United States
Environmental Protection
Agency

Industrial Environmental Research
Laboratory
Cincinnati OH 45268

Research and Development

EPA-600/S2-82-038 August 1982

EPA

Project Summary

Carbon Fiber Data Base: Review and Assessment of Carbon Fiber Release Into the Environment

The investigation described in this report was conducted as part of the carbon fiber disposal research effort undertaken by the Environmental Protection Agency. The purposes of this investigation were (1) to determine, from a literature search, the sources, extent, and frequency of carbon fiber releases to the environment, the risks related to these releases, and means of coping with the resulting problems, and (2) to assess future requirements and methodologies for minimum-risk disposal of carbon fiber materials.

This Project Summary was developed by EPA's Industrial Environmental Research Laboratory, Cincinnati, Ohio, to announce key findings of the research project that is fully documented in a separate report of the same title (see Project Report ordering information at back).

Introduction

Carbon fibers are used in combination with polymers to form lightweight, high-strength composite materials that will find increasing use in automobiles, sports equipment, and aircraft parts. During the manufacture of such composites or during the production of items made from them, some of their carbon fiber content may be accidently released to the environment. When items containing the composites are disposed of in municipal waste treatment systems employing conventional incinerators, significant amounts of the carbon fibers may be released to the environment with the flue gases from the incinerator. The freed carbon fibers, which are electrically conductive, can cause shorting out of electrical and electronic equipment. The potential health effects of short, small-diameter airborne fibers are presently under investigation.

This Project Summary presents results from an EPA-sponsored study on problems related to the production and use of carbon fiber materials. The final report upon which this summary is based identifies and evaluates potential environmental and health impacts of carbon fibers, and examines methods for controlling their release to the environment, in light of the increasing prevalence of carbon fiber composites in consumer goods and transportation equipment.

The study evaluates overall systems for disposal of carbon fiber materials. The evaluation identifies major potential sources of fibrous carbon expected to enter municipal waste streams, assesses the capabilities of solid waste disposal techniques applicable to carbon fiber materials, estimates the quantities of carbon fibers that will be released from municipal incinerators under various degrees of control, and estimates the number of electrical equipment failures expected to result from such releases.

The report reviews the carbon fiber programs being conducted by various Federal organizations. These programs focus on accidents that cause fires, effects of airborne fibers, and development of measurement techniques for airborne fibers.

The report also presents the results of a survey of current literature, which reveals that the following types of information are available: the effects of combustion of carbon fiber composites; the impacts of airborne carbon fibers, including incidents involving electrical failure; the present and projected future applications of composites; trends in current research into materials, processes, use, and environmental impacts; and the present manufacturers and users of fiber and of carbon fiber composites. Selected items from a research bibliography of some 600 pertinent publications and data sources are provided.

The study was performed by Bionetics Corporation under EPA Contract No. 68-03-2848. The work was completed in September, 1980.

Survey of Existing Information

A major endeavor in the carbon fiber project was to identify, acquire, and summarize data relevant to carbon fibers and composites in general and specific information on evaluations of projected risks of carbon fiber releases into the environment. This program involved an extensive survey of the literature. Informational areas included the determination of means of producing carbon fiber materials and their resultant properties, identification of principal uses of carbon fiber materials, identification of available reports on composites evaluations, investigations of fiber incineration hazards, and results of current assessments related to carbon fibers and composites utilized in specified applications.

Properties and Production of Carbon Fiber Materials

The physical properties of carbon fiber materials hinge on the type and proportion of fiber, as well as the type of resin matrix employed. The first production stage forms long strands of spun, multifilament fiber on spools. The spooled material, called tow, is either shipped to the ultimate parts fabricators or utilized directly for weaving into cloth or for chopping into matting/molding elements. Particular applications (cloth or tape formation) benefit from prepregging — an impregnation of the fiber tow with resin prior to layup. The parts manufacturer then forms and cures the layups or moldings in fabrication of the carbon fiber composite article. The degree of carbon fiber graphitization (affected by curing temperature, pressure, and time) determines tensile strengths and material stiffness characteristics. Step-by-step flows of the materials and processes in the production of carbon fiber composites are presented in the report. Important material properties are numerically tabulated. Names and locations of U.S. producers and users of carbon fiber materials are listed in the report. A listing of 138 users of such materials, nationwide, is given.

Principal Applications of Carbon Fiber Materials; Anticipated Increases

Major uses foreseen for carbon fiber composites include consumer products/sporting goods, surface transport vehicles, industrial equipment/hardware, medical equipment (orthopedic implants, furniture), aircraft, and spacecraft.

The authors of the final report found that the greatest potential growth area for carbon fiber composites is in highway vehicles.* In aircraft applications, a nominal fleet of 3,000 commercial aircraft will probably require about 3,000 metric tons of carbon fiber composites, or about one metric ton per aircraft. Some production models of next-generation military aircraft are expected to utilize cumulatively in excess of 450 metric tons of carbon fiber materials.

Reporting of Composites Evaluations

Both U.S. and foreign publications emphasized aerospace applications of carbon fiber composites, principally documenting the physical/mechanical properties, analytical techniques, design and fabrication methods, and component testing. Somewhat less research has been conducted in the properties and production of fibers and resins. About 400 U.S. documents and more than 200 foreign documents were reviewed in the literature search. A selected research bibliography is included in the report.

*Author's note. Since the final report was written, a shift in potential carbon fiber use has occurred, with automobile usage decreased and aerospace industry usage increased

To facilitate interchange of information, a "Directory and Locator for the National Graphite Fiber Program" is presented. Included in the Interagency Data Exchange are Federal offices, agencies, departments, and support operations. Interagency generators of data as well as potentially interested recipients of data are tabulated, and likely major subject categories are cross-referenced.

Fiber Incineration Hazards

Categories of optically distinguishable types of materials released from carbon fiber composite fires are shown in Table 1. All categories except the single fibers have settling rates generally sufficient for their capture within the flow passages of an incinerator. Low free fall rates of single fibers contribute to their remaining in the gas stream, thence lofted from the stack to drift downwind in the plume.

Test results of carbon fibers released from burning of composites are presented in Figure 1. Shown are the typical distributions of free carbon fibers, fire residue (multiple-fiber constituents remaining after test combustion) and completely oxidized fiber (release of CO_2) to effect a mass balance based on the initial preburned weight of fiber in the composite. The fraction of escaping single fibers accompanying incineration tends to increase with increased stirring or agitation of the burning material.

Estimated releases of carbon fibers from the fire zones of municipal incinerators with low agitation are as follows:

- Up to one percent by weight of the input fibers would appear in the exhaust as single fibers *greater* than 1 mm long. These longer fibers vary in length essentially within an exponential distribution with a mean of about 1.8 mm. Oxidation during burning would reduce the diameters of up to 80 percent of this population of fibers from an as-produced diameter of 8 micrometers to around 4 micrometers.
- Up to four percent of the incinerator input fibers would appear in the exhaust stream as discrete fibers *less* than 1 mm long and with an average length of about 0.25 mm. Oxidation effects would again be expected to reduce about 80 percent of the population to diameters of the order of 4 micrometers.

Table 1. Fire-Release Fiber Categories

Category	Description	Free Fall Rate In Air
1. Single Fibers	Single fibers up to 8μm in diameter, and up to 10mm in length	0.032 m/sec (max)
2. Lint	A group of fibers loosely bound, randomly aligned	0.22 m/sec
3. Brush/Clump	A group of fibers, bound together with well defined alignment	0.88 m/sec
4. Fragments	Pieces of burned composite with dimensions ranging from 2 mm to 25mm	1.5 to 1.9 m/sec
5. Strips	Elements of composite having lengths comparable to the dimensions of the item being burned	2.0 to 10.0 m/sec

Source:
(1) Lieberman, P., Chovit, A.R., Sussholz, B., and Korman, H.F., "Data Reduction and Analysis of Graphite Fiber Release Experiments," NASA CR-159032, 1979.
(2) Bell, V.L., "Releases of Carbon Fibers from Burning Composites," NASA Conference Publication 2119, December 4-5, 1979, pp. 29-57.

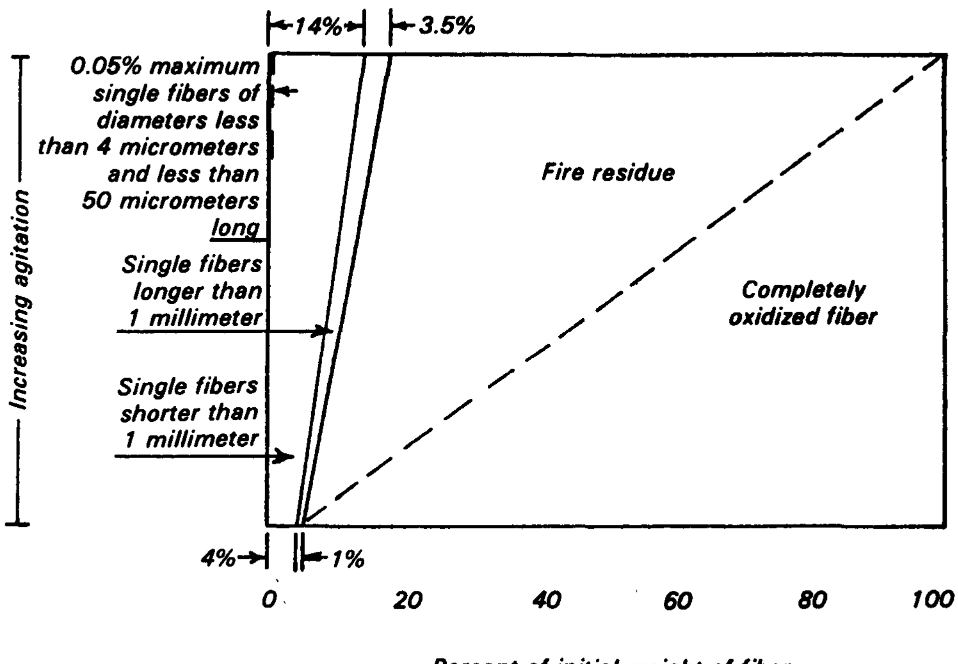

Figure 1. Mass balance for carbon fibers from burned composites.

Source:
Bell, V.L., "Release of carbon fibers from burning composites," NASA Conference Publication 2119, December 4-5, 1979, pp. 29-57.

- At the extreme short end of the short-fiber population (the short dashed line at the upper left edge of the curves in Figure 1), about 0.05 percent of the input fibers would appear as emitted particles shorter than 50 micrometers, with as-incinerated diameters reduced below 4 micrometers.

In these three portions of the fiber population emitted during burning at low agitation, the longer fiber segment is principally responsible for electrical hazards and resultant system failures. The shorter fibers fall into the category which is currently under investigation for health-related effects.

The tendency for airborne carbon fibers to create electrical failures is defined in terms of the exposure of electrical equipment to time-integrated fiber concentrations. Repeated tests of specific items of electrical equipment at established levels of airborne fiber concentrations for extended times have yielded an average value of exposure that produces an electrical failure. Based on actual operational exposures compared with average test specimen exposures to produce equipment failure, probabilities of equipment failure levels have been modeled.

Electrical equipment degradation that causes electrical shock hazards to the user appears to occur rarely. Downwind dispersion of airborne carbon fibers is generally adequate to dilute the plume concentrations to the point where such hazards appear to be random, i.e., not readily distinguishable from insulation-related failures from other causes.

As produced, carbon fibers have diameters larger than the air passages leading to the alveoli within the lungs. Studies of animals exposed to chopped fiber have produced no conclusive results. Partial oxidation of fibers reduces their diameters, making them more respirable. At the present time, the mechanism for human interaction with respirable size fibers has not been defined and studies in this area are continuing.

Current Assessments

Assessments of incremental risks from releases of carbon fibers conducted under governmental sponsorship as well as by governmental laboratories are reviewed and summarized. Losses in terms of economic impact (malfunctioning of electrical and electronic components) have been investigated by NASA, based on carbon fiber releases from accidents and fires involving commercial aircraft; a counterpart study has been conducted by the Department of Transportation for fire-releases likely to result from surface vehicle accidents. The Department of Energy has evaluated the economic losses of power system outages due to carbon fiber short-circuiting.

The Department of Health and Human Services/NIOSH is conducting experiments in which laboratory test animals were exposed to fibers in the respirable range (diameters less than 3.5 μm and length-to-diameter ratios in the range, 3:1 to 10:10). The Department of Labor/OSHA is monitoring the results toward establishing regulatory needs, if they are deemed necessary.

The Department of Defense has examined the effects of carbon fiber fallout on the operation and availability of electronics and electrical components, vital for national defense.

Department of Commerce investigations (completed) have addressed present and future production of carbon fiber materials.

The President's Office of Science and Technology Policy (OSTP) designated other Federal organizations to perform other research related to carbon fiber utilization. In the EPA, the Environmental Sciences Research Laboratory at Research Triangle Park, North Carolina, has the responsibility for conducting the Carbon Fiber Monitoring Research Program. The program focuses on the development of instrumentation and monitoring techniques for measuring airborne emissions of carbon fibers. Also, the Municipal Environmental Research Laboratory in Cincinnati, Ohio*, is overseeing studies in disposal technology for carbon fiber materials.

The Federal Emergency Management Agency is engaged in identifying, analyzing, and reporting civil incidents involving carbon fibers. The Federal Aviation Administration is to summarize identifying information on aircraft incorporating the composites and to report accidents related to aircraft which contain carbon fiber composites.

Assessment of Release Mechanisms and Disposal Techniques

Once a level of anticipated usage of carbon fiber composites is determined, assessments of carbon fiber disposal and damage hinge on factors such as handling procedures thoroughout the life cycle of the commercial products, the characteristics of the disposal techniques, and carbon fiber emission mechanisms.

The likelihood of controlled or uncontrolled releases of disposed carbon fiber materials is expected to depend on the type of application of the material, whether in transport aircraft, automobiles, sporting goods, or medical devices. Any industries that dispose of production scrap without control could be expected to contribute to the overall fiber release problem.

The potential releases of airborne carbon fibers from waste composites in disposal systems are evaluated. The two major disposal methods are *bulk* (landfilling and recycling) and *combustion/oxida tion.* Adverse impacts associated with carbon fiber material disposal are deterined by:

- the probability of fibers becoming airborne, which in turn is a function of fiber release from the matrix, fiber destruction, and process retention of the fibers (e.g., filtration and removal in the exhaust)
- the released fiber characteristics (e.g., dimensional, electrical)
- duration and magnitude of the release.

The report evaluates three categories of carbon fiber composite disposal methods: (1) municipal disposal techniques in current use; (2) potentially applicable techniques; and (3) special-purpose disposal techniques that require further development. Among the various disposal techniques single-step, mass burning and refuse-derived fuel processes are considered "good" based on potential for fiber oxidation, but are expected to require particle control. The mass-fired two-step burn process is rated "good" and probably will not require downstream particle control. Pyrolitic processing is similarly rated "good" but may require a precipitator or scrubber to remove particles from the exhaust stream. Molten salt and wet air oxidation are two techniques which are believed to possess an "excellent" potential for fiber oxidation, and need no downstream particle removal.

No obvious large-volume source of carbon-fiber-type wastes currently exists. Although automotive applications and sporting goods scrap rates are expected in the future to generate large volumes of waste materials, projections indicate that carbon fiber composites will comprise only about 1.15×10^{-3} percent of the total mass of waste handled in municipal waste streams, with an assumed 5.2 percent of that material being incinerated, or about 110 metric tons per year.

The report presents order of magnitude calculations of the potential effects of carbon fiber incineration in the 1990's. By application of Bureau of Census demographic projections and a simplified plume dispersion model, the resulting total release of incinerated fibers, nationwide number of sources, and prevalent depositions of fibers for sizes of electrical and of respirable concern are estimated. Only a small number of household electrical appliances are likely to fail annually as a result of shorting by carbon fibers. Correspondingly, individuals receiving the maximum calculated exposure to respirable carbon fibers downwind of incinerators would require an estimated 7400 years of exposure to even accumulate the equivalent of the current NIOSH workplace limit on asbestos fiber exposure.

Conclusions and Recommendations

Projections of increasing usage of carbon fiber composites indicate that electrical electronic shorting problems are a small but definable risk with uncontrolled releases of unburned fibers during incineration of expended products or of scrap materials.

Manufacturing processes also may release concentrations of fibrous airborne particles which require protective measures for nearby production personnel; in production areas, exhaust filtering/collection systems are conventionally installed, and production workers are customarily required to use protective breathing apparatus. Also, the diameters and lengths of the airborne raw fibers, prior to reduction by combustion, generally exceed the dimensions which can be carried into the air cells of the lungs. Ongoing research is focused on investigating the potential for production of respirable particulates during manufacturing.

While incinerators may produce significant concentrations of released carbon fibers, the emission of *respirable* fibers has been observed to be low. Health hazards of exposure to respirable carbon fibers are still under investigation.

*Disposal research responsibility has recently been shifted within EPA to the Industrial Environmental Research Laboratory, Cincinnati, OH

The report authors anticipate that properly designed and controlled incinerators may be capable of completely destroying most free carbon fibers—to the point of even nullifying any need for fiber entrapment. Nevertheless, limited quantities of uncontrolled carbon fiber composites still would be expected to find their way into the municipal waste streams that feed conventional incinerators. Since conventional incinerators may not be designed exclusively for destruction of carbon or graphite substances, the flame temperatures and retention times may be inadequate for complete combustion of carbon fibers.

Carbon fiber composites will have extensive use in aerospace structures as well as in medical applications and industrial hardware, but the major sources of *uncontrolled* disposal are likely to be consumer sporting goods and automotive products (discarded mainly by body shops or backyard mechanics). *Controlled* disposal, as in the case of wastes from manufacturers, is expected to be directed to suitable facilities such as dedicated incinerators or secure landfills.

The following recommended research activities should be accorded prompt attention:

- Evaluation of particle control technology, namely, the effectiveness of electrostatic precipitators, wet scrubbers, and baghouses in cleaning up incinerator exhaust gases during operations with carbon fibers of various diameters and lengths and mixed with other exhaust products.
- Estimation of possible levels of airborne fibers produced from front-end, pre-incineration operations including refuse shredding, screening, crushing, air classifying, compacting.
- Determination of the efficiency of mass-fired two-stage incinerators for handling carbon fiber composites, especially designs of units and operational means to reduce uncertainties in production of carbon fiber emissions.
- In the longer term, it is recommended that EPA evaluate the need for dedicated facilities for disposal of carbon fiber materials, especially landfilling operations resulting in the release of the loose carbon fibers.

The authors are staff of the Carbon Fiber Data Base Project Group, The Bionetics Corporation, Hampton, VA 23666.

***R. A. Carnes** is the EPA Project Officer (see below for contact).*

The complete report, entitled "Carbon Fiber Data Base: Review and Assessment of Carbon Fiber Release Into the Environment," (Order No. PB 82-236 027; Cost: $19.50, subject to change) will be available only from:

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone: 703-487-4650

*For information contact **B. L. Blaney** at:*

Industrial Environmental Research Laboratory
U.S. Environmental Protection Agency
Cincinnati, OH 45268

☆USGPO: 1982 — 559-092/0475

United States
Environmental Protection
Agency

Center for Environmental Research
Information
Cincinnati OH 45268

Postage and
Fees Paid
Environmental
Protection
Agency
EPA 335

Official Business
Penalty for Private Use $300

RETURN POSTAGE GUARANTEED

PS 0000329
U S ENVIR PROTECTION AGENCY
REGION 5 LIBRARY
230 S DEARBORN STREET
CHICAGO IL 60604