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CARBON/GRAPHITE FIBERS: ENVIRONMENTAL EXPOSURES AND POTENTIAL HEALTH IMPLICATIONS

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Health effects related to carbon (7440440), and graphite (7782425) fiber exposure are discussed. Industrial production of the fibers is reviewed. Data on fiber release and particle size is included. The results of epidemiological and animal toxicologic studies with fibrous glass (14808607), rock wool wollastonite (13983170), fibrous clay, asbestos (1332214) and carbon fibers are described. The authors recommend animal toxicity tests based on fiber size, deposition pattern and cause of death. The synergistic effect between carbon/graphite fiber exposure and cigarette smoke also should be studied. Worker exposures to these fibers should be kept as low as possible and managed in the same way as exposure to fibrous glass.

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INTRODUCTION

During January 1978, the Office of Science and Technology Policy (OSTP), through an interdepartment/interagency committee, recommended an action plan to study the potential problems associated with the use of carbon/graphite fibers. A major directive was to evaluate the hazards to electrical and electronic equipment from the inadvertent airborne release of carbon fibers, primarily as a result of an aircraft crash and burn. Likewise, the Department of Health and Human Services/National Institute for Occupational Safety and Health (HHS/NIOSH) was given the responsibility to assess the carbon/graphite fiber exposure data, evaluate the health implications, and determine the need for further research. The following is a review of carbon/graphite fiber studies conducted to characterize fibers released from burning composite materials, and an assessment of toxicological and epidemiological data as related to carbon/graphite fiber exposures.

HISTORY

The introduction of carbon fibers dates back to before 1880 when Thomas Edison made carbon filaments by carbonizing natural cellulose fibers from cotton and linen. In 1909, a patented process was developed in which carbonized cellulose fibers were coated with pyrolytic graphite by flashing at temperatures up to 2200°C. However, with the introduction of tungsten filaments, interest in carbon fiber applications declined. Within the last 20 years, a renewed interest in the utilization of carbon fiber composites has been brought about because of their unique properties, which result in a significant reduction in structural weight yet maintain the strength and durability of steel. The greatest use of carbon/graphite fiber composites is in commercial and military aircraft, with expanding usage in consumer goods (e.g., boats, fishing poles, racquets, musical instruments, etc.) automotive components, industrial hardware (e.g., gears, valves, fittings, etc.), and medical equipment.

Carbon and graphite fibers are made commercially from any carbonaceous, fibrous raw material that pyrolyzes to a char and leaves a high carbon residue. The physical properties of the final carbon fiber material are dependent upon not only the type of precursor material, but also such manufacturing variables as the rate of heating, maximum baking temperatures, baking environment, and the strain applied to the fiber during pyrolysis. Technically, the term "carbon fiber" is applied to those fibers that have been pyrolyzed at temperatures of 1200°C and consist essentially of amorphous carbon. The term "graphite fiber" is applied to the carbon fibers that have been heat treated at temperatures between 2200°C and 2700°C, resulting in a crystalline fiber structure.

Figure 1 illustrates the production of carbon/graphite composites. Rayon was the starting material, called a precursor, most often used for the production of carbon or graphite fibers prior to 1973, with a polyacrylonitrile (PAN) precursor being preferred since 1976. In recent years, a petroleum pitch precursor has been utilized because of its low cost and availability. Once the pitch or PAN fiber tow has been made, it undergoes a fiber formation process in which carbonization or graphitization takes place. The multifilament tow of carbon/graphite fiber (mean fiber diameter of 8.0 micrometers) is then woven into cloth, spun or chopped, and impregnated or mixed with a resin. Resins used in carbon/graphite composites are listed in Table 1. The molded fibers are then cured into a composite material for specialized application. Table 2 lists some of the structural properties of carbon/graphite fibers along with the manufacturers which produce these composite materials.

SUMMARY OF CARBON/GRAPHITE RELEASE STUDIES

A primary concern of the OSTP committee was to quantify the risks to the public resulting from the use of carbon/graphite composites. Of the studies conducted by the respective governmental agencies on the OSTP committee and their contractor organizations, those performed by the National Aeronautics and Space Administration (NASA) provided most of the documentation on potential airborne exposures to carbon/graphite fibers. These exposure data were accumulated as a result of studies designed to quantify the risks associated with the accidental release of carbon fibers resulting from an aircraft crash.

The tests conducted by NASA involved the burning of carbon/graphite composites to determine the number and sizes of released carbon fibers.[1] These tests included small-scale laboratory research along with outdoor simulated aircraft burns. The studies were designed to characterize fiber sizes (>1 mm length) thought to be responsible for electrical interference of power supples. Observations from the laboratory tests, in which composites were burned and subjected to mechanical agitation, airstreams, and explosives, indicated the release of single fibers up to 3.5% of the original fiber mass. Typical results from the outdoor fire, tests indicated that between 15% and 60% of the original composite mass remained in place after the fire with single fibers accounting for only 0.10% to 0.23% of the mass. Likewise, in a shock tube test, in which various type of electrical and electronic equipment were exposed to burning composite material, single fibers accounted for 0.75% of the fiber originally available. As illustrated in Figure 2, both the outdoor and shock tube tests indicated a small release of single fibers, with as much as 50% of the original composite mass consumed by oxidation in the fire. These outdoor tests confirmed the laboratory observations of the release of fibers under various test conditions (Figure 3).

Fiber lengths measured in these studies averaged between 2 and 3 mm, with few fibers longer than 4 mm. An investigation of fibers smaller than 1 mm in length indicated that these fibers constituted 67 to 74 mass percent of the total fibers released in undisturbed fires, and as high as 98 mass percent for those fibers released in fires accompanied by explosions. When fiber diameters were evaluated for fibers longer than 1 mm there was an observed reduction in size from the typical 7 to 8 micrometer (μm) diameter of the product material to an average of between 4.0 to 4.7 μm, at a lower detection limit of 1.0 μm.

A more extensive study was then conducted by NASA to characterize those fibers thought to be potentially respirable (lengths <80 μm and diameters <3 μm) which were being released during the burning of composite materials.[2] It was estimated that fewer than 24% of the fibers released during the composite burn tests fell into this size range. Likewise, a fiber size distribution performed by optical microscopy indicated an average of fiber diameter of 1.5 μm and an average length of 30 μm. These dimensions were based on lower detection limits of 0.4 μm for diameters and 2.0 μm for lengths, and a length-to-width aspect ratio of ≥ 3:1.

Approximately 50% of these fibers had aspect ratios $\leq$ 20:1, with 85% $\leq$ 40:1. It was evident from the microscopy analysis that some of the carbon/graphite fibers being released from the burning composite material were of a smaller diameter than that of the product material (normally 7 to 8 μm); this phenomenon was attributed to a fiber oxidation and fibrillation effect.

Based on the fiber size data collected during the outdoor burn tests, a laboratory controlled-burn experiment was conducted to investigate the mechanisms of fiber release and oxidation, and to find a means to collect and characterize released fibers.[(3)] The results of the experiment indicated that, depending upon the fire condition, a certain percentage of the fibers will partially oxidize and fracture into small diameter (needle-like) fibers. Many of these released fibers, although not quantified in the study, appeared to have diameters < 3.0 μm.

As a result of the fiber characterization studies, two studies were initiated in an attempt to quantify airborne fiber concentrations during the burning of carbon/graphite composites. One study used a theoretical approach based on fiber release data obtained in previous laboratory and outdoor burn tests.[(2)] Only those fibers considered to be potentially respirable (<3.0 μm in diameter and >8 μm in length) were utilized in predicting fiber exposures. The number of respirable-size fibers generated per kilogram of carbon fiber released during an aircraft accident and burn was estimated to be 5×10^{11}, with a mass fraction of 5% of the total fiber released. Based on these criteria, an estimated peak exposure of 5×10^{6} fibers/m^3 was determined with an upper limit exposure estimated at about 3.2×10^{8} fibers/second/m^3 for fibers within the smoke plume.

The other NASA study attempted to quantify and characterize fiber exposures during the burning of carbon/graphite composite materials by collecting air samples on a "Jacob's Ladder" suspended in the smoke plume (Figure 4).[(4)] Sampling was performed using battery-operated sampling pumps which drew air (2.0 liters per minute) through a cellulose membrane filter. Filters were analyzed utilizing phase contrast optical microscopy at 400X magnification with all fibers ($\geq$ 3:1) counted.[(5)] Based on a 20-minute burn time, concentrations were determined and these indicated a range from none detected to 0.14 fibers per cubic centimeter of air (fibers/cm^3). All fibers observed were $\geq$ 5 μm in length and < 3.5 μm in diameter, with 77% of the fibers $\leq$ 1.7 μm in diameter.

SUMMARY OF RELATED EPIDEMIOLOGIC AND ANIMAL TOXICOLOGIC STUDIES

Ever since the first reported death due to pulmonary fibrosis resulting from asbestos exposure in 1900, and subsequent comprehensive studies indicating an association between asbestos and respiratory diseases, the cause and effect relationships have been intensely investigated.[6,7] In one animal study using chrysotile asbestos, it was concluded that the fiber shape and size were more important factors in carcinogenesis than chemical composition.[8] This theory was substantiated in another animal study in which a series of different mineral dusts were injected into the pleural cavities of mice to test their relative fibrogencity.[9] The degree of cellular granulomatous adhesions which were found between the lungs, diaphragm, and chest wall were dependent upon particle size and morphology. The highest degree of fibrosis within the granulomata was demonstrated using long fibrous minerals. The amount of fibrosis decreased with shorter fibers and particles.

The precise fiber dimensions required to observe pathologic responses have been impossible to determine experimentally because of the difficulties encountered in producing fibers of specific size.[10] However, the results from some of the more recent studies suggest that long, thin fibers play an important role in eliciting a biological response. In a National Cancer Institute fiber implantation study, it was concluded that fibers $< 1.5\ \mu m$ in diameter and longer than $8.0\ \mu m$ in length may be the most important for production of pleural sarcomas.[11]

Epidemiologic Studies

To date, no epidemiologic studies have been conducted on persons exposed to carbon/graphite fibers. Likewise, few epidemiologic studies have been able to differentiate the pathologic responses (e.g., pulmonary fibrosis, lung neoplasms) in man with regard to fiber types and dimensions. The following is a cursory review of those occupational studies conducted by HHS/NIOSH to determine health implications from exposures to various fibrous materials. Similar research studies have been conducted by other groups, but are not included in this review.

Fibrous Glass (large diameter)[12]

Fibrous glass studies which have been conducted among workers producing fibrous glass of relatively large fiber diameter ($> 3.5\ \mu m$) have not shown an excess cancer risk. However, a slight excess mortality risk for nonmalignant respiratory disease, excluding influenza, has been observed.

Fibrous Glass (small diameter)[13]

A study of workers exposed to small diameter ($< 1.5\ \mu m$) fibrous glass is continuing for observation of any excess mortality. Latency from onset of exposure has been approximately 25 years, which is considered to be the minimum time period necessary for the initiation of both nonmalignant and malignant respiratory disease.

Rock Wool[14]

Results of an epidemiologic study of workers producing rock wool and slag wool suggest a possible increased risk of respiratory and gastro-intestinal cancer with long latency periods (> 30 yrs). Observed fiber diameters indicated a median of 2.2 µm, with 75% of all fibers being < 3.5 m in diameter. Airborne fiber concentrations ranged from 0.10 to 1.95 fibers/cm^3.

Wollastonite [15, 16]

In a morbidity study conducted on miners and millers exposed to wollastonite (a fibrous monocalcium silicate mineral), several abnormal medical findings were discovered, but no definite association of wollastonite exposure and excess morbidity could be demonstrated. However, because of the small number of subjects (N=92) studied and the short latency period (average 11.2 yrs) from onset of exposure, the sensitivity of the study was low. Typical airborne exposures indicated a median fiber diameter of 0.22 µm with varying fiber lengths (0.3 to 41.0 µm).

Fibrous Clay(17)

The preliminary mortality study results of workers exposed to a fibrous clay (attapulgite) indicate no statistical excess mortality. Workers are currently being categorized by exposure concentration and latency to determine if a dose-response relationship exists. The median fiber sizes observed in airborne exposures were 0.07 µm diameter and 0.40 µm length with no fibers observed longer than 2.50 µm.

Asbestos[18]

A morbidity study was initiated to study the health risks of workers associated with low level exposures to asbestos fibers during automotive brake servicing. The results of the study suggest no increase in respiratory diseases. A mortality study is being contemplated to determine if an excess mortality exists for this population. Exposures to asbestos for workers employed in this type of work indicate time-weighted average (TWA) exposures below the NIOSH recommended standard (of 0.1 fibers/cm^3). Most of the airborne fibers observed (>80%) were shorter than 5.0 µm in length with diameters 1.0 µm.

TOXICOLOGIC STUDIES

Carbon Fibers [19,20]

To date, two independent toxicologic studies have been conducted using carbon fibers. One study reported on the long-term toxicity of carbon fiber implants in rats and mice. Termination for those animals which survived was at 18 months for mice and 24 months for rats. Histological examination was carried out on all tissue sections from the implant areas and for specific organs removed at post-mortem examination. Only one malignant tumor (fibro-sarcoma) was found in relation to an implant. Fiber size data were not reported; however, it was assumed that the fibers used were of a commercially produced size (6 to 8 μm in diameter).

In the other study, guinea pigs were exposed to airborne chopped carbon fibers for time periods up to a maximum of 104 hours. About 99% of the airborne particles generated were nonfibrous and about 1.0 μm in diameter. Few of the airborne fibers observed were of a respirable size (reported as 1.0-2.5 μm diameter and < 10 μm length) with most fibers ≥ 10 μm in diameter and > 100 μm in length. Animals were sacrificed at intervals ranging from 1 to 144 days after exposure. Microscopic examination of lung tissue indicated the presence of four particulate types:

1) carbon fibers approximately 10 μm in diameter and > 100 μm in length,
2) nonfibrous carbon particles with diameters ranging from submicron to several microns,
3) carbon fibers ranging in diameter from 1.0 to 2.5 m and ≤ 15 μm in length, and
4) transparent fibers (unknown composition) typically 1.5 μm in diameter and up to 30 μm in length.

Most of the nonfibrous carbon particles observed in the lung tissues were in macrophages with most fibers found extracellular. No tumors were observed.

Fibrous Glass[21]

NIOSH has initiated a chronic inhalation study of fibrous glass. Both rats and monkeys are being exposed using four different exposure parameters.

1) concentration 15 mg/m^3 - fibers 4-6 μm dia./40-50 μm length
2) concentration 15 mg/m^3 - fibers 1 μm dia./ 10 μm length
3) concentration 5 mg/m^3 - fibers 1 μm dia./ 10 μm length
4) concentration 5 mg/m^3 - fibers 1 μm dia./ 10 μm length

This is an 18-month study in which pulmonary function tests will be given at periodic time intervals and with all animal sacrificed at the completion of the study for tumorigenic observation. After 15 months of the study, no significant decrease in pulmonary function has been observed.

Asbestos[22]

A chronic inhalation study with chrysotile asbestos shorter than 5 μm in length is currently under way at NIOSH. Both rats and monkeys are being exposed over an 18-month period to an asbestos concentration of 1.0 mg/m^3, 7 hours/day, and 5 days/week. After 15 months of the study, animal sacrifices have indicated asbestos fibers in the tissues, but no indication of fibrosis.

DISCUSSION

Although the respirability of airborne fibers is not clearly understood, it is thought to be mainly dependent on the fiber diameter. Studies have suggested that the two major mechanisms of fiber deposition in the upper airways (gravitational settling and inertial deposition) are chiefly dependent upon particle aerodynamic diameter[23] Fibers with densities < 3.5 g/cm^3 and diameters <3.5 µm may escape deposition by these two mechanisms and penetrate deeply into the lungs of humans.

Based on the current epidemiologic and toxicologic research with fibrous materials, it appears that fibers with diameters >3.5 µm have little effect in producing malignant diseases, and only a slight effect in inducing nonmalignant health risks in humans. Studies to date on carbon/graphite composite materials suggest that fibers released during the use of these materials are mostly >3.5 µm in diameter, except when exposed to high temperatures (900°C to 1100°C). As demonstrated during the burn tests of composite materials, a small percentage of carbon/graphite fibers are released with diamters <3.5 µm and lengths $>$ 10 µm. When exposures from outdoor burn tests ($\sim$20 minute duration) were quantitated for these small diameter fibers, concentrations appeared to be < 0.1 fibers/cm^3. Based on a theoretical model, the carbon/graphite exposures when extrapolated for a potential aircraft burn, indicated a release of small diameter fibers of 3.2×10^8 fibers/second/m^3; and, if accompanied with an explosion fiber release was estimated to increase by a factor of 3.5.

If we evaluate these exposures in the most restrictive manner, that is, comparing carbon/graphite fiber exposure data with the NIOSH-recommended occupational standard for asbestos, or, in a less restrictive manner, using the NIOSH-recommended standard for fibrous glass and other man-made fibers (Table 3), then the observed exposures to carbon/graphite fibers, to date, have always been some magnitude less than either of the NIOSH-recommended fiber standards.

The toxicologic mechanisms for the production of pulmonary fibrosis and respiratory cancer from exposure to certain fibers (e.g., asbestos, fibrous glass) are not well understood; however, a growing body of animal data suggest that these effects may be due to the fibers' dimensional morphology rather than physico-chemical properties. Numerous animal studies have shown that many types of fibrous materials produce fibrosis and tumors upon injection or implantation; yet, the exact delineation of fiber size characteristics necessary for animal tissue damage and tumor production is unknown. The ability of fibers with appropriate dimensional characteristics (diameter and length) to reach critical sites such as the pulmonary spaces or the gastrointestinal tract must be considered. In addition, respiratory clearance for different fiber types may be very important; differences in fiber clearance may be related to reactions with lung macrophages and to cytotoxicity of the material in question.

RECOMMENDATIONS

Based on the current exposure data for carbon/graphite fibers, and in view of the paucity of toxicity studies, it appears prudent that well-designed animal toxicity studies be performed with carbon/graphite composite materials which reflect the fiber characteristics observed in field and laboratory tests to date. Since the latency period from the onset of the first potential carbon/graphite fiber exposure to present, for either the general population or occupationally exposed persons, has probably been short (< 20 years), and, because fiber exposures documented to date appear minimal, it does not seem appropriate at this time to conduct either a mortality or morbidity study of persons who were potentially exposed. Likewise, an appropriate population for study would be extremely difficult to assemble and characterize.

It is suggested that the best means for evaluating the potential health effects of carbon/graphite fiber exposures would be through animal inhalation toxicity studies in which at least two species are used to determine deposition, retention, and cause of death. Typical carbon/graphite fiber exposures (e.g., as a result of burning, cutting, grinding, etc.) and fiber characteristics (e.g., certain size parameters for diameters and lengths) should be utilized under animal lifetime conditions, with care given to determining the actual deposition and retention in tissues and the appropriate health-effect end points. Since a synergistic association is known to exist between asbestos fibers and cigarette smoking, it may be appropriate to conduct at least one study that combines exposure to carbon/graphite fibers and cigarette smoke.[24]

In view of the environmental and health data, compiled to date it would be advisable to handle carbon/graphite composite materials and treat airborne fiber exposures in the same manner recommended by NIOSH for fibrous glass. Appropriate measures should be taken when working with carbon/graphite composite materials to minimize the potential for generating small diameter fibers and to control airborne exposures to the lowest feasible level.

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Table 1

Resins Used in Carbon/Graphite Composites

	GENERIC TYPE	CHEMICAL COMPOSITION	MELTING POINT (°C)	O_2 INDEX	NO. MFGS.
THERMOSETTING	EPOXY	Copolymer of epichlorohydrid and 2, 2 *bis* (4 hydroxy phenyl-piperazine)	215	29-46	140
	MELAMINE/UREA FORMALDEHYDE	Cross-linked amino resins	†	30-36	9
	PHENOLIC	Copolymer of phenol and formaldehyde	300	28-40	14
	POLYAMIDE/ POLYIMIDE	Specific group of amide-imide resins	300 - 400	*	8
	POLYESTER (unsaturated)	Copolymer of alkylene glycols and unsaturated acids	300	32-48	24
THERMOPLASTIC	ABS	Acrilonitrile-butadiene-styrene copolymer	80 - 125	19-29	18
	FLUOROPLASTIC	Fluorinated hydrocarbon polymers (CTFE)	Increases with fluorine content	> 95	27
	NYLON	Specific group of polyamide resins (nylon 6, 66, 610, 10, 11, 12)	197 -264	22-26	23
	POLYACETAL	Polymer of single or double carbon aldehydes	165	16	8
	POLYARYL OR POLYETHER SULFONE	Modified polysulfone polymers	160 - 230	38	3
	POLYCARBONATE	A linear polyester of carbonic acid	241	25-30	9
	POLYESTER (PBT)	Copolymer of alkylene glycols and phthalic acid	224	23-33	10
	POLYETHYLENE	Polymerized ethylene	135 - 141	26	32
	POLYPHENYLENE SULFIDE	Thiophenolic polymer	285	46-53	4
	POLYPROPYLENE	Polymerized propylene	141 - 171	18-28	24
	POLYSTYRENE	Aromatic substituted linear polymer	†	18-28	23
	POLYSULFONE	Aromatic sulfonic acid polymer	200	32	5
	SAN	Styrene-acrilonitrile polymer	†	19-28	8

† - Variable within generic type
* - High temperature distortion, > 260° C; high thermal stability, > 370° C.

From: Bionetics Corporation Report: EPA Contract No. 68-03-2848

Table 2

Manufactures of Carbon/Graphite Composites
and the Structural Properties of the Fibers

MANUFACTURER	MFG. LOCATION	TRADE NAME	GRADE	DENSITY g/cm^3	DENSITY (lb/in^3)	TENSILE STRENGTH GPa	TENSILE STRENGTH (lb/in^2)	TENSILE MODULUS GPa	TENSILE MODULUS $(10^6\ lb/in^2)$
AVCO	Lowell, Mass.	Gravco		1.75	(0.063)	2.76	(400,000)	207	(30.0)
Celanese Plastics & Specialties Co.	Summit, N.J.	Celion	GY-70	1.97	(0.071)	1.86	(270,000)	503	(73.0)
	Rock Hill, S.C. (Proposed)								
Great Lakes Carbon Co.	Elizabethton, Tenn.	Fortafil	3	1.72	(0.062)	2.48	(360,000)	207	(30.0)
			5	1.77	(0.064)	2.76	(400,000)	331	(48.0)
Hercules	Magna, Utah	Magnamite	AS	1.80	(0.065)	3.10	(450,000)	234	(34.0)
			HTS	1.66	(0.060)	2.76	(400,000)	248	(36.0)
			HMS	1.83	(0.066)	2.21	(320,000)	365	(53.0)
HITCO	Compton, CA	HI-TEX	1500	1.80	(0.065)	3.17	(460,000)	248	(36.0)
	Gardena, CA		3000	1.80	(0.065)	3.03	(440,000)	241	(35.0)
			6000	1.80	(0.065)	2.90	(420,000)	234	(34.0)
			12000	1.80	(0.065)	2.72	(395.000)	234	(34.0)
Stackpole Corp.	Lowell, Mass.	Panex	30	1.75	(0.063)	2.76	(400,000)	221	(32.0)
			30Y/800D	1.75	(0.063)	1.86	(270,000)	262	(38.0)
Union Carbide Corporation	Fostoria, Ohio	Thornel	VMA (mat)	1.99	(0.072)	1.38	(200,000)	172	(25.0)
	Greenville, S.C.	Thornel 50	WYR 30	1.80	(0.065)	2.43	(350,000)	393	(57.0)
	Greenville, S.C. (Under construction)		WYR 15	1.80	(0.065)	2.21	(320,000)	393	(57.0)
		Thornel 300	WYP 90	1.75	(0.063)	2.92	(423,000)	236	(34.2)
			WYP 30	1.75	(0.063)	2.81	(408,000)	229	(33.2)
			WYP 15	1.72	(0.062)	2.69	(390,000)	229	(33.2)
		Thornel P-55	VS-32	2.03	(0.073)	2.07	(300,000)	379	(55.0)
		Thornel P-75	VSC-32-S	2.00	(0.072)	2.07	(300,000)	500	(75.0)

From: Bionetics Corporation Report: EPA Contract No. 68-03-2848

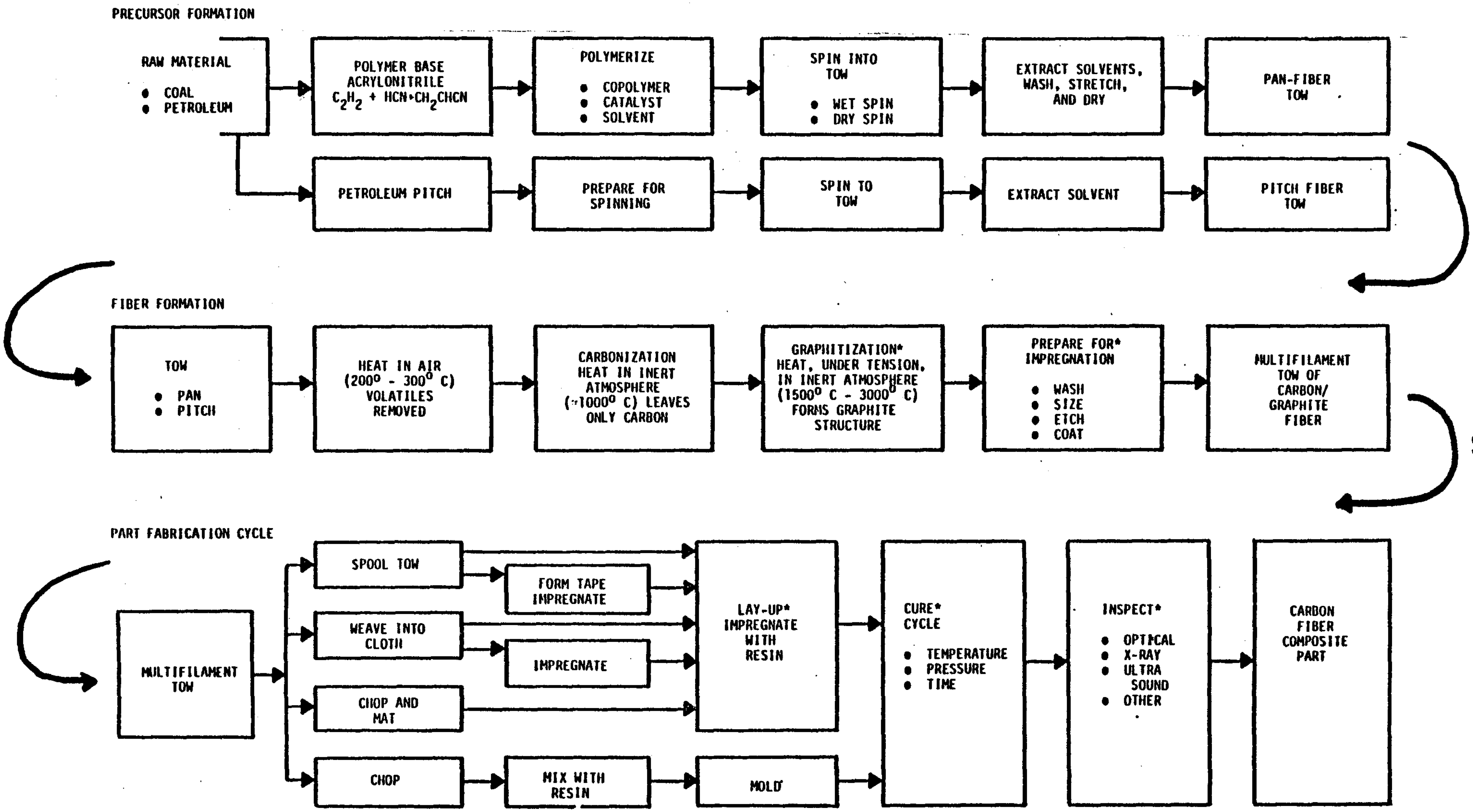
TABLE 3

NIOSH-Recommended Occupational Standards for Asbestos and Fibrous Glass

Asbestos	• Maximum occupational exposure concentration of 0.1 fibers/cm^3 (> 5 μm length) for up to an 8-hour workshift
	• Peak concentration of 0.5 fibers/cm^3 (> 5 μm length) based on a 15-minute sample period
Fibrous Glass	• Maximum occupational exposure concentration of 3.0 fibers/cm^3 for up to an 10-hour workshift in a 40-hour workweek for fibers $\leq$ 3.5 μm in diameter and length $\geq$ 10 μm
	• Fibers > 3.5 μm in diameter, airborne exposure concentrations should be limited to a time-weighted concentration of 5 mg/m^3

Figure 1

Flow Diagram for the Production of Carbon Graphite Composites



*MAJOR AREAS OF LITERATURE

From: Bionetics Corporation Report: EPA Contract No. 68-03-2848

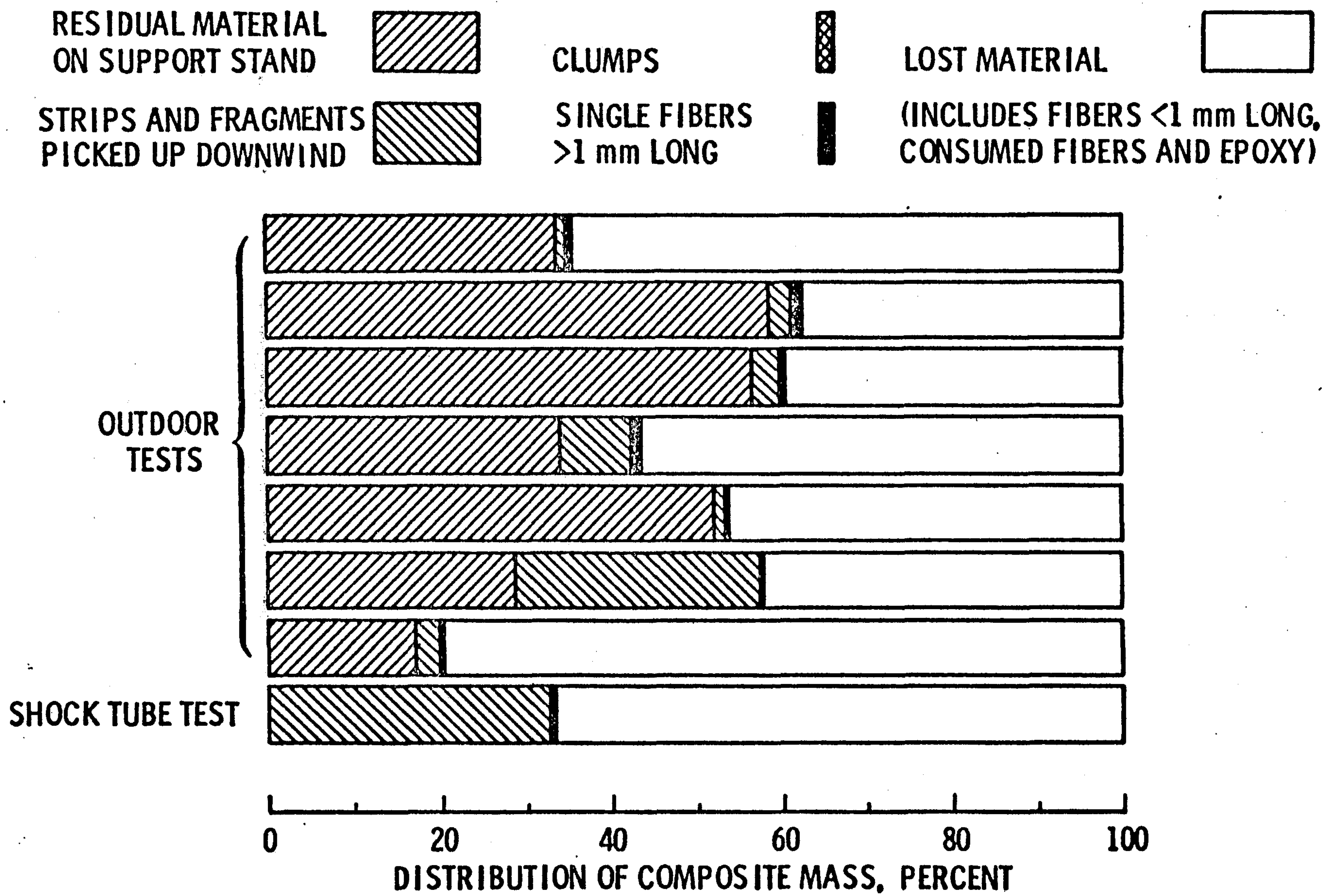


Figure 2.- Mass balance analysis of the composite materials burned in aviation jet fuel fire tests.

From: NASA Report - "The Risk to the Public From Carbon Fibers Released in Civil Aircraft Accidents," 1980.

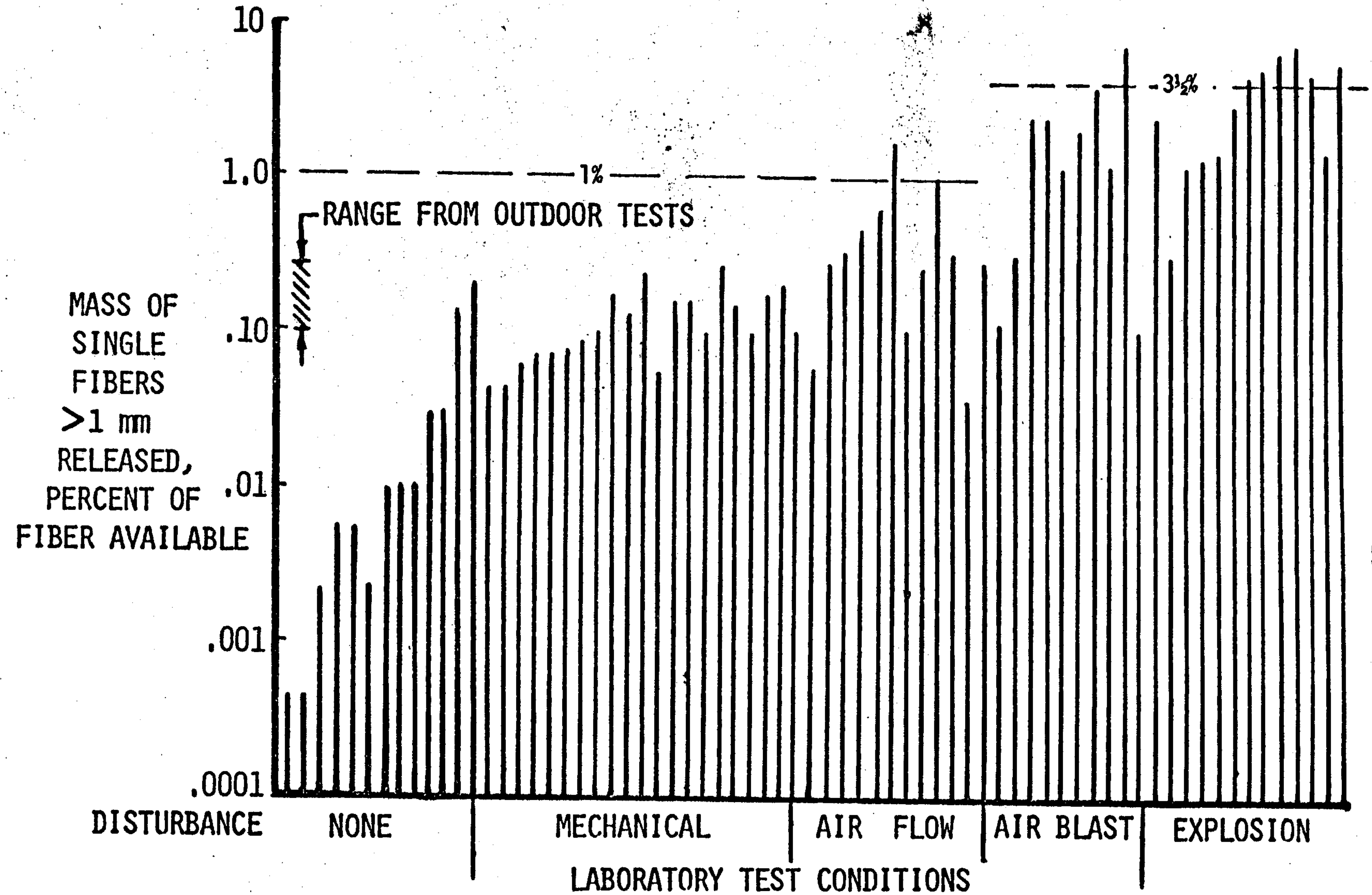


Figure 3 .- Results of fiber release tests.

From: NASA Report - "The Risk to the Public From Carbon Fibers Released in Civil Aircraft Accidents," 1980.

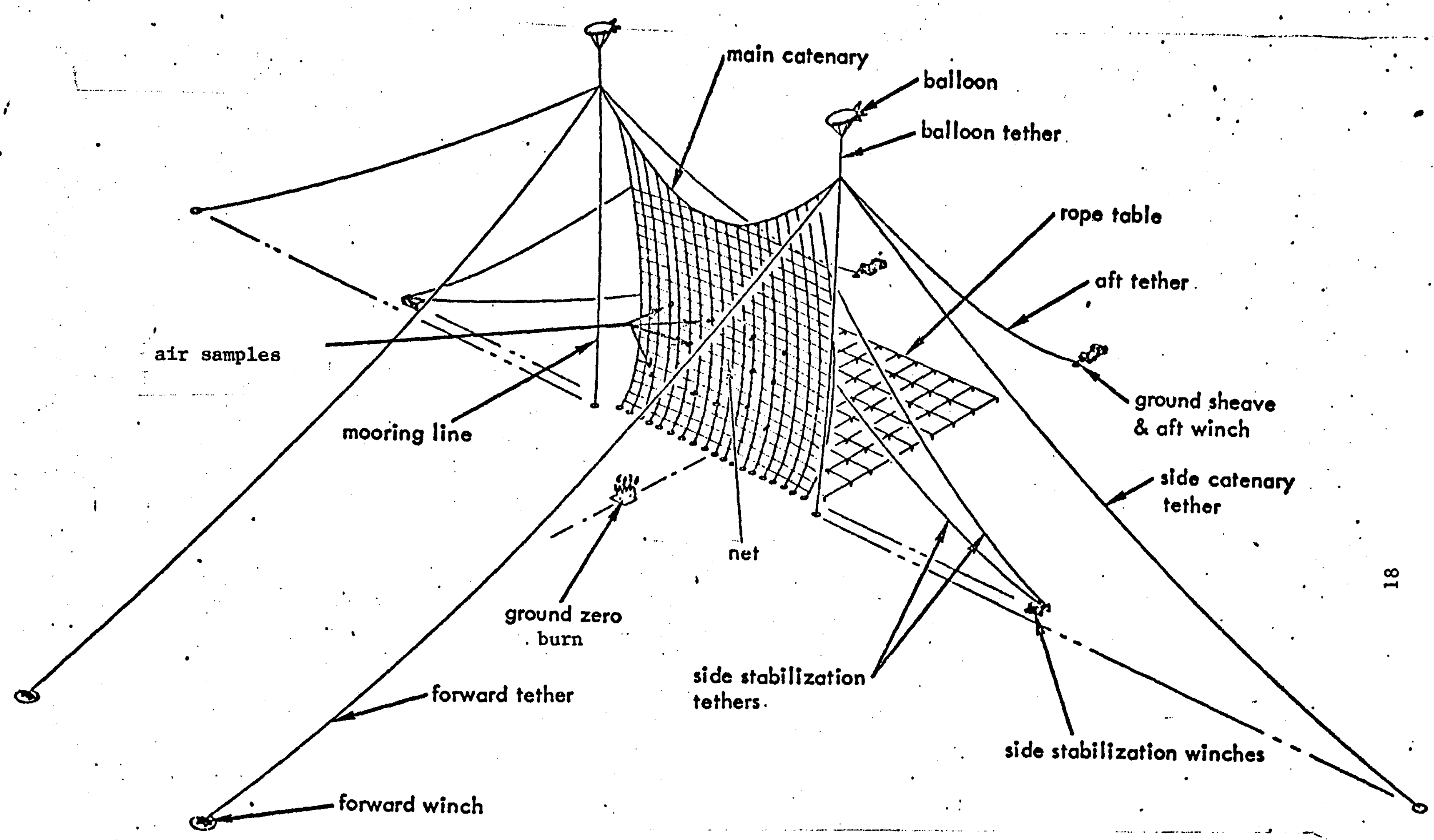


Figure 4. - Airborne Sampling for Carbon/Graphite Fibers During the Burning of Composite Materials: Jacob's Ladder Dugway Proving Ground, Utah