recommended for use in work necessitating tear-out, or blowing, or at any time when there is the likelihood of getting large quantities of airborne fibers in the eyes.

Well-designed and properly maintained local exhaust systems with appropriate capture velocities can minimize contamination of workers' breathing zones in production facilities. Manufacturing operations are often conducted at fixed locations where established principles of engineering control (e.g., ventilation, enclosure, or isolation) of operations could be applicable. In the majority of applications of fibers, certain operations are performed which have the potential for dispersing fibers into the air. These operations include cutting, sawing, grinding, sanding, and polishing. As with any other material subjected to such particulate dispersing operations, the basic engineering objective should be to prevent the particles from entering the general workplace air. The most generally applicable control measure is local exhaust ventilation, including high velocity, low tool attachments. Such ventilation should follow the principles presented in Industrial Ventilation, a Manual of Recommended Practices, published by the American Conference of Governmental Industrial Hygienists, or in Fundamentals Governing the Design and Operation of Local Exhaust Systems, Z9.2 (1971), published by the American National Standards Institute. Other control measures, including enclosure, isolation, or change of process could be useful in many situations and should be given consideration.

The use of compressed air to clean off various cutting surfaces or machinery often results in increasing airborne dust. Appropriate capture hoods should be used when compressed air is used.