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Reference Document

Carbon Structure Hazard Control

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Carbon Structure Hazard Control

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Definitions

Carbon Fiber - Long continuous graphite fiber that measures roughly 5 to 10 micron (μm) in diameter. Multiple fibers are then bundled together to make up a TOW.

Catastrophic Event - A failure mode of a composite structure that results in laminar destruction and potential exposure of personnel to overpressure, fragmentation, and carbon hazards.

Composite - A material created from a fiber (or reinforcement) and an appropriate matrix material to maximize specific performance properties. The constituents do not dissolve or merge completely but retain their identities as they act in concert.

Composite Overwrapped Pressure Vessel (COPV) - A vessel constructed by winding a reinforcement fiber over a liner and then curing the structure in a matrix resin. The reinforcement fiber may be any of the glass, aramid, or carbon family types. Liners may be constructed from metallic, polymeric, or composite materials. Matrix resins include epoxies, isocyanate-based polymers, polyamides, and other polymer blends that are proprietary in their composition.

Composite Structure - Any hardware constructed of multiple constituents usually involving a resin system and a reinforcing material. The hardware may or may not have a liner that is load bearing. It may be constructed by molding, filament winding, or fiber placement and cured per multiple methods (i.e., room cure, autoclave, etc.).

Critical Hardware - Property classified as Ground Support Equipment (GSE), or of critical nature as classified by the customer. This includes classification of Flight (I, II, III), GSE, or Proto-flight.

Damage Control Plan - A document (generally written by the Prime Contractor or Design Agency) that identifies damage threats that may occur during the entire life of the component, designates visual inspections points, provides direction on threat mitigation and component protection, and data retention requirements. It should also list other acceptable nondestructive evaluation/examination (NDE) methods, standards, inspector qualifications, quality expectations, and any possible accept/reject criteria. It may also be referred to as a Mechanical Damage Control Plan or Impact Control Plan.

Disintegration - The act or process of separating into constituent elements or functional components of the composite structure. This could include fly/dust, tows, or tapes of reinforcement fiber, metallic or nonmetallic liner, or a combination of the components.

Fly - Filaments of carbon fiber that tend to remain airborne for long durations after an event or release. This material is often neat fiber that occurs during fabrication, finishing/machining, or a catastrophic event especially involving fire.

Fixing - The use of a fluid to control and capture loose fly and dust. Fixing can include various control and capture methods such as ventilation/filtration, liquid agents applied by spray, or encapsulation.

Handling - Operations involving an undamaged, clean composite structure that include transportation, inspection, integration, and non-detrimental service evaluation.

Hardware - For the purposes of this document, hardware is defined as a composite structure (COPV, Solid Rocket Motor (SRB) Case, etc.) that is being designed, constructed, and processed for test and analysis purposes or service.

Hazard Control - The types of measures that may be used to protect workers, prioritized from the most effective to least effective, are engineering controls, administrative controls, work practices, and personal protective equipment (PPE).

Interrogation - Any activity that involves contact or inspection of the composite structure at any time during the service life.

Level I Damage - Visible damage to the surface of a composite structure that does not affect or reduce the residual strength. This level of damage is limited to the matrix system or sacrificial layers. Level I damage to the component is considered non-detrimental and the vessel is acceptable for use.

Level II Damage - Visible damage to the surface of a composite structure that results in broken or cracked fibers, discoloration, gross ply disorientation, or unidentifiable hardware. Level II damage will result in a discrepant condition or nonconformity resulting in the need for a material review (MR).

Neat Fiber - Carbon fiber that has not been cured or coated with matrix material. This fiber may still be on the bobbin or even wound into the structure.

Nuisance Dust - Nuisance dust, or inert dust, can be defined as dust that contains less than one percent quartz. Because of its low content of silicates, nuisance dust has a long history of having little adverse effect on the lungs. Any reaction that may occur from nuisance dust is potentially reversible; however, excessive concentrations of nuisance dust in the workplace may reduce visibility, may cause unpleasant deposits in eyes, ears, and nasal passages, and may cause injury to the skin or mucous membranes by chemical or mechanical action.

Personal Protective Equipment (PPE) - Equipment, tools, or garments that are required to prevent exposure or injury to personnel/workers.

Personnel Certification – A formal procedure by which an accredited or authorized person or agency assesses and verifies (and attests in writing by issuing a certificate) the attributes, characteristics, quality, qualification, or status of individuals or organizations, goods or services, procedures or processes, or events or situations, in accordance with established requirements or standards. Per ANSI/AIAA S-081A-2006 and other Launch Range and NASA standards, personnel performing Nondestructive Testing (NDT) shall be certified in accordance with or equivalent to a nationally recognized practice or standard such as American National Standards Institute (ANSI)/American Society for Nondestructive Testing (ASNT) ANSI/ASNT-CP-189, SNT-TC-1A, or a similar document. The practice or standard used, and its applicable revisions, shall be specified in any contractual agreement between the parties involved. Similar qualifications and programs are subject to approval by the appropriate approval authority.

Personnel Qualification - NDT personnel shall be qualified by accepted training programs, applicable on-the-job (OJT) training under a competent mentor, or component manufacturer. OJT and manufacturer's qualification will only be applied to the manufacturer's specific component and shall only be under direct manufacturer's training. All qualification records and level are subject to approval from the appropriate approval authority.

Pitch - A residual petroleum product used in the manufacture of certain carbon fibers.

Safety Data Sheet (SDS) - written or printed material concerning a hazardous chemical that is prepared in accordance with paragraph (g) of 29 CFR 1910.1200, *Hazard Communication*, and includes identification, hazard(s) identification, composition/information on ingredients, first-aid measures, firefighting measures, accidental release measures, handling and storage, exposure controls/personal protection, physical and chemical properties, stability and reactivity, toxicological information, ecological information, disposal considerations, transport information, regulatory information, and other information, including date of preparation or last revision.

Standard Operating Procedure – Detailed instructions written to achieve uniformity in a process or job function.

Total Encapsulating Coverall – Full body garments generally spun from high density polyethylene that, together, protect the entire body including head (ears and scalp) and feet.

Total Encapsulating Chemical Protective Suit - A full body garment that is constructed of protective clothing materials, covers the wearer's torso, head, arms, legs, and respirator, may cover the wearer's hands and feet with tightly attached gloves and boots, and completely encloses the wearer and respirator by itself or in combination with the wearer's gloves and boots.

Test Articles - Test articles will include all program-supplied and/or program-purchased composite pressure vessels (CPVs), composite material test panels, and any other program test materials that require program control and coordination.

Thermal Deply - A destructive test and evaluation method used to remove the resin of a composite structure by a controlled thermal process.

TOW - An untwisted bundle of continuous filaments that may contain from 10,000 (10 K) to as many as 320,000 (320K) filaments. A combination of TOWs wound onto a liner/mandrel is used to build up the laminate plys of a composite structure.

Yarn - Continuously twisted fibers or strands suitable for use in weaving into fabrics.

Acronyms

ACGIH	American Conference of Governmental Industrial Hygienists
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASNT	American Society for Nondestructive Testing
CFR	Code of Federal Regulations
CNG	Compressed Natural Gas
COPV	Composite Overwrapped Pressure Vessel
CPV	Composite Pressure Vessel
DCP	Damage Control Plan
DOT	Department of Transportation
ES	Emergency Services
f/mL	Fibril per Milliliter
FAA	Federal Aviation Administration
FEMA	Federal Emergency Management Agency
GSE	Ground Support Equipment
HEPA	High-Efficiency Particulate Air
HVAC	Heating, Ventilation, and Air Conditioning
IARC	International Agency for Research on Cancer
µm	micron
MRB	Material Review Board
NASA	National Aeronautics and Space Administration
NDE	Nondestructive Evaluation/Examination
NDT	Nondestructive Testing
NFPA	National Fire Protection Association
NIOSH	National Institute for Occupational Safety and Health
NTP	National Toxicology Program
NTSB	National Transportation Safety Board
NWC	Naval Weapon Center
OJT	On-the-Job Training
OSHA	Occupational Safety and Health Administration
PAN	Polyacrylonitrile
PEL	Permissible Exposure Limit
PMC	Polymer Matrix Composite
PPE	Personal Protective Equipment
QA	Quality Assurance
RT	Radiographic Examination
SACMA	Suppliers of Advanced Composite Materials Association
SCBA	Self-Contained Breathing Apparatus
SDS	Safety Data Sheet
SEM	Scanning Electron Microscopy
S&MA	Safety & Mission Assurance
S/N	Serial Number
SOP	Standard Operating Procedures
SRB	Solid Rocket Motor
TE	Total Encapsulation
TECA	Total Encapsulating Coverall
TECPS	Total Encapsulating Chemical Protective Suit
TLV	Threshold Limit Value
TWA	Time-Weighted Average
VT	Visual Inspection
WSTF	White Sands Test Facility

Executive Summary

Carbon composite structures are widely used in virtually all advanced technology industries for a multitude of applications. The high strength-to-weight ratio and resistance to aggressive service environments make them highly desirable. Automotive, aerospace, and petroleum industries extensively use, and will continue to use, this enabling technology. As a result of this broad range of use, field and test personnel are increasingly exposed to hazards associated with these structures. No single published document exists to address the hazards and make recommendations for the hazard controls required for the different exposure possibilities from damaged structures including airborne fibers, fly, and dust. The potential for personnel exposure varies depending on the application or manipulation of the structure. The effect of exposure to carbon hazards is not limited to personnel, protection of electronics and mechanical equipment must be considered as well. The various exposure opportunities defined in this document include pre-manufacturing fly and dust, the cured structure, manufacturing/machining, post-event cleanup, and post-event test and/or evaluation. Hazard control is defined as it is applicable or applied for the specific exposure opportunity. The carbon exposure hazard includes fly, dust, fiber (cured/uncured), and matrix vapor/thermal decomposition products. By using the recommendations in this document, a high level of confidence can be assured for the protection of personnel and equipment.

1.0 INTRODUCTION

1.1 Background

The strong drive to reduce weight and optimize performance in aerospace applications has pushed designers to adopt composite structures constructed with high modulus carbon reinforcement fibers embedded in an epoxy matrix.

Carbon fiber composite materials have high fatigue strength and are corrosion and fire resistant, which provides functional integration by design, results in lower weight, and hardware that can be formed into many complex shapes. Composite structures are typically constructed of multiple laminates that bond the high strength fibers with a matrix or resin system. For a typical polymer matrix composite, the fibers comprise about 55 percent of the laminate with the polymer resin. Carbon fiber consists of extremely fine fibers ~5-10 µm in diameter and are extremely strong for their size. A single fiber is shown in Figure 1 compared to a human hair. Several thousand carbon fibers twisted together form yarn, which can be used in the raw form or woven into a fabric. A single tow of fiber may contain 12,000 fibers (Figure 2) and up to 320,000 for some applications. When combined with resin and wound or molded to form composite materials, a high strength-to-weight ratio is achieved.

1.2 Carbon Composite Materials

Carbon fiber is currently produced by two predominant manufacturing processes: pitch (coal tar and petroleum products) and polyacrylonitrile (PAN). Rayon was the preferred raw material for carbon fibers prior to 1973, but PAN and pitch have replaced rayon as preferred precursor materials (Edwards 1991).The fiber manufacturing process is part chemical and part mechanical. It involves mixing a precursor and a co-monomer and then drawing the fiber out of the chemical mixture and mechanically stretching and coating the fibers. The coating of the fiber is called sizing and involves chemicals other than carbon. The types of carbon fiber precursors used to manufacture the filament affect the severity of risk associated with exposure. The resin systems are generally two-part epoxies and are known to be carcinogenic when burned. Personnel conducting certain types of testing and evaluation, and as first responders to a catastrophic transportation event such as bus fires or aircraft crashes, are exposed to burning and disrupted composite structures and their hazards. Appropriate hazard control is required for managing carbon fiber-based materials and components, including structures.

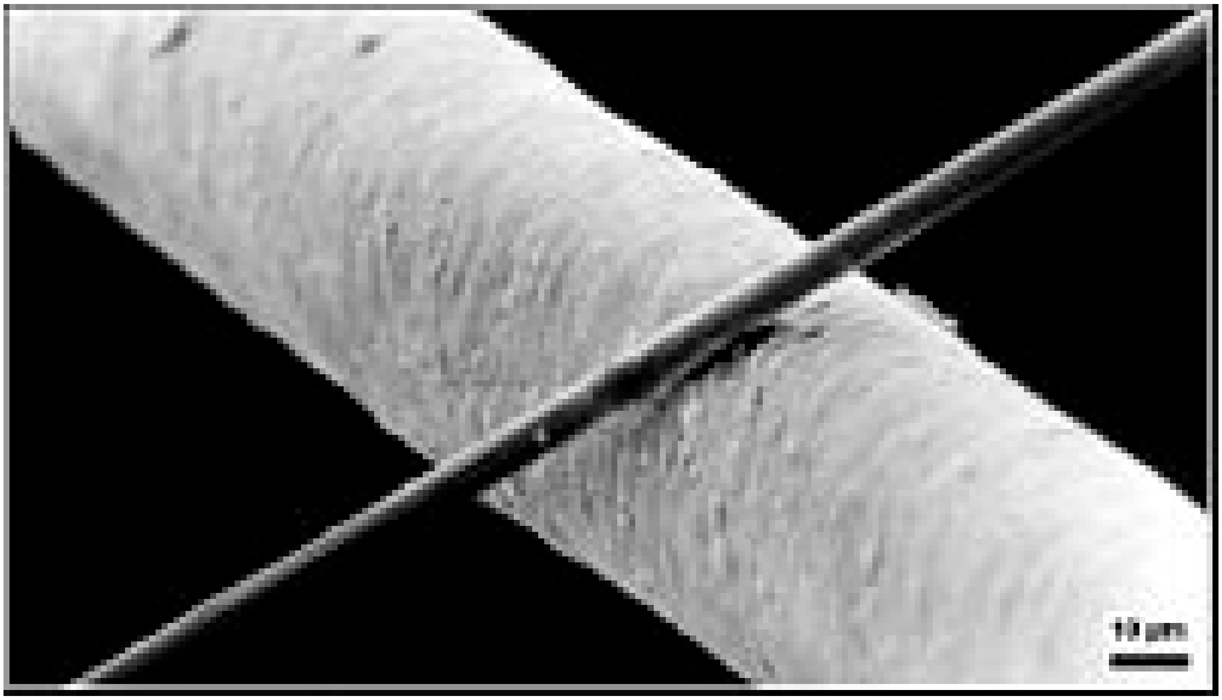

Figure 1
Carbon Fiber (~6 µm) (Above) Compared to a Human Hair (Below)

As an enabling technology for so many applications, carbon composite structures present many opportunities for exposure to carbon fibers throughout the normal life of the component from the pre-manufacturing process to use or disposal. Risk of exposure is dramatically increased in the area of test and evaluation and exposure is expected during posttest analysis and failure investigations. The extent of hazardous exposure to carbon fiber depends greatly on the size of the composite structure and level of destruction.

A site or employer-specific document is needed by employees to understand the hazards of exposure to composite structure materials and provide the hazard controls for these different exposure possibilities. The level of detail needed is driven by the level of destruction (fiber disruption), ventilation, and loose fiber fixing. Incident response training is the responsibility of the employer and governed by federal regulation as part of Occupational Safety and Health Administration (OSHA) requirements. This document provides guidelines and data to help determine the appropriate hazard controls to protect against carbon fiber exposure.

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Figure 2
Typical Tow of Carbon Filaments

1.3 Controls

OSHA and safety and health professionals use a framework referred to as the “hierarchy of controls” to select ways of mitigating workplace hazards. The hierarchy of controls prioritizes intervention strategies based on the premise that the best way to control a hazard is to systematically remove it from the workplace. The types of measures used to protect laboratory workers, prioritized from the most effective to least effective, are:

- Engineering controls
- Administrative controls
- Work practices
- Personal protective equipment (PPE)

Employers often use a combination of control methods and evaluate their particular workplace to develop a plan for protecting their workers. The plan may combine both immediate actions as well as longer term solutions. The four most common routes of chemical exposure in the order in which they are most likely to occur are inhalation (respiration), absorption (skin or eyes), ingestion (eating or swallowing), and injection (mechanical introduction into the body). To prevent any of these from occurring, or to minimize their likelihood or risk, OSHA recommends a “Hierarchy of Controls,” as shown in Figure 3.

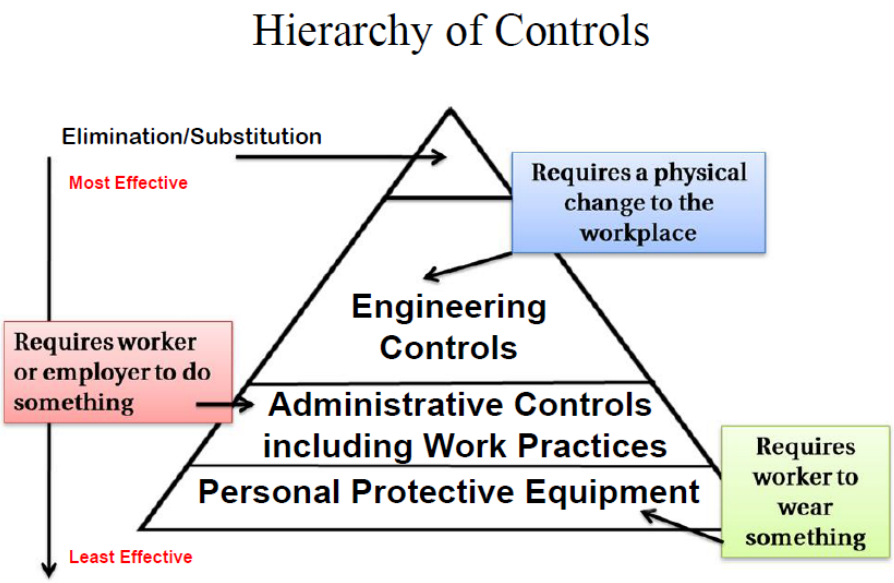

Figure 3
Hierarchy of Controls

Elimination controls eradicate the hazard by physically removing it, which is the most effective hazard control. For example, if employees work in an environment where composite dust exists, a fixing agent may be used to prevent the dust from getting airborne.

Substitution controls provide a less hazardous alternative, or more ideally, a nonhazardous, alternative, and is the second most effective hazard control. To be an effective control, the new product must not produce another hazard. Use of substances of lower toxicity and in lower concentrations is a means of substitution.

Engineering controls are those that involve making changes to the work environment to reduce work-related hazards. Engineering controls are preferred over all other controls because they make permanent changes that reduce exposure to hazards and do not rely on worker behavior. By reducing a hazard in the workplace, engineering controls can be the most effective solutions to protect workers. Examples include:

- Forced ventilation to remove hazard materials from the work area
- Remotely controlled operations (versus hands-on operations)
- High-efficiency particulate air (HEPA) filters in heating, ventilation, and air conditioning (HVAC) equipment to prevent contamination downstream of the filters

Administrative controls are those that modify workers' work schedules and tasks in ways that mitigates their exposure to workplace hazards. Examples include:

- Minimizing work done in the areas that hazardous substances are present
- Developing a written Hazard Communication Program that is relevant to the job
- Training employees accordingly
- Developing Standard Operating Procedures for safe material handling

Work practices are procedures for safe and proper work that are used to reduce the duration, frequency, or intensity of exposure to a hazard. When defining safe work practice controls, the employer should communicate with workers for their suggestions since workers have actual experience with the tasks as actually performed, not as they appear on paper. These work practice controls need to be understood and followed by everyone. Examples include:

- Prohibition of eating and drinking in work areas and requiring frequent hand washing before engaging in such activities
- Chemical substitution where feasible (e.g., selecting a less hazardous chemical for a specific procedure)

Personal protective equipment (PPE) is protective wear needed to keep workers safe while performing their jobs. Examples of PPE include respirators, goggles, face shields, chemical resistant garments, and disposable gloves. While engineering and administrative controls and proper work practices are considered to be more effective in minimizing exposure to many workplace hazards, the use of PPE is also very important. Legally, PPE must be:

- Selected based upon the hazard to the worker
- Properly fitted and in some cases periodically refitted (e.g., respirators)
- Conscientiously and properly worn (donned)
- Regularly maintained and replaced (in accord with the manufacturer's specifications)
- Removed (doffed) and disposed avoiding contamination of self, others, or environment
- If reusable, properly removed, cleaned, disinfected, and stored

Employees must be trained in a variety of ways to use PPE as required by 29 Code of Federal Regulations (CFR) 1910.132, *Personnel Protection – General Requirements*. Each such employee shall be trained to know at least the following:

- When, where, and what PPE is necessary
- How to properly don, doff, adjust, and wear PPE
- Limitations of the PPE
- The proper care, maintenance, useful life, and disposal of the PPE

Employees must demonstrate an understanding of the training and the ability to use PPE properly, before being allowed to perform work requiring the use of PPE, and when the employer has reason to believe that any affected employee who has already been trained does not have the understanding and skill needed to use it properly, the employer shall retrain each such employee.

Circumstances where retraining is required include, but are not limited to, situations where:

- Changes in the workplace render previous training obsolete
- Changes in the types of PPE to be used render previous training obsolete
- Inadequacies in an affected employee's knowledge or use of assigned PPE indicate that the employee has not retained the requisite understanding or skill.

In addition, it must be documented that an OSHA-required workplace hazard assessment has been performed in accordance with 29 CFR 1910.132, *Personnel Protection – General Requirements,* through a written certification that identifies the workplace evaluated; the person certifying that the evaluation has been performed; the date(s) of the hazard assessment; and, which identifies the document as a certification of hazard assessment.

2.0 HAZARDS

2.1 Types of Hazards

The principal hazard in handling carbon fibers is the risk of direct physical contact by personnel. The two major routes to employee exposure from reinforced fiber materials are dermal and inhalation. The disrupted carbon fiber is easily airborne and widely distributed. Carbon fiber exposure can cause mechanical irritation and abrasion similar to that of glass fibers (OSHA 1999). Skin rashes often occur and are reportedly more severe than from glass fibers. Commonly used carbon fibers are greater than 5 µm in diameter, making them small enough to be inhaled, but large enough to allow lung tissue to encapsulate the fibers and expel them from the body. Carbon fibers are very fine and easily broken by stretching (by less than two percent elongation), and can become a fine dust or fly during any handling operations. This includes manufacturing, qualification, processing, test and evaluation, service, and disposal. If uncontrolled, these composite structures and associated microfibers have the potential to stick to human skin or mucous membranes and cause irritation, particularly to eyes, skin, and lungs. This is compounded when high energetic events are coupled with fire during service or destructive evaluation. Additionally, in the service environment, elements of dispersion are much harder to control and thus contain the carbon hazard.

Other hazards include punctures, cuts, or lacerations from the disrupted composite surface or edge of a vehicle, structure, or coupon (Gandhi and Lyon 1998). An important distinction can be made between fibers and chemicals when assessing the dose-response relationship. In the case of chemicals, the agent itself changes due to metabolic reactions within body fluids and it is excreted after producing a pathological response. In contrast, the fibers used in composite structures are inert and can be long lasting.

The adverse toxic hazard as defined by the Safety Data Sheet (SDS) is classified as an acute toxic substance with no known cause of disease but carbon dust and fly can cause transient skin irritation. This effect is compounded by the curing agents used for fiber sizing, in which case human contact should be limited by the use of proper hazard controls. Pitch-based fiber has demonstrated in some studies to be associated with an increased risk of skin cancer, although evidence is weak (Ahmad 2009, OSHA 1999).

The following are the control parameters and exposure limits regarding exposure to carbon fibers. The different levels are defined by the Labor Safety and Health Act in Japan, OSHA, and American Conference of Governmental Industrial Hygienists (ACGIH). The results are taken from the SDS listed in Table 1.

Table 1
SDS Exposure Control/Personnel Protection[a]

Content (Source)	Carbon Fiber Exposure Limit ppm (mg/m^3)
Labor Safety and Health Act (JAPAN)	2.9 mg/m^3 (reference value by "Kokuji" by Min. of Labor, Japan 1995)
OSHA	2.0 mg/m^3 as the total dust of first class dust by the Japanese regulation (reference value)
ACGIH	10.0 mg/m^3 total dust of synthetic graphite

[a] SDS No: CFA-004

Clastogenic effects (a form of mutagenesis) have been observed in mutagenicity (genetic altering) studies of pitch-based fiber but not of PAN-based fiber. It was thought that the pitch-based fiber is able to genetically alter or breakdown chromosomes of DNA but a ten-year study of carbon fiber manufacturing personnel did not indicate those effects (Jones, Jones, and Lyle 1982; Ross and Lockey 1994).

Aramid fibers are larger and show no potential for skin sensitization and low potential for dermatitis irritation and the physical structure making it difficult to generate significant amounts of airborne dust and fly. These guidelines are conservative for Kevlar and most glass types and therefore, if followed, will provide adequate personnel protection against exposure to those types of dust, fly, and fiber. As a result, the hazard control considerations of this document are conservative for aramid and glass fibers. This also demonstrates that the type of reinforcement fiber should be known prior to potential exposure. By reviewing the manufacturing materials documentation, hazards can be properly identified and controlled.

2.2 Reinforcement Fiber

Most of the reinforcing materials (fibers) used in the industry have the potential to cause eye, skin, and upper respiratory tract irritation as a result of the mechanical-irritant properties of the fibers. The chemical irritation caused by resins can compound the mechanical irritation caused by the fibers. The potential synergism between mechanical irritation and chemical irritation has not been clearly defined.

Carbon/graphite fibers dominate the advanced composites industry and may be made from any of three precursors; however, the PAN-based carbon fibers are the predominant form in use today. To evaluate the hazards it is important to ascertain which type of carbon-fiber precursor is used. Pitch-based carbon fibers may be associated with an increased risk of skin cancer, although the evidence is weak. PAN-based carbon fibers did not cause tumors when the same test was conducted. Standard mutagenicity tests conducted on PAN-based carbon fibers were negative.

The principal hazards of carbon-fiber handling are mechanical irritation and abrasion similar to that of glass fibers. Skin rashes are common and are reportedly more severe than from glass fibers. Carbon fibers commonly used are greater than six micrometers in diameter, making them unlikely to be respirable. An ongoing survey of workers in a carbon-fiber production plant shows no pulmonary function abnormalities and no evidence of dust-related disease.

Carbon fibers may be coated with a material to improve handling, known generically as sizing. The sizing materials are typically epoxy resins. They may be biologically active and cause irritation or sensitization.

Aramid fibers are made from a polymer, poly (p-phenylenediamine terephthalate). Animal and human skin tests of Kevlar®[1] aramid fibers show no potential for skin sensitization and low potential for irritation. While Kevlar fibers are too large to be inhaled (12-15 mm), they may be fractured into respirable fibrils in some composite manufacturing processes. Industrial process monitoring shows that airborne respirable fibril levels are low in typical operations. Measured exposure levels from composite machining are typically below 0.2 fibrils per milliliter of air (0.2 f/mL), as an 8-hour (h), time-weighted average (TWA), while continuous filament handling generates less than 0.1 f/mL. The physical structure of aramid fibers makes it extremely difficult to generate airborne concentrations.

Glass fibers, used as reinforcement in polymer matrix composite (PMC) processes, are a continuous-filament form and not the glass-wool (random) type. Practically all glass fibers for composite reinforcement are greater than 6 µm in diameter. Airborne fiber of this diameter does not reach the alveoli and is non-respirable. Glass fibers break only into shorter fragments of the same diameter. Their diameter cannot be reduced by machining, milling, or other mechanical processes.

Mechanical irritation of skin, eyes, nose, and throat are common hazards associated with glass-fiber exposure. Continuous-filament glass fiber is not considered fibrogenic. Lung clearance mechanisms are effective for glass fibers.

In June 1987, the International Agency for Research on Cancer (IARC) categorized continuous-filament glass fibers as not classifiable with respect to human carcinogenicity. The evidence from human and animal studies was evaluated by IARC as insufficient to classify continuous-filament glass fibers a possible, probable, or confirmed cancer-causing material.

Like carbon fibers, glass fibers may also be coated with a sizing material to improve handling. Sizing materials may be epoxy resins, polyvinyl acetate-chrome chloride, polyvinyl acetate-silane, polyester-silane, or epoxy-silane compounds. These materials may be biologically active and cause irritation or sensitization.

2.3 Dust

Dusts may be generated in several ways in advanced composite processes. The common dust-generating processes are machining and finishing cured parts, repairing damaged parts, and component test operations. Much of the dust generated in these processes can be very fine and should be considered respirable. Studies of some graphite-epoxy finishing operations found respirable fractions ranging from 25 to 100 percent.

More dust is usually generated in finishing and repair processes since large surface areas are involved. Grinding, routing, and sanding are frequently used methods in both processes. The repair process may require the use of abrasive blasting as well as sanding to remove existing paint or coatings. Typically a synthetic blasting agent, e.g., plastic media blast, is used. Ingredients of the paint or coating being removed, such as lead or chromates, may also be of

[1] Kevlar® is a registered trademark of E. I. DuPont de Nemours and Company, Wilmington, Delaware.

concern. The repair process may also require cutting or sawing to remove the damaged part area, and both may generate significant amounts of airborne dust.

In general, studies on composite dusts indicate the following:

- The dusts are particulate in nature and usually contain few fibers
- The dusts are thermally stable up to 250 °C (482 °F) and exhibit a high degree of cure
- Toxicology studies indicate the dusts should probably be controlled at levels below the permissible exposure limit (PEL) for inert dust, but not approaching the PEL for crystalline quartz

2.4 Inhalation

Airborne composite fibers pose a potential respiratory hazard to personnel and therefore must be protected against. There is a higher potential if the composite is exposed to machining operations, highly energetic events, and/or fire. The ACGIH (2013) has established a threshold limit value (TLV) of 2 mg/m^3 for graphite (all forms except graphite fibers) on the basis of pneumoconiosis, a group of interstitial lung diseases caused by the inhalation of certain dusts and the lung tissue's reaction to the dust.

Generally the human body is able to encapsulate the dust and fly and expel it. Nuisance dust may cause temporary but reversible respiratory irritation if inhaled; however, long-term exposure to any dust could aggravate existing respiratory or pulmonary conditions. This is demonstrated by long-term human exposure to coal dust.

The fiber dimensions and total deposition deep into the lung determine the inhalation hazard from fibers (Gandhi and Lyon 1998). Fibers with diameters smaller than 3 mm (0.12 in.) and lengths shorter than 80 mm (3.15 in.) have the ability to be respired and can penetrate deep into the lungs. The fiber retention time inside the lung is primarily dependent on the fiber dimensions. Fibers smaller than 15 mm (0.59 in.) are cleared from the lungs by cellular activity; however, longer fibers saturate the self-clearance mechanism of the lungs and can lead to pathological effects. Animal studies on exposure to respirable-sized raw PAN and pitch-based carbon fibers do not indicate there are significant adverse health effects. Studies involving animals exposed to aerosols of composite dust and carbon fibers from machining and grinding of fiber composites are inconclusive with respect to pathological effects. Data from fire tests and crash-site investigations suggest that only a small fraction of the fibers released in fires is of respirable size; however, detailed chemical analysis of organic vapors revealed a high number of toxic organic compounds that are associated with the fibers. Several of the organic chemicals are known carcinogens and mutagens in animals. Further work is needed to assess the health implications of any synergistic interactions between the chemical and fibrous combustion products.

The airway passages in a human lung consist of a series of branching capillaries called bronchioles that become progressively smaller. The immense amount of bronchi divisions greatly increases the cross-sectional area of the airways that are exposed to fiber deposition. The aerodynamic diameter governs the mechanism of fiber deposition in the airways. In larger airways, fibers with greater terminal velocity are deposited by impaction against the inside walls of airways. Impaction against the airway walls occurs where the fibers cannot overcome their inertial drag and cannot adjust to changes in the angle and velocity of the airflow. In smaller airways where the airflow velocity becomes very small, sedimentation is the primary mode of fiber deposition. Three other potential mechanisms of fiber loading in lungs are interception, diffusion, and electrostatic deposition.

Table 2 provides a summary of the known studies on inhalation hazard of carbon fibers reported in Department of Transportation (DOT)/Federal Aviation Administration (FAA)/AR-98/34, *Health Hazards of Combustion Products from Aircraft Composite Materials* (Gandhi and Lyon (1998)). As summarized in this report, Owen et al. (1986) exposed rats to 7 µm PAN-based carbon fibers at aerosol concentration of 40 f/cm^3 for 6 h/day, 5 days/wk, for up to 4 months. The physiological responses of animals were monitored for up to 32 weeks. No pulmonary inflammation, lung function impairment, or fibrosis effects were detected. Thomson et al. (1990) tested the respirability of carbon fibers 3.5 µm in diameter and 3.5 mm long. The length to diameter L/D ratio of these PAN-based carbon fibers was 1000. Rats were exposed to fiber concentration of 40, 60, and 80 f/cm^3 for 1 h/day for 9 days. No changes in physiological response were observed after post-exposure periods of 1 and 14 days. Micrographs of lung tissue did not reveal presence of carbon fibers in Scanning Electron Microscopy (SEM) analysis. Studies by both Owen et al. (1986) and Thomson et al. (1990) used carbon fibers with physical dimensions beyond the respirable range, i.e., fiber diameter >3 µm and length much greater than 80 µm. The toxicological significance of these studies is questionable because of the non-respirable nature of fibers used.

Table 2
Summary of Carbon Fiber Toxicity Studies

Species	D (µm)	L (µm)	Conc. (f/cm^3)	Hours/ Day	D/Wk	Wk	Post Exposure Recovery	Recovery Results	Ref.
Rat	7	20-60	40	6	5	16	32 weeks	No adverse effects on lung function No Fibrosis	Owen et al. 1986
Rat	3.5	3500	40-80	1	5	2	1, 14 days	No carbon in tissue No abnormal pulmonary function	Thomson et al. 1990
Rat	3	10-60	40	6	5	16	15, 80 weeks	Some non-fibrous particles in lung tissue, No abnormal pulmonary function	Waritz et al. 1990
Rat	1-4	NA	50-90	6	5	-	4, 12 weeks	Temporary lung inflammation (reversible after 10 days) No histopathological response or lung fibrosis	Warheit et al. 1994

Consistently, there were no significant pulmonary function changes or evidence of fibrosis in either the pitch or PAN-based carbon fibers. The author concluded that unlike the silica-based asbestos fibers, pitch-based carbon fibers do not cause pulmonary fibrosis. Based on the studies it appears that toxicity of respirable, raw carbon fibers and composite dust is substantially different from well-known carcinogenic effects such as asbestos and man-made mineral fibers. The toxic hazards of carbon fibers and dust rank significantly lower compared with the crystalline silica dusts. It has been suggested that, composite dusts should be regarded as more hazardous than the so-called nuisance dusts.

2.5 Skin Contact

There are two separate carbon fiber threats to exposed bare skin. One is the result of the jagged broken surface or edge of a composite structure, which is generally a result of a high energy catastrophic event. In this case cured fibers are very rigid and pose a high probability for laceration and impregnation/puncture. The other credible threat is a result of the deposition of airborne composite dust or fly onto the surface skin. Carbon dust and fly is easily worked into the skin surface through mechanical aggravation and can cause irritation and rashes. This reinforces the need to completely cover exposed skin during operations, which is especially critical for the eyes, ears, and mouth. Chemical irritation caused by resins can compound the mechanical irritation caused by the fibers. This should be avoided by using heavy rubber or leather gloves to prevent cuts and lacerations caused by stiff rigid fibers. Gloves should be taped to the sleeve of upper body total encapsulating coverall (TECA) to prevent carbon composite material from contacting open skin. Boots and or booties should also be taped to lower body TECA to prevent carbon composite material from contacting the legs. Applications of these techniques are show in Table 4.

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Figure 4
Proper Taping of Glove and Boots to Total Encapsulating Coverall

2.6 Eyes

Dust and fly cause agitation to the eyes through contact and abrasive action. Abrasive action could damage the outer surface of the eye and be aggravated by blinking. Contact with the eye can cause severe pain. If a sufficient amount of ventilation is available and personnel can stay clear of the exposure threat (i.e., fume hood, glove box, test chamber, etc.) regular safety glasses may be appropriate. Otherwise, safety glasses are not acceptable protection when large amounts of dust and fly are present. Contact lenses should not be worn if personnel are expected to come in contact with airborne dust or fly of any material type. If employers approve the wearing of contact lenses, the wearers should also wear appropriate eye and face protection devices in the laboratory. Contact lenses are not protective devices and eye protection appropriate to the hazard must be worn. Policies for wearing contact lenses in the work environment must be made by the employer.

2.7 Ingestion

Ingestion is not likely due to the physical nature of carbon fiber material, though risk of ingestion of dust is increased by the *peri*oral exposure process (Christopher et al. 2007). Through normal protection against respiration threat, ingestion is inherently protected against. Any work practices or procedures that limit hand-to-mouth contact will minimize hazards due to ingestion. Additionally, good industrial practices will minimize this hazard by using appropriate personal and workplace hygiene, which includes limiting food, drink, tobacco consumption, use of cosmetics, etc., in the area where potential exposure could occur, and by requiring hand washing and other sanitary measures prior to performing such activities.

2.8 Electrical

Carbon fiber is electrically conducive, and has the potential to cause short circuiting of electrical equipment. If airborne carbon fiber dust or fly penetrates electrical switches or equipment in sufficient density, short circuits or electric shock could occur. Carbon fiber sticking to an electrical cord could cause an electric shock when the plug is inserted into an electrical outlet. Although some studies (USA Advanced Composites Leaders Guide, 12Nov96) indicate that the threats are not as serious as first anticipated, protection from these threats should not be underestimated. When dust or fly settle on electronics the conductive fibers may cause shunting, short circuits, transient or sustained arcs. Dust and/or fly have the potential to change local dielectric properties of free air and cause equipment to malfunction and/or fail over time. Electrical devices should be removed or isolated from the exposure environment when possible, otherwise pneumatic actuated tooling and/or shielded electric motors should be used. Isolation can be obtained through ventilation or filtration.

This threat of electronic short circuit is exacerbated by large events (aircraft crash), high winds, and intense heat sources (fires). Airborne fibers released from burning composites are carried by the fire plume and dispersed downwind in the atmosphere. Pitch and PAN-based carbon fibers have electrical resistivity of about 250 and 1800 µohm-cm, respectively, which is on the order of 10 percent of the conductivity of metals. This poses potential risk to nearby power distribution lines, transformers, radar, and electronic equipment.

2.9 Other Associated Hazards

Other hazards exist during the various handling operations of composite structures including, but not limited to, combustion and volatile solvents. This report does not provide guidance for these hazards, but includes them to provide a thorough resource detailing all composite structure hazards. Firefighting and chemical processing of solvents involve greater regulation for personnel protection and are covered through local and federal government regulation.

2.9.1 Combustion

When a composite structure burns, the toxicity of the combustion produced must be protected against through full respiratory protection. Even though carbon fiber is not listed as a carcinogen by the National Toxicology Program (NTP), International Agency for Research on Cancer (IARC), or OSHA, and no case of disease caused by carbon fiber has been reported, in a catastrophic event involving fire, this is not assumed to be the case. This level of fire and combustion by-product personnel exposure is generally regulated by the National Fire Protection Association (NFPA). Airport firefighting and rescue personnel are adopting conservative protection measures in absence of detailed knowledge of the health effects of carbon fibers released in aircraft fires. This is demonstrated by standard operating procedures (SOP) including approach paths of the fire brigade, airborne material suppression by deluge or foam, and TECA PPE required in most instances involving burning aircraft.

Combustion of the carbon fiber usually does not occur, but as shown in Table 3, the resin may ignite and cause wide distribution of the fiber. The resulting fire causes containment and collection problems that require hazard controls. The ensuing plume should be considered carcinogenic and avoided through ventilation (good wind direction) and with full respiratory protection employed.

Table 3

Ignition Temperature of Carbon/Epoxy Compared to Aluminum

Aluminum	Carbon/Epoxy
Melting temperature = 660 °C (1220 °F)	Resin ignition = 400 °C (752 °F)
Burn through <1 min	Resistant to burn through >5 min
Low Thermal Coefficient	High Thermal Coefficient
(Dissipates heat)	(Holds heat)

The potential health risks associated with burning fiber-reinforced polymer composites is the fly and dust particles released during burning. As the matrix burns off, the reinforcing fibers are exposed to mechanical disruptions and thermal lifting that causes them to break up and erode into small fragments and individual filaments. Once airborne, this material can be inhaled and deposited in the lungs and the large sharp fiber fragments can penetrate the skin.

The National Aeronautics and Space Administration (NASA) led a government-wide effort to characterize the carbon fibers emitted from combustion of composites structures used in aircrafts (NASA 1980). NASA-SP-448 reports the initial focus of this study was to evaluate environmental hazards due to the conductive carbon fibers. It was of concern that accidental release and dispersal of carbon fibers from composites longer than 1 mm (0.039 in.) could cause shorting or arcing in power distribution lines and other electrical equipment, so a series of large-scale fire tests with composites were conducted to simulate aircraft fires. One series of tests was conducted by the Naval Weapon Center (NWC) at China Lake, CA with composites suspended above 15.2 m (50 ft) jet fuel (JP-5) pool fires. The NWC tests subjected two different aircraft composite parts, a Boeing 737 spoiler and an F-16 fuselage section, to flames for 4 to 6 min. Fibers released during the fire tests were collected on adhesive-coated papers 20 x 25 cm (0.66 x 0.82 ft) located on elevated platforms 0.3 m (1 ft) above ground; however, this sampling procedure was found inadequate due to the low amounts of single fibers collected. A massive smoke plume that reached a height of ~1000 m (3280 ft) carried the majority of the single fibers away from the test location to distances beyond the instrumentation limit of 2000 m

(6561 ft). The sampling size was also reduced due to difficulties in separating the fibers from the paper, thus limiting the number of fibers analyzed for size distribution.

When a vehicle accident involves high energetic events coupled with fire, the concentration and distribution of airborne dust, fly, and microfibers increases dramatically. In addition, the toxic chemicals produced from the combustion of the organic resin may enter the respiratory system with acute or chronic effects.

2.9.2 Solvents

Volatile components of solvents, matrix system (resin and/or hardener), and potentially matrix dissolving solutions, are not covered by this document. These substances are usually specific to manufacturing operations and hazard controls established by the industrial chemical committees.

3.0 OPERATIONS

Based on the wide variety of uses, composite structures come in all shapes and sizes. Handling these structures can range from tedious and painstaking at the fiber level with the use of forceps and a microscope up to the nearly unmanageable at the vehicle level (such as spacecraft or airliners) that requires heavy-lift equipment and large work crews. The various operations described below only address issues with the composite structure. Because these structures are constructed using high modulus fibers that are known to be weak in shear, care must be exercised to prevent mechanical damage. Steps to address this risk to the hardware should be covered in a damage control plan (DCP), credible threat analysis, and program or site handling documentation. Depending on the use environment (production floor, clean room, etc.), site (integration shop, launch pad, etc.) or program (automotive, airline, aerospace), the hazard controls required will vary and therefore employees must be familiar with governing documentation.

3.1 General Handling

General handling is required in all service life aspects of the composite fiber and structures. The hazard controls should be covered by the general site or shop guidelines for handling hardware. This may be no-shedding type gloves in the laboratory or leather or shop gloves in the service environment. It may occur in the manufacturing environment, integration shop, or service environment. General handling does not include any form of cleanup, manufacturing, or analysis; basically, any time the vehicle, structure, or hardware is in a cured condition free from fly and dust. This may also include vehicle or system integration, transportation, or inspection. Aerospace workers are shown with minimal PPE as required for the radiographic inspection of a composite overwrapped pressure vessel (COPV) in Figure 5.

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Figure 5
PPE Requirements for General Handling

3.2 Manufacturing (Finishing and/or Machining)

The manufacturing of carbon filaments can expose workers to hazardous conditions consisting of toxic atmospheres during mixing of the PAN solution and drawing of the filament. This could require respiratory and dermal protection to safe against the specific chemical exposures. As the filament is processed, exposure to high temperatures and toxic atmospheres can exist. Once the filament is sized the hazard may include dust and fly.

Manufacturing of composite structures requires handling of the neat fiber and uncured composite structure. This may also include the cured structure during required acceptance testing. During all phases of manufacturing the carbon should be protected from external or uncontrolled contamination. The probability of respiratory or dermal exposure is greatly decreased once the fiber and matrix are cured.

Composite structures often require machining or finishing for removal of sharp edges, conforming structure to specific dimensions/finishes, or allowing for installation of various instrumentation. Additionally, composites may be cut for forensics or to perform analysis and evaluation. Forensics are often required after a catastrophic event where the structure has been disrupted and causes a higher potential for sharp edge hazards. This may occur at any time during, or even after, the service life of the structure. As the composite structure is altered (grinding, milling, cutting), the filament and epoxy can be obliterated and create dust and fly as shown in Figure 6. Machining speeds and feed rates should be slow to protect the structure as well as limit the amount of dust and fly generated. This also minimizes the heat generation and potential for fire. Cutting operations should be performed wet if possible to cool the tooling and composite and to reduce dust and fly generation. Dry operations should use a collection system (vacuums with HEPA filters) and personnel isolation.

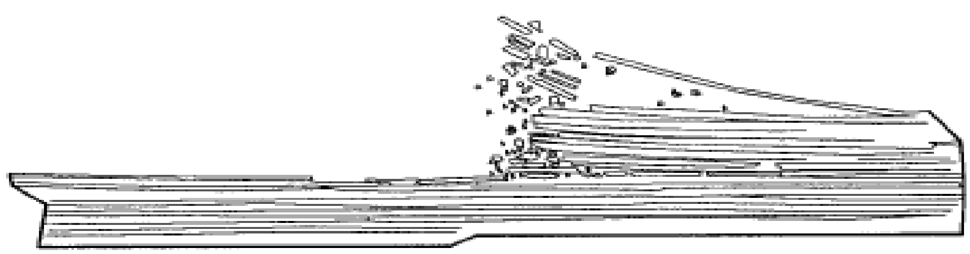

Figure 6
Fly and Dust Generation from Cutting/Machining

Analysis of composite structures both before qualification and during forensic evaluation often involves sectioning of the structure. This can be performed either in the shop or in the field. In the shop it is much easier to control dust and fly during the operation. This may involve a skill saw or band saw (diamond wire saw). The preferred method is a water knife or an operation that uses large amounts of high flow water. This helps keep the cutting surface cool and prevents the dust and fly from becoming airborne.

3.3 Catastrophic Event

Catastrophic events such as a vehicle crash, explosion, or fire will usually involve the destruction of a composite structure at a microscopic level. The amount of energy involved in the rapid disassembly of the composite elements will determine the potential and severity of exposure to the hazard. A catastrophic event can either be planned, as in test and evaluation experiments, or unplanned or prepared for, such as airplane or launch vehicle crashes.

Additionally, the event may involve fire or explosions that create large amounts of dust and fly. Hazards in the field or service environment often result in the dust and fly being distributed and deposited in a downwind plume. It is important for investigators and first responders to understand and evaluate the ability/availability to use and control ventilation and or wind currents to manage control and containment efforts after a catastrophic event. Some events may be conducted in controlled ventilation systems or with water deluge in which cases the respiratory exposure potential may be eliminated and the risk limited to skin exposure to sharp objects. A catastrophic event may occur in one of two environments, either in the laboratory or the field environment. The location will greatly affect the ability to manage the control and containment efforts and the required hazard controls.

3.3.1 Small Scale Catastrophic Event

Small scale catastrophic events are usually limited to the test and evaluation of smaller composite structures such as strands, strips (Izod (ASTM D256)/Charpy (ASTM D4508)), or coupon level test specimens. In these cases there is little or no dust and fly generation that is of concern. In the event the structures or samples are not obliterated into respirable particles they may only require minor handling PPE (gloves) and no respiratory protection. A minor event that results in only a small amount of hazard control may occur in a test chamber that can be atmospherically isolated and/or purged with a water rinse down. In any case, a minor event does not expose personnel to the respiratory carbon hazard and is generally limited to hazards that occur during handling. An example of coupon level testing that requires minor levels of hazard control is shown in the hypervelocity impact of a composite panel (Figure 7). As long as the loose fiber on the surface is not made airborne by turbulence or agitation, no respirator protection would be required. Additionally, any handling or analysis operations could be performed in a fume hood to ensure no personnel exposure.

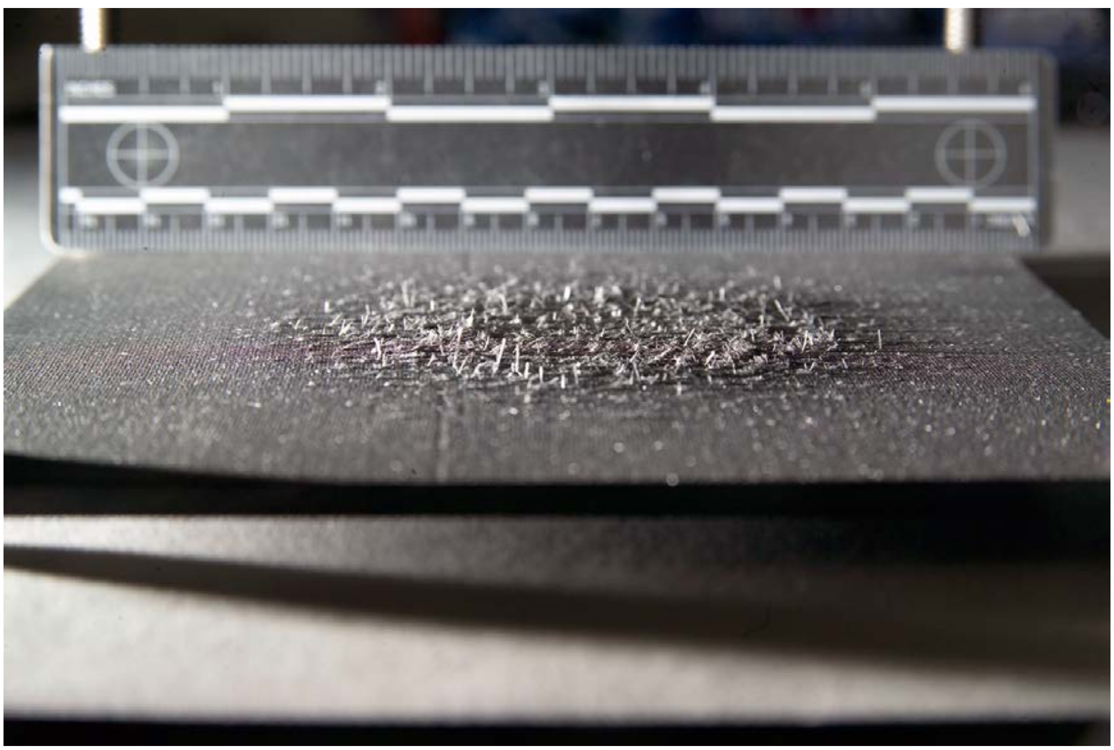

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Figure 7
Small Scale Composite Surface after Hypervelocity Impact

3.3.2 Large Scale Catastrophic Event

Large scale catastrophic events that can cause large amounts of carbon dust and fly to be released may include, but are not limited to, airplane crash, missile system failure, or COPV rupture. The type of composite structure involved, amount of energy, weather conditions, and location of the event all drive the severity of the potential exposure.

As reported by Olson (1994), damage to advanced composites materials caused by fire, explosion, and/or high-energy impact in a mishap presents unique environmental, safety, and health hazards. In typical aircraft fires of 1000 to 2000 °C (1832 to 3632 °F), organic matrix materials, or polymers, burn off around 400 °C (750 °F) creating toxic combustion or pyrolysis products and liberating the reinforcement, or fibers. Depending on the fiber, the reinforcement dynamics can vary. Glass or aramid fibers tend to melt under extreme heat, whereas carbon or graphite fibers are oxidized by the heat, thereby altering their size, shape, porosity, and other characteristics. Intense thermal and mechanical forces in such a mishap generally cause "explosive" fracture or dis-bonding and degradation of advanced composite structures. While absorbing this energy, the reinforcement, usually stiff and strong, may be broken into particulate fibers, turned to dust, or protrude from the vehicle structure. Because of their stiffness, carbon fibers can readily penetrate the skin. The absorbed and adsorbed pyrolysis and combustion products (assumed toxic) on activated, oxidized fibers can be a significant injection or inhalation hazard. Chemical products can be injected into the body. Though peripheral, this phenomenon could be especially critical in mishap scenarios where bloodborne pathogens may be present on damaged debris. In all cases, the type, amount, and extent of damage to advanced composites drive the level of health hazard because of the importance of concentrations.

Carbon fly and dust can be widely distributed in a catastrophic event as shown in Figure 8. Note the shadowing of the carbon dust plume in all directions from the epicenter of the catastrophic event located in the middle of the image below. This type of high energy event has the potential to expose personnel to multiple carbon hazards. Major catastrophic events are difficult to isolate and control through ventilation. Access to and controls of these incident locations should be controlled through Federal Emergency Management Agency (FEMA) incident command hierarchy
(FEMA 2013).

Some catastrophic events can occur during hydraulic testing and inherently have deluge or water rinse down as shown in Figure 9. A majority of the dust and fly are trapped and contained in the test fluid or liquid media during the event. This is a major advantage in cleanup and limiting personnel exposure. If enough time is allowed, a majority of the airborne dust and fly will settle and respiratory protection may not be required. The area may need to be rewetted to ensure the dust or fly does not dry out and become airborne.

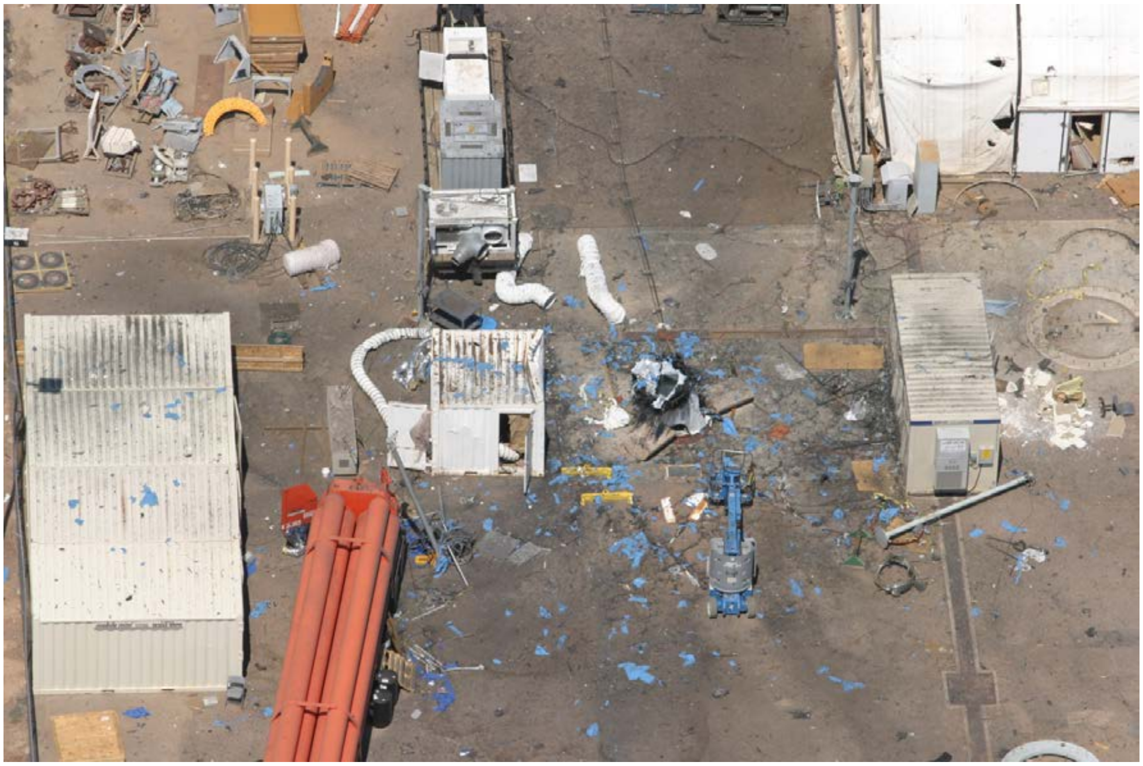

Figure 8
Large Scale Catastrophic Event of Carbon Composite Structure Failure

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Figure 9
Fly and Dust Entrained in Process Fluid

In most catastrophic events the release of high energy causes extensive damage and wide field distribution of dust and fly, depositing it on exposed surfaces. The result is a high potential for respiratory and skin exposure (Figure 10).

NASA-WSTF 1295-2855

Figure 10
COPV Burst Dry Catastrophic Event

3.3.3 Catastrophic Event Involving Fire

Wright et al. (2003) compiled an extensive review document entitled *Review of Composite Materials in Aircraft Mishaps Involving Fire: A Literature Review*. The focus of their literature search was in the areas of:

1. General characteristics of composite combustion and fiber release from aircraft composite materials during combustion
2. Toxicology of combustion products released from burning aircraft composite materials
3. Current research projects addressing the problems associated with the combustion of aircraft composite materials
4. Availability of instructional courses that cover firefighting and cleanup procedures for composite aircraft mishaps
5. Response guidelines for incidents involving aircraft composite materials

In this literature review, a brief background on composite fire history and materials was presented and followed by a detailed discussion of each of issue. Based on this analysis, recommendations for future actions were presented.

Catastrophic events can occur anywhere but will be separated into two different categories for this document. One category is the laboratory environment in which failure is often anticipated, and the other is in the field or service setting. The latter usually involves large structures, big fires, and city, state, or federal government response. This level of event should be controlled by FEMA incident response criteria and follow the same level of regulation for control and containment.

Major catastrophic events involving fire generally release large amounts of carbon dust and fly to the atmosphere. Incidents include airplane crashes, missile system failures, or compressed natural gas (CNG) bus fires. These can also be at the component level and driven by oxygen systems. In most uncontrolled fires the matrix is consumed, allowing the dust and/or fiber to easily become airborne. The type of composite structure involved, amount of energy, intensity of the fire, location of the event, and weather conditions all drive the severity and distribution of the potential exposure hazard. The affected area is worsened by high winds, carcinogenic combustion plumbs, and mass chaos.

These types of high energy events have the potential to expose personnel to multiple carbon hazards. Major catastrophic events are difficult to isolate and control through ventilation. In most instances involving fire, the use of large amounts of water is required and ultimately aids in the control and containment of the composite hazard. This also tends to assist the cleanup by washing down all the loose fly and dust. Fire brigades are encouraged to approach the fire at ~45 degrees from the corners of the vehicle or structure and the best established upwind direction. Again, events of this nature should be coordinated and controlled through the FEMA incident response hierarchy. This is demonstrated by the fire brigade responding to the aircraft fire in Figure 11. Note the direction of the plume that most likely contains carcinogenic burn products mixed with dust and fly.

As the fire consumes the matrix material it creates highly oxidizing and turbulent environments with lots of thermal lift and agitation. Combined with the disrupted structure, this allows significant and widespread potential for exposure to the dust/fly and plume.

The U.S. Navy has protocols and check lists in their response guidelines to an aircraft mishap involving composite materials (Wright et al. 2003). The use of a fixing agent is an important initial means of hazard control. Specific aircraft authority and investigators should be consulted before applying fixing agent, although safety concerns may override delayed application. Considerations include that a “hold down” solution or fixing agent should be obtained, such as polyacrylic acid or acrylic floor wax and water. If acrylic floor wax and water is used, it should be mixed in a 10:1 water to wax ratio. A heavy coating of the fixing agent should be applied to all burned composite material and to areas containing scattered/settled composite and the coating should be allowed to dry.

Google images

Figure 11
Catastrophic Event Involving Fire

Catastrophic events involving fire may also occur in the laboratory setting by design or unintentional release. Proper test preparation and safety review should establish blast containment (fragmentation and fiber dispensation) and other hazard controls such as the use of fixing solutions appropriate to the event. With proper controls the exposure is eliminated through the course of test and evaluation. This is performed by personnel exclusion, blast containment, and controlled ventilation. When fire is expected or required, the operation should be performed in areas with high ventilation and filtration. This is demonstrated in Figure 12 as matrix resin is being pyrolized and burned from a composite coupon. The intense heat and lifting turbulence is evident in the self-supporting combustion process.

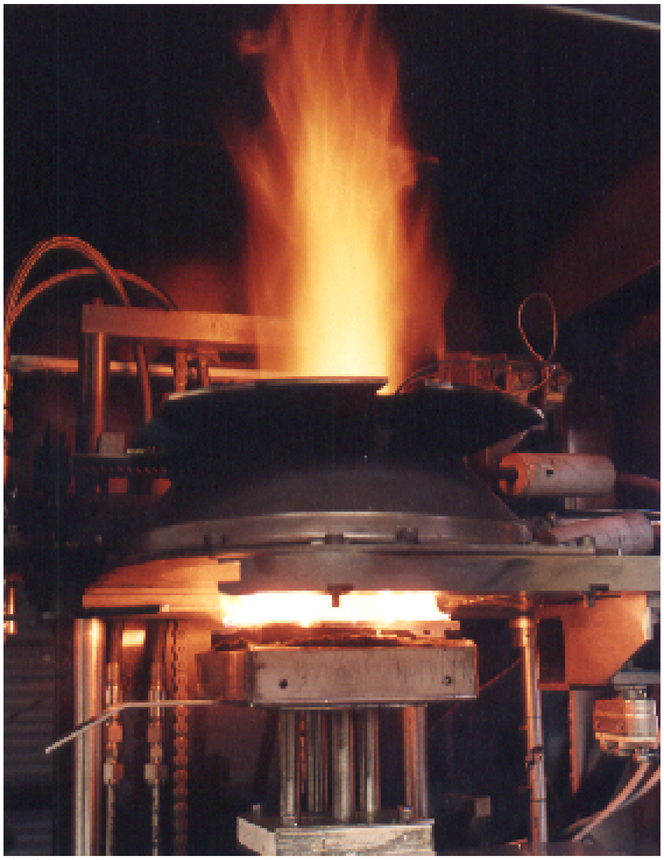
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Figure 12
Combustion of Composite Sample for
Thermal De-Ply Analysis

The Naval Air Warfare Center Weapons Division has performed testing and evaluation and developed standardized protocols and checklists for response guidelines to an aircraft mishap involving composite materials (Wright et al. 2003). These guidelines include the application of fixing solutions, such as such as polyacrylic acid or acrylic floor wax and water, which stabilize the composite and prevents them from becoming airborne. The Naval Air Systems Command (2009) also has developed precautions and procedures for carbon/graphite (and boron/tungsten) fibers that can become airborne as a result of fires or a crash/explosion scenario which may fragment sections of a composite aircraft. Evidence of this application is shown on the surface of the aircraft in Figure 13.

3.4 Analysis

The analysis of composite structures is very important for understanding and improving the performance of composite structures. Analysis can occur any time during the design, qualification, service, or forensics of the structures. Most types of analysis techniques can be conducted both in the field and in the laboratory at the vehicle or fiber level. Ideally the higher fidelity scientific methods of test and evaluation should be conducted in laboratory conditions where the environment can be better controlled. This will drive the required hazard controls during handling of the structure and potential exposure to the carbon hazard. Analysis may be nondestructive in nature and performed on composites that have not been exposed to a catastrophic event. In this case, general handling PPE could be used as a minimum in addition to that required by the site or program documentation.

3.4.1 Vehicle, Structure, or Fiber Level Forensics

The majority of fly, dust, and loose fibers should have been removed, isolated, and/or encapsulated during cleanup. Postmortem analysis is conducted after the item has been stabilized (cleaned of loose dust/fly) or had the loose dust/fly fixed, as long as there was no fire or chemical ingestion of the matrix, and the composite structure still maintains some structural integrity and a majority of the matrix/resin system is still intact. As long as the dust/fly hazard has been addressed the only remaining hazard is the potential for skin punctures or lacerations caused by the sharp broken fibers. This type of post-event forensic activity is usually highly documented and controlled by independent investigators. In Figure 13, dust and fly have been removed and analysis is about to be conducted on a crashed missile system that did not involve fire or a large release of energy.

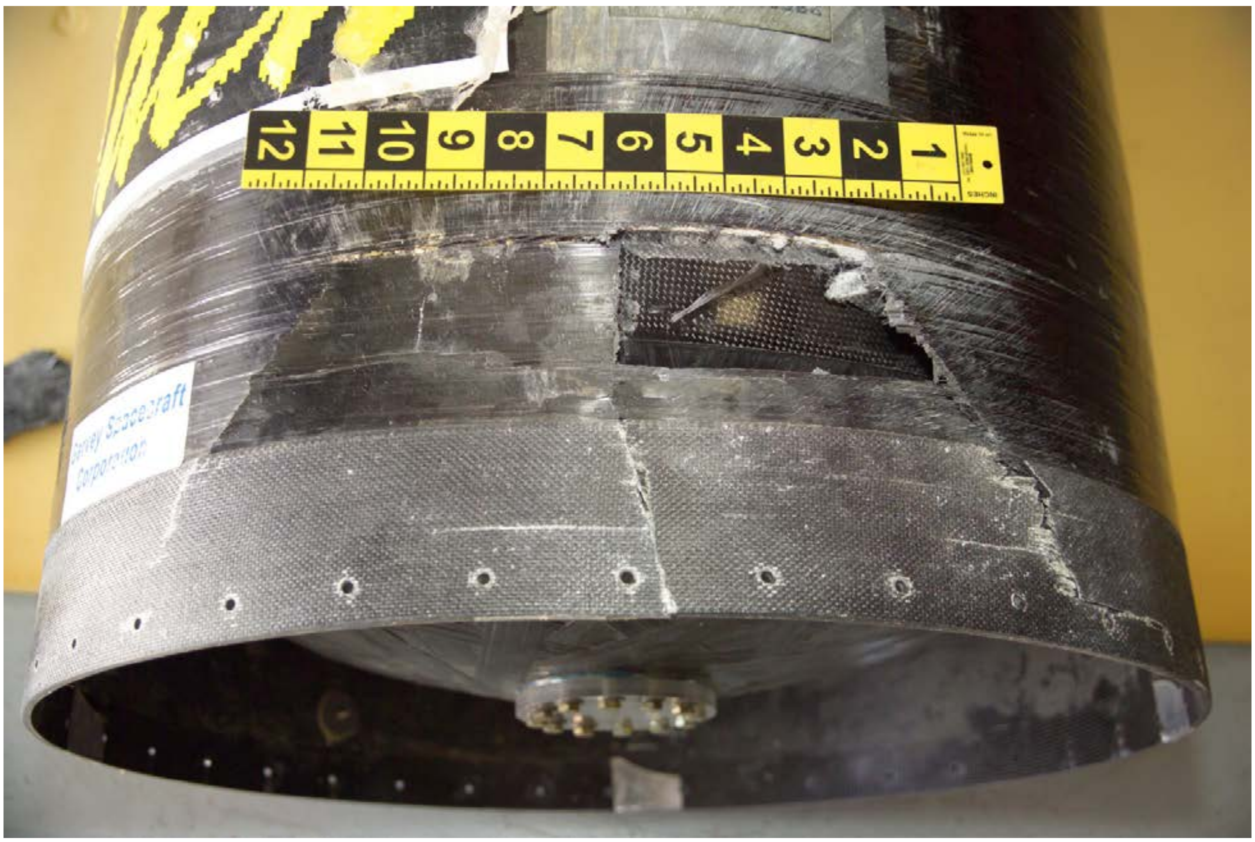

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Figure 13

Failed Missile System Ready for Analysis: Post-Catastrophic Failure

3.4.2 Vehicle, Structure, or Fiber Level Forensics Involving Fire

The majority of dust and loose fibers should have been removed, isolated, and encapsulated during cleanup. For the postmortem analysis the hardware should be stabilized or fixed. The structure or component has the appearance of neat fiber and is no longer in a cured form (i.e., matrix burned from majority of component) as shown in Figure 14. Because the carbon material was not secured or fixed, this coupon required forensics to be performed inside of a fume hood. Additionally, the vehicle went through a high energy event that may have caused further destruction of the laminate structure.

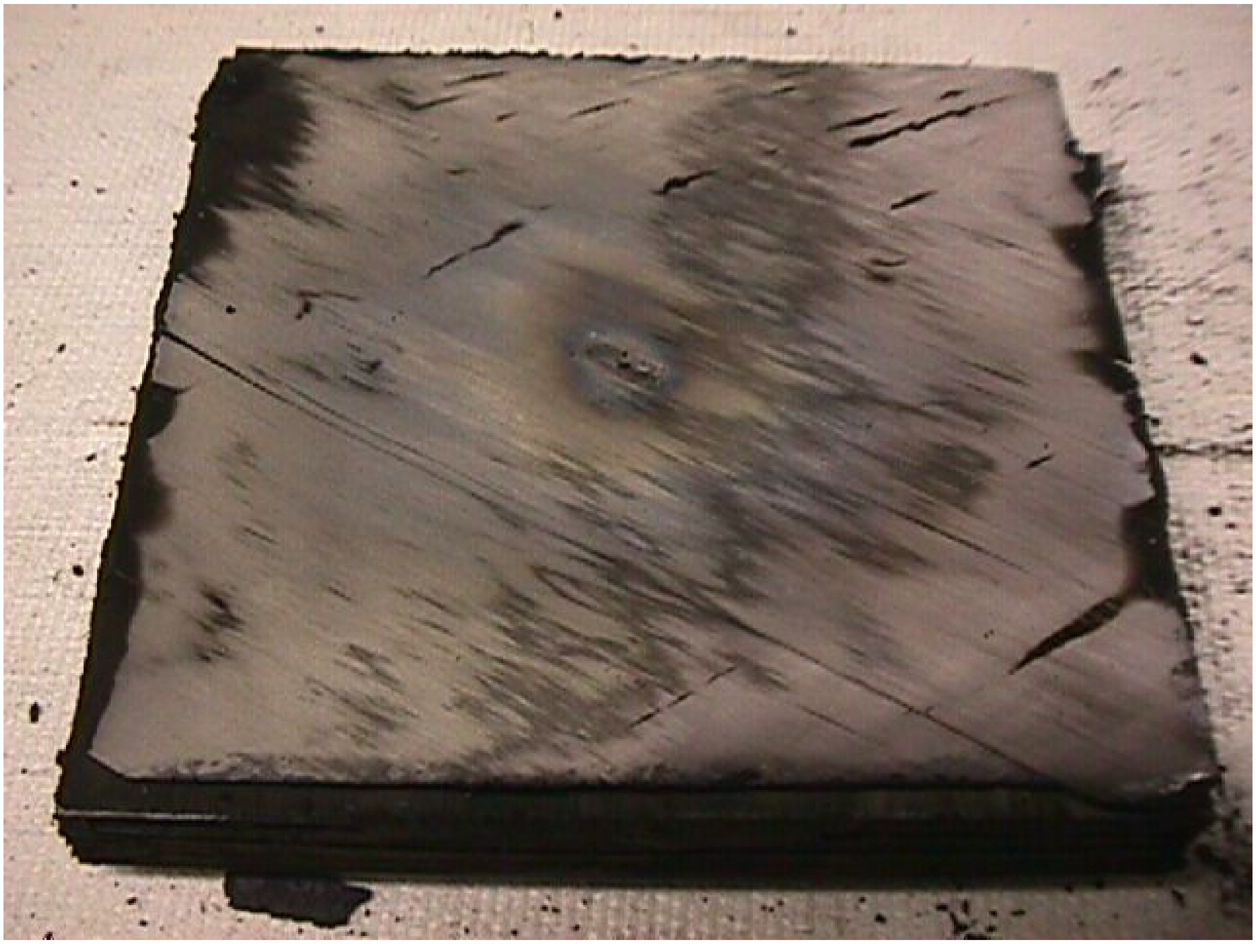

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Figure 14
Forensics on Post-Fire Coupon

4.0 HAZARD CONTROLS

Hazard controls vary greatly based on the amount and potential dispersion of composite fly, dust, or fiber. Appropriate engineering controls in addition to work practices, procedures, and PPE must be employed. Personnel must employ appropriate hazard controls prior to exposure to the potentially hazardous condition. A hazard evaluation must be performed and protective practices suitable for the environment must be determined. This includes engineering controls, administrative controls, work practices, and PPE.

In general, the most common routes of exposure to hazardous substances are inhalation, absorption, injection, and ingestion. Inhalation can be controlled by fixing, containment, ventilation, or respiratory protection. Absorption can be controlled by fixing, containment, ventilation, and appropriate PPE that will also avoid contact with the skin, eyes, and mucous membranes.

Injection is not a particularly credible route of exposure to composite fly, dust, or fiber, though puncture can be a hazard when the body is exposed to sharp edges. Engineering controls such as padding, long handled tools, and PPE including suitable gloves can help to avoid puncture as well as general skin contact, which can lead to irritation and dermatitis. As described by Olson (1994), if fibers are contaminated by potentially infectious material, exposure to bloodborne pathogens is a risk (such as in a catastrophic event) where sharp edges may have been exposed to blood. ("The potential for multiple injections of Hepatitis B and HIV caused by infected remains on damaged advanced composites." Olson 1994)

Ingestion can be avoided by minimizing hand-to-mouth contact and the *peri*-oral route, prohibiting consumables and consumption (food, drink, gum, tobacco), avoiding the use of cosmetics, and by washing hands frequently after any operations involving composite hardware, even when gloves are worn.

In environments with heavy amounts of dust and fly where PPE is used, it is recommended to have designated areas (change rooms with washing facilities) that are enclosed or contained for employees to don and doff PPE, clean themselves as necessary, and to change into clean clothes without risk of contamination. Employees must be trained in the appropriate means of doffing PPE in a manner that does not expose them to contaminants that may have accumulated on surfaces. Techniques such as cuffing and rolling gloves off so the exterior of the glove is not touched should be employed. Employees should completely wash with soap and water after the operation in areas that are equipped for this purpose and are able to be decontaminated after use. Change rooms should be equipped with storage facilities for street clothes and separate storage/disposal facilities for the protective clothing. OSHA has requirements for sanitation (29 CFR 1910.141) and several of the hazardous substance-specific standards have requirements for sanitation (changing garments, showers, etc.) (29 CFR 1910 Subpart Z). Information from these can be adapted to specific facility operations as applicable.

Personnel must be trained to use the selected PPE and fully understand the nature and level of exposure hazards. The level of PPE must be appropriate to protect against the hazards. In situations where large amounts of dust and fly are expected and engineering controls are not sufficient, personnel must don TECA PPE. This level of PPE allows no potential for contact or exposure to any of the carbon hazards. It is not defined as total encapsulating chemical protective suits (TECPS) although that level of protection is acceptable when total encapsulation (TE) is required. Wearing appropriate gloves and disposable work clothing limits exposure. If airborne fly, dust, or fracture fiber surfaces are observed in the manufacturing environment, the air should be sampled to determine the density and distribution levels. Exposed fractured surfaces should be fixed to protect from lacerations or impregnation of carbon fibers. These factors will drive the amount of PPE required. If the material is airborne, TECA PPE is used to fully protect the employee from all exposure to the hazard. TECA PPE is generally comprised of the following:

1) Respiratory protection (description below)
2) Spun high density polyethylene (such as Tyvek®[1]) TECA suit (hood and booties)
3) Protective gloves
4) Safety shoes (leather, non-porous, steel toe), or overshoes (booties, disposable or otherwise)

TECA PPE will be worn by the employee over the respiratory PPE (though supplied air is sometimes used), tucking appropriate gloves under the Tyvek sleeves and taping around sleeves to prevent fly or dust from contacting the skin. The same method should be applied to the area between pant legs and booties. This method of taping openings is shown in Figure 15.

wstf0113e00074

Figure 15

Proper Methods to Prevent Exposure at Cuffs and Ankles

In extreme environments, TECPS may be appropriate but their use is generally avoidable if other protective measures can be taken to mitigate the hazards. In practice, TECPS is costly

[1] Tvyek® is a registered trademark of E. I. DuPont de Nemours and Company, Wilmington, Delaware.

and may be compromised by sharp objects. TECPS may also become impregnated with carbon fiber, eventually becoming compromised, and pose a risk to personnel handling the suits over time.

All associated electrical equipment should also be protected in some manner by using high flow shop and/or local ventilation systems and ensuring ventilation exhaust systems are equipped with HEPA filters.

Respiratory protection in this document is defined and constituted by PPE in any one of the following methods:

1) Self-Contained Breathing Apparatus (SCBA)
2) Full-face airline respirator
3) Full-face negative air pressure, air purifying respirator outfitted with HEPA filters
4) Half-face negative air pressure, air purifying respirator with HEPA filters and protective splash goggles
5) Positive displacement welding helmet with HEPA filter

Local policies dictate whether contact lenses may be worn. Contact lens should not be worn in any work environment that may increase the effects of the employee's exposure to any airborne particulate, especially if its carbon fiber or dust hazards. In an extreme case the fiber will get entrapped in the contact or worse, behind the contact, and cause severe damage to the cornea. The recommendation not to use contacts when carbon exposure is possible is widely stated in various carbon fiber SDSs. Safety glasses are sufficient protection when no dust or fly is encountered or expected. This is limited to situations where sharp objects are the primary threat. If particle counts and/or high dust/fly environments are expected, chemical splash goggles or eye protection with SCBA, TECPS, or full-face respirators may be recommended.

Hands should be protected from dust and fly as well as sharp objects caused by fractured composite structures. Prevention of contact is the first defense from the hazard. The specific hazard shall drive the type of glove selected. In any case, if the threat is from sharp objects, thick rubber or leather gloves are recommended. If the threat is dermatitis caused by dust and/or fly disposition, other laboratory gloves are acceptable. Examples would include handling operations of a cured component or forensics of a fixing composite structure in a fume hood. Various types of gloves and the hazards they protect against are shown in Table 4.

Table 4
Glove Types and Hazard Protection

Glove Type	Protects Against
Cotton	Abrasions
Disposable Plastic (Latex)	Microorganisms, mild irritant, fibers
Natural Rubber (Latex)	Acetone (<1hr), epoxies, Methyl ethyl ketone (MEK)
Leather, Aramid	Abrasions, punctures, and fibers
Neoprene	Acetone (>1hr), epoxies, N-methylpyrrolidone (NMP)
Nitrile	Epoxies, isocyanates
Polyvinyl alcohol	Methylene chloride, toluene, Methyl isobutyl ketone (MIBK), styrene, Tetrahydrofuran (THF)
Polyvinyl chloride	Dimethylsulfoxide (DMSO), isopropyl alcohol, epoxies
Butyl rubber	Dimethylformamide (DMF)
Viton	Methylene chloride, 1,1,1-trichloroethane, toluene

SHARP 1998. **A Guide to Preventing Dermatitis while Working with Advanced Composite Materials Publication 55-03-1999**

Feet should also be protected from dust and fly as well as sharp objects caused by fractured composite structures. If possible, prevention from contact is the first defense for foot protection from the hazard. The specific hazard shall drive the type of foot protection selected. In general, industrial approved footwear is acceptable for protection from carbon hazards. Full-grain leather safety shoes are recommended. Steel toe shoes that are non-porous rate the best. If high concentrations of airborne or particulate carbon are encountered, the boot should be covered with a disposable bootie (such as Tyvek). Booties should be disposed of after carbon fiber exposure and boots should be inspected to determine if fiber impregnation has occurred. Small amounts of the fiber may be removed from the leather in the same manner as from skin as described in Section 5.0, First Aid. If exposure is too extensive to safely control or contain, the boot should be disposed of in accordance with Section 6.0, Disposal.

In the following sections the health hazards, threats, probability of exposure, and recommended PPE are addressed. These are generally detailed in a table specific to the associated operations section. Recommendations on general safety aspects and assumptions are also discussed. For the analysis operations the section is separated into two sections to address PPE that is recommended for the laboratory and service or field environment. The significant difference between the field environment and the laboratory setting is the ability to control the ventilation and subsequent containment of airborne dust and/or fly.

4.1 Handling

As long as the structure is free from damage, PPE is not required. Care should be given as mandated by program requirements regarding contact with the hardware. Follow vendor, site, or program requirements for proper handling. The requirements documents should define the PPE, quality, and certification requirements. If PPE requirements are not defined, this document can provide guidance for employee PPE. Composite structures generally have sharp edges associated with fiber ends and epoxy edges. Padding is an engineer control against contact with sharp objects that should be employed before resorting to PPE. The composite can be visually inspected globally to determine what level of hand protection may be required prior to any handling, but hand protection is prudent in any case. Leather or aramid gloves should be used to protect against sharp edges or surfaces. Nylon, rubber, or latex gloves should be used if contamination of the composite from the skin needs to be avoided. This is demonstrated in

Figure 16 where personnel are protected from potential puncture and contamination of the composite aerospace structure by gloves and TECA.

Respiratory protection and dermal protection are not required for general handling operations. This assumes that no dust or fly exists from manufacturing (machining or finishing) or control and containment. An example of a level of minimum PPE suggested for handling operations is listed in Table 5.

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Figure 16
PPE used for Handling Composite Structure in a Clean Room

Table 5
Minimum PPE for Handling Operations

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	N/A	Negligible	N/A	N/A
Respiratory	N/A	Negligible	N/A	N/A
Eye	Physical Contact	Low	Fiber/Structure	Safety Glasses
Skin	Physical Contact	Low	Fiber/Structure	TECA, Leather or Aramid Gloves

4.2 Manufacturing (Finishing and/or Machining)

In the manufacturing environment, neat fiber should not be contacted directly by the employee. During required handling operations, neat fiber or bobbins should be bagged or placed in a ventilated area at all times possible. If required, contacting bobbins of fiber using the paper tube minimizes contamination and potential damage/disruption. Wearing nylon or leather gloves and normal work clothing limits exposure. If fly and/or dust are observed in the manufacturing environment, the air must be sampled to determine the level. This will drive the amount of PPE required. If this material is airborne, conservative PPE is to fully protect the employee from all exposure to the hazard.

The list of hazards, mechanism, probability, material, and recommended PPE for manufacturing (machining and finishing) are shown in Table 6.

Table 6
Minimum PPE for Machining (Machining and/or Finishing)

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	Deposition	Moderate	Dust/Fly	Respiratory
Respiratory	Inhalation	High	Dust/Fly	Respiratory
Eye	Deposition/Physical Contact	High	Dust/Fly/Fiber	Full-face or Splash Goggles
Skin	Deposition/Physical Contact	High	Dust/Fly/Fiber	TECA, Thick Rubber or Leather/Aramid Gloves (Inner Glove), Safety Shoe

Finishing and/or machining of composite structures can occur during all phases of use. It is mainly limited to the manufacturing and integration phases of use, but may be required for analysis, forensics, and even disposal. These operations generally create a large amount of dust, associated fly, and some microfibers. Full body PPE is required during these operations. Operations should be conducted in isolated environments to limit the extent (area and volume) of dust/fly control and containment. The use of liquid-cooled methods is recommended to prevent tool wear and heat buildup and to limit the amount of airborne dust/fly. The control and containment of cooling fluids will require assessment and management measures in addition to approved disposal procedures. It is recommended that any dry machining or finishing operations use high local ventilation as shown in Figure 17. The decision to protect equipment should be made based on the amount of operations, importance of the operations, and replacement cost of the associated equipment.

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Figure 17
Cutting Operation with Dust/Fly Collection, Ventilation, and Filtration System

4.3 Control and Containment (Catastrophic Event)

The control and containment after a catastrophic event has the highest potential for personnel exposure to carbon fiber hazards. This often occurs after unplanned, highly energetic events. In large scale events involving fire, the first responders are often unaware of the many hazards present. Many times volunteer fire brigades are unprepared and ill-equipped for catastrophic events involving composites. As a result many have been hospitalized after exposure. This section discusses and recommends procedures and PPE for catastrophic events. The section is separated by catastrophic events that involve fire and events that do not involve fire. For catastrophic events that do not involve fire, the control is separated into dry cleanup and wet cleanup. In either case, containment is essentially the same.

After a catastrophic event, whether it involves fire or not, all electrical devices should be isolated and/or placed on protected ground fault circuits. This will prevent or reduce the threat of electrocution caused by short circuit from the conductive carbon fibers and/or water rinse-down or deluge. Preplan to employ blast containment and isolation of electrical equipment in test and evaluation operations. Removal of electrical equipment is shown in Figure 18 where the data acquisition and control systems are removed and isolated outside of the potential carbon threat environment.

If total removal is not possible, expensive and sensitive electrical equipment (e.g., high-speed cameras) can be fortified and isolated from exposure as shown in Figure 19. Regardless of precautions, caution must be used when powering up electronics because the carbon short circuit hazard is compounded by water.

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Figure 18
Electronics Isolated from a Potentially Catastrophic Event

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Figure 19
Fortification and Isolation of Sensitive Electrical Equipment

After an event, even if control measures were employed, the containment of the carbon hazard must be performed. This should always start by fixing the carbon fibers and can be accomplished using a water deluge system (fire extinguishing system, fire brigade, etc.) and/or advanced fixing agents. Advanced fixing agents include polyacrylic acid or floor wax. Prior to using fixing agents, incident command and local environmental representatives should be consulted for approval. There may be forensics or environmental controls that may prevent the use of certain fixing agents. To fix hazards on components or parts that are generated from sharp objects, dust, and fly, use several layers of thick tape and/or multiple wraps of plastic “cling” wrap. Carbon dust, fly, and fiber can be fixed/contained in filter elements during vacuuming of the affected area. High-efficiency particulate air (HEPA) filtration needs to be installed on vacuum exhausts to prevent exhaust of particulates. Industrial hygienists should evaluate particulate size and make recommendations on HEPA filter sizing. Vacuuming can mechanically break fibers and this must also be taken into consideration. Wet vacuuming or mopping may be suitable for small areas. The procedures for collection of fibers and dust onto or into wetted media must not allow the media to dry, which can allow fibers and dust to become airborne.

A minimum of 10 min should be allowed for carbon fly and dust to settle prior to personnel entering the immediate area. In most field or service environments this is not an option if public safety is at risk and a large scale fire ensues. Fire brigades should don TE ensembles with respiratory protection. The U.S. Air Force Advanced Composites Program has developed guidelines establishing minimum safety and health protection requirements for firefighters, investigators, and cleanup crews in accidents involving advanced composite materials. Firefighters are required to wear SCBA, chemical protective clothing, leather gloves, and coveralls to minimize exposure to fibers. After the fire is extinguished, the debris is sprayed with a fixing agent to contain dust and fly and to encapsulate fractured/frayed edges of composite structures. Demonstration of fixing agent being applied and the associated PPE is shown in Figure 20. Guidelines have been adopted by the U.S. Navy, the FAA, and the National Transportation Safety Board (NTSB) for automotive and aircraft accident investigation, cleanup, and recovery tasks. A handbook from the Suppliers of Advanced Composite Materials Association (SACMA) considers skin irritation due to mechanical abrasion to be the principal health concern (SACMA 1991). The Naval Air Warfare Center Weapons Division has performed testing, evaluation, and has developed standardized protocols and check lists for response guidelines to an aircraft mishap involving composite materials (Wright et al., 2003). These guidelines include the application of fixing solutions, such as such as polyacrylic acid or acrylic floor wax and water, which stabilize the composite from becoming airborne. The Naval Air Systems Command (2009) also has developed precautions and procedures for carbon/graphite (and boron/tungsten) fibers that can become airborne as a result of fires or a crash/explosion scenario that may fragment sections of a composite aircraft.


Google images F-19 failure investigation

Figure 20
Appropriate PPE for Applying Fixing Agent

4.3.1 Wet Containment

The cleanup of composite materials should be performed when the material is fixed and/or wetted. The area may involve hydraulic fluid as a wetting agent or wetting may be performed during incident response. If the event involved fire or occurred in an area with a deluge water system, the fire suppression system should be employed to wash down or knock down airborne dust, fly, and fibers.

The control and containment of carbon fiber should be considered prior to the event, if possible. This would include the isolation of all affected electrical equipment. Containment/confinement and/or inert gas purge of electrical equipment is recommended. Containment of the event is recommended to control and contain dust, fly, fiber, and associated fragmentation. This is done through blast containment in bunkers, blast enclosures, or fume hoods. These areas should be remote, when possible, and equipped with positive flow ventilation (filtered exhaust on the entrance) and/or water deluge systems. Filters on the entrance of ventilation systems prevent contamination of the duct work. Otherwise TECA PPE will be required to service or dispose of duct workings (vents). Once the event is complete, the material should be allowed to settle for durations greater than 10 min. If possible, the area should be purged or deluged during this time. Prior to entering the containment area personnel should don TECA PPE as shown in Table 7. The large material should be fixed if possible with fixing agents listed and sharp objects covered with tape or other similar protective coverings. The containment area should then be vacuumed with HEPA-filtered vacuums and wiped down with damp shop towels. The filters and wipes should be disposed of in the same manner as carbon fiber, composite structures, and any other contaminated media. Contaminated media might include clothes, gloves, and other forms of PPE.

Personnel responding to a service/field catastrophic event with fire should consider immediate protection of critical electrical equipment, approach should be from upwind direction, and then wash down with water suppression, maintaining a safe distance during fire suppression operations. When evaluating the safe distance consider the potential of pressurized cylinders rupture and potential propellant wash from helicopter blades. Maintain and control locations within the downwind plume to protect equipment, bystanders, and approaching emergency services (ES) personnel. Containment should address containment of dust/fly, media, and fragmentation. Use water deluge and or vacuum with filtered exhaust with direction from incident command. Use appropriate hazard controls as required for fire suppression.

If at all possible, power down all possible electrical sources and equipment prior to the application of water deluge, water spray, or fixing agent to the structure. Ensure fire control and containment has been achieved and incident command has authorized entry to the affected area. Enter contaminated area and wet down the area using recommended fixing method. Use approved fixing agent or water mister with a light spray to wet and maintain a wetted affected area. If practical, and in TECA PPE, the area should be vacuumed to fix loose dust and fly or fibers or to remove the dry material. Again, it is recommended to place HEPA filters on the intake of vacuums to prevent contamination of vacuum lines. The area should then be wiped down with a damp shop towel. All exposed filters, shop towels, and PPE must be treated as contaminated with carbon dust, fly, and fiber. Cautions should be taken when backing out of a carbon exposure scenario. Support equipment (filters, fire hoses, vacuums) contaminated by carbon hazards should be neutralized and cleaned prior to removal of TECA PPE. The composite wastes should also be disposed using the approved double bag method described in Section 6, Disposal. In a controlled area, the contaminated PPE should be removed in a predetermined and practical manner. Hoodies should be removed first followed by the TECA suit. The suit should be rolled outward to contain the loose fiber and debris. If severely affected, the suit should be rolled out over the gloves and booties, and then placed directly into the first of two bags for disposal. Label the bags as necessary (see Section 6 for direction).

Table 7
Control and Containment PPE for Wet Cleanup

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	Deposition	Low	Dust/Fly	Respirator
Respiratory	Inhalation	Low	Dust/Fly	Respirator
Eye	Deposition/Physical Contact	Moderate	Dust/Fly/Structure	Full-Face Respirator or Splash Goggles
Skin	Deposition/Physical Contact	Moderate	Dust/Fly/Structure	TECA, Thick Rubber or Leather/Aramid Gloves (Inner Glove), Safety shoe

4.3.2 Dry Containment

Dry containment has the highest potential for employee carbon fiber exposure. The carbon fiber is easily made airborne in dry conditions. This is the case when fire is involved or high impact energies are encountered. Air currents from the weather and personnel movements are enough to make dust and fly airborne. If other hazard controls are not sufficient, it is recommended that personnel don respiratory protection and TECA PPE prior to entering an area for dry material containment.

Ventilation is used as a first level control for removal and fixing of the fly and dust. It should be ensured that HEPA filters are installed on the inlets (close to the intake) of all cleanup vacuum or ventilation systems. As a minimum, TECA PPE is used, or dry cleanup PPE as required, for inspecting, repairing, or replacing the filters. Debris and filters are disposed of as described in Section 6, Disposal. If ventilation is not possible, a minimum of 10 min is allowed for carbon fiber and dust to settle prior to entering the immediate area. The fixing technique that will be used is determined and PPE donned. Dry cleanup PPE is defined as respirator (SCBA, full-face airline respirator, half-face negative air pressure, air purifying respirator with HEPA filters and protective splash goggles, full-face negative air pressure, air purifying respirator outfitted with HEPA filters), goggles, thick rubber or leather gloves (nylon inner glove is recommended), and a TECA suit (hood and booties). Contact lenses should not be worn under goggles for operations that could produce airborne particulate.

All possible electrical sources and equipment must be powered down prior to application of water deluge, spray, or fixing agents. It must be ensured that fire control and containment has been achieved and incident command has authorized entry to the affected area. The contaminated area and wet down area can be entered using the recommended fixing method, as required. An approved fixing agent or water mister with a light spray is used to wet and maintain a wetted, affected area. If practical, and in TECA PPE, the area should be vacuumed to fix loose dust and fly or fibers or to remove the dry material. Again, it is recommended to place HEPA filters at the intake of vacuums to prevent contamination of vacuum lines. The area should then be wiped down with a damp shop towel. All exposed filters, shop towels, and PPE must be treated as contaminated with carbon dust, fly, and fiber.

Caution should be taken when backing out of a carbon exposure scenario. Support equipment (filters, fire hoses, vacuums) contaminated by carbon hazards should be neutralized and cleaned prior to removal of TECA PPE. The composite wastes should also be disposed using the approved double bag method described in Section 6, Disposal. In a controlled area, the contaminated PPE should be removed in predetermined and practical manner. Hoodies should be removed first followed by the TECA suit. The suit should be rolled outward to contain the loose fiber and debris. If severely affected, the suit should be rolled out over the gloves and booties, and then placed directly into the first of two bags for disposal. The bags should be labeled as directed in Section 6. PPE shown in Table 8 is recommended for dry containment of carbon fibers and structures.

Once all the PPE has been fitted and ready for use, cleanup operations may commence.

Table 8

Control and Containment PPE for Dry Cleanup

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	Deposition	Low	Dust/Fly	Respirator
Respiratory	Inhalation	Low	Dust/Fly	Respirator
Eye	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	Full-Face Respirator or Splash Goggles
Skin	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	TECA, Thick Rubber or Leather/Aramid Gloves (Inner Glove), Safety shoes

Dry containment efforts have the highest potential for personnel exposure to the various carbon hazards. Strict adherence to hazard control requirements and industrial hygiene practices must be followed to prevent injury. If the event is reoccurring, sampling should be performed to thoroughly evaluate the level of carbon exposure. Best practices documents exist on how to sample and evaluate the density and distribution of the hazard. If this data is unavailable, then TECA PPE must be used to protect against dermatitis, respiratory exposure, or lacerations/sharp objects. The composite must initially be fixed before any PPE requirements can be relaxed. Fixing the composite will allow containment, and then forensics or disposal. It is recommended that all PPE (TECA suits, gloves, monitoring equipment, etc.), manufacturing equipment (saws, mills, etc.), control/containment equipment (ventilation ducts, filters, contaminated fire hoses, etc.) be cleaned or disposed of after a dry containment cleanup event. The operation should be performed while in TECA PPE. After the operation is completed, the TECA PPE should be removed in a controlled area and disposed of per Section 6.0, Disposal.

4.4 Forensic Analysis

The degree of hazard control is strongly influenced by the environment or work area available or present during forensic analysis. Based on the ability to control the natural influence of wind currents or further hazard generation, two distinct environments are recognized: the laboratory and the field or service environment. In either environment, if forensic analysis is performed outside of machining operations or independent of a catastrophic event, general hazard controls may be adequate to protect against exposure to composite hazards. If machining or catastrophic events are involved, the composite structure should first have control and containment operations performed to remove the threat of airborne material. This should remove or fix a majority of the dust and fly and reduce the probability of exposure caused by airborne material. It should also fix the sharp objects and reduce possibilities of lacerations or sticks.

In the laboratory, if the structure has been properly controlled and captured, then any hazard associated with airborne particulate is negligible and the only credible threat is from the sharp edges of the disrupted composite structure. This assumes airborne dust and fly were removed during control and capture operations, or at least minimized by fixing (wax or tape/plastic wrap). The PPE required for most laboratory analysis operations is designed to prevent exposure to sharp objects including disrupted carbon fiber or carbon structures. Respiratory protective equipment is typically not required when particulate material is still cured, has been fixed, or when fume hoods are being used. The work area should have controlled, gentle ventilation and/or air currents if at all possible. Agitation of the composite structure should be avoided. If ventilation or agitation during deconstruction efforts cannot be avoided, the operation must be performed in a fume hood with the required PPE or TECA PPE. If the fiber is not fixed or does not remain wet during the entire analysis operation, and dust and fly can become airborne by shifting or uncontrolled wind direction, then TECA PPE should be worn. These conditions should be considered prior to the operation and the proper level of PPE determined prior to commencing efforts.

4.4.1 Laboratory

Control of potential disruption of dust and fiber during analysis or forensics activities are made much easier when performed in the laboratory. Although the composite should be fixed as a result of control and containment procedures, this may not always be the case. If the structure cannot be fixed, personnel must remain clear of the affected area. This can be achieved by placing the structure inside a fume hood or large area where drafts and wind currents can be maintained and controlled. Caution must be exercised when disturbing the composite structure to prevent dust and fly from becoming airborne. If the potential for airborne dust and fiber cannot be avoided, then TECA PPE must be employed. Otherwise, PPE may be limited to prevent contact with sharp objects, thus preventing lacerations or puncture. This is generally managed by the use of appropriate eye protection (splash goggles) and aramid or leather gloves. The analysis of a burned composite coupon is shown in Figure 21. The coupon is shown inside a fume hood with indication of positive air flow. If positive air flow is lost, the analysis efforts should be halted and the fume hood sash closed until positive flow can be reestablished. Care should be taken when working with composite fibers in a fume hood. The composite should be placed well within the fume hood to minimize the eddy effect of air currents and prevent contamination from exiting the fume hood. After operations are complete in the fume hood, any surface where dust and fly may have been deposited should be vacuumed and wiped down with a damp shop towel. These operations should be performed with respiratory protection and a TECA with aramid or leather gloves. If filters are at the exhaust outlets, then the entire duct work may require a damp towel wipe down. Locating filters close to the source eliminates potential contamination of duct/vent workings.

The level of PPE required if the composite is fixed and/or located in a fume hood are shown in Table 9. If analysis of forensic efforts requires the disruption of the composite structure that could release dust or fly, then TECA PPE should be used. Additionally, if concern of exposure exists, the air should be sampled and the levels compared to that listed on the SDS and the proper level of PPE used. Fume hood surfaces should be wet-wiped clean and the debris bagged for disposal.

wstf0311e01910

Figure 21

Sample Ready for Post-Fire Forensic Analysis

(NOTE: Fume hood and tail-tail ribbon indicating positive air flow)

Table 9
Minimum PPE for Analysis in the Lab

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	Deposition	Negligible	Dust/Fly	N/A
Respiratory	Inhalation	Low	Dust/Fly	Positive Air Flow
Eye	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	Safety Glasses
Skin	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	TECA, Aramid or Leather Gloves (inner glove)

4.4.2 Service/Field Environments

Analysis of composite structures in the field or service environment require proper fixing of the loose dust and fibers during the control and containment phase. If proper fixing of the loose material cannot be achieved in the field or service environment, then respiratory protection should be employed. Uncontrolled wind currents have the potential to cause dust and fly to become airborne during analysis. These events usually are associated with larger vehicles or structures making it more difficult to properly fix the loose debris. If a fire was encountered, the matrix is generally compromised and dust, fly, and loose fibers have a high potential to become airborne with any amount of wind. Regardless of fixing, the composite in the affected area should be controlled so analysis personnel do not agitate or disrupt loose dust and fiber. These types of forensics are generally conducted and regulated by federal agencies and fall under OSHA requirements for PPE as shown in Table 10.

Table 10
Minimum PPE for Analysis in Service/Field Environments

Health Hazard	Mechanism	Probability	Material	PPE
Ingestion	Deposition/Physical Contact	Low	Dust/Fly	N/A
Respiratory	Inhalation	Low	Dust/Fly	N/A Fixed material and upwind position
Eye	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	Splash Goggles
Skin	Deposition/Physical Contact	Moderate	Dust/Fly/Fiber	TECA, Thick Rubber or Leather Gloves (inner glove), Safety shoes

4.5 Displays

Displays or exhibits of intact or damaged composite structures must be subject to appropriate hazard controls to avoid contaminating the display environment (office or common area, museum, etc.), personnel who display them, and the viewers. Ruptured structures are exceptionally impressive and fascinating to many interested onlookers and storyboards or timelines of their demise provides great talking points of their history, use, circumstances under which they were damaged, extent of damage, and other aspects of engineering curiosity.

Unfortunately, irresponsible display and unwitting behavior may result in workplace hazards and hazards to the public. A damaged structure displayed in public may have the same or similar hazards to a damaged structure in a test or mishap configuration. Over time, a damaged structure will shed more dust that will accumulate or become airborne. This can be seen with almost every “heritage” burst vessel that is stored rather than disposed. Consequently, displays must be engineered responsibly, primarily to protect against airborne material and curious hands.

Most displays will not be presented in a fume hood, nor are viewers required to wear the appropriate PPE, such as laboratory coats and gloves. Rather, displays are often proudly presented in an open area such as an office or hallway display area where dust can become airborne and probing fingers can become punctured and contaminated. If picked up, clothing can also become contaminated. Consequently, damaged composite structures should only be displayed when the appropriate hazard controls have been implemented. Smaller structures can be safely displayed when fixed and hermetically sealed, such as in a glass display case. The display case must be protected from impact or dropping and should be labeled to prevent it from being opened outside of an approved ventilated area, such as a fume hood. Larger vessels present a more challenging means of containment, and consideration must be given to fixing them prior to display. Structures should be monitored for dust and continued deterioration while on display, and they should be removed if they present a hazard to personnel in the area.

4.6 Storage

Many damaged composite structures are not immediately disposed but are retained for future examination or reexamination, or preservation for historical purposes. While the scientific and/or engineering validity of storing damaged structures for future examination or reexamination is not within the scope of this document, storage presents similar safety challenges as it does for displays.

Inevitably, stored damaged structures will deposit dust, which will accumulate. Secondary containment (such as plastic bagging) may also be punctured either externally by various means or internally by sharp edges and/or the bags will simply degrade due to environmental conditions and age, and dust and fibers will be released from the primary containment. Over time, as boxes or other containers of damaged structures become accumulated, stacked, restacked, moved, dragged, and otherwise disturbed, more and more damage and debris may result. The end result may be that the storage area becomes contaminated with damaged composite structure debris and personnel who are in the area are exposed. Stored damaged composite structures should be kept secured (locked), inventoried, controlled, and periodically monitored. Disposal, rather than accumulation, should be evaluated to avoid situations where a safety hazard develops due to excessive and inadequate storage.

5.0 FIRST AID

By using the appropriate hazard controls, prevention is the best approach to avoid exposure to carbon fibers and composites; however, if exposed, personnel need to react immediately. In all cases of exposure, personnel must be removed from the contaminated environment to apply first aid. Removal must be accomplished in a manner that does not contaminate attending and/or non-protected personnel. Flushing with large amounts of water is recommended, so safety showers and eye wash stations must be accessible. This might require mobile/portable units or other acceptable deluge facilities to be placed in near proximity. The American National Standards Institute (ANSI) offers guidance on emergency showers and eyewashes (ANSI Z358.1). Advanced medical treatment should be administered after initial first aid techniques have been applied. Personnel who have been exposed to carbon fibers should continue to monitor and document at a regular interval any noticeable effects and set up a follow-up medical appointment for continued care.

Some carbon fiber exposure first aid and safety measures are derived from SDS sheets released by Toray Carbon Fibers America, such as SDS No: CFA-004 for Carbon Fiber, Genium Publishing Corporation Graphite (natural/synthetic) (No. 233), and the Japan Carbon Fiber Manufacturers Association. Considerable literature exists regarding follow up to exposures of first responders to fires and crashes of composite-based aircraft. Other first aid and safety measures can be found in several of the references in this document, including Wright et al. (2003) and SHARP (1998), but medical personnel associated with the facility or operation should make recommendations for the appropriate first aid.

Medical personnel must always be notified in case of an exposure. The Japan Carbon Manufacturers Association suggests that for skin exposure, the affected area should be rinsed and flushed with soap and water. If fibers and irritation persist, sticky tape, or even fixing-type glue, can be used to grab and remove the fibers (SHARP 1998). Larger fibers can be removed by hand or with tweezers. If irritation persists, professional medical attention must be sought. Although carbon fiber is difficult to image, X-ray radiography may be performed in addition to pulmonary studies.

If skin or eye exposure occurs, flushing with water should be performed for a minimum of 15 min in an ANSI Z358.1-compliant emergency shower or eyewash, if available, or any other flushing facility if not available, using potable water or other suitable flushing fluid.

If contact lenses remain in the eye after flushing, the lenses may require medical help to remove. The contact must be removed from the eye prior to further flushing and rinsing behind the eyelid. It was believed that contact lenses can absorb irritants and cause further damage, including cornea damage, during flushing, but the American Chemical Society Committee on Chemical Safety and National Institute for Occupational Safety and Health (NIOSH) have debunked this as unproven. However, contact lenses, like food, beverages, items of a personal nature, clothing, PPE, etc., should not be reused if exposed to carbon dust or fly. The exposed eye must be flushed for a minimum of 15 min while medical personnel are notified.

Contaminated clothing should be removed while flushing the skin. Once exposed personnel are in the care of emergency medical personnel, the medic will determine if additional flushing, first aid, and/or further medical treatment is required. Exposed items should be decontaminated if possible and if this is unachievable, should be disposed.

In case of inhalation, the victim is typically moved to fresh air and medical personnel are consulted.

In case of ingestion or injection, medical authorities will make the determination of appropriate first aid procedures.

In the unlikely event that ingestion occurs, skin exposure first aid is applied, followed by dilution by drinking 2 to 3 glasses of water; however, this is a medical issue and medical authorities will make the appropriate determination of treatments.

6.0 DISPOSAL

Structures constructed of carbon fiber are for the most part inert and stable once cured, contained, or fixed. The composite is considered fixed when the potential exposure to dust or fly no longer exists. Double bagging, wrapping or taping sharp or exposed edges, and encapsulation are appropriate ways to fix a disrupted composite structure. Carbon fiber that has experienced a combustion and/or highly energetic event is tenacious and much more difficult to control and contain. The severity and method of disposal is largely a function of the amount of material that requires disposal; however, even though uncontaminated carbon fiber is not U.S. Environmental Protection Agency regulated hazardous waste, it is still subject to local landfill disposal requirements.

Catastrophic events involving large structures such as spacecraft or airplanes may require approval for spot landfill. In this case, once approval is obtained, personnel should don appropriate PPE and approach from an upwind direction to bury the composite. Using water deluge when possible prevents dust and fly from becoming airborne. Using water for fire suppression of catastrophic events afloat or on land often removes a majority of the dust and fly. Regardless of location, all fire suppression activities should be approached from the upwind direction and all personnel or civilians should be cleared from the downwind corridor. Any personnel required to work downwind should be in full PPE (total encapsulation and with respiratory protection).

Local and federal regulations must be followed in the disposal of carbon composites. Hardware structures or components must first be fully emptied/depressurized and decontaminated, if necessary, and should be rendered unusable by cutting in half or in the case of pressure structures, drilling at least two holes 12.7 mm (0.50 in.) or greater in diameter completely through the side wall. All marking should be obliterated from the hardware. Grind off stamped marks and remove or deface (such as with paint) all labels. These methods of destruction are accepted in CGA-C-6.4 (Methods for External Visual Inspection of Natural Gas Vehicle (NGV) and Hydrogen Gas Vehicle (HGV) Fuel Containers and their Installations) and various other COPV manufacturers’ literature. Disposal of the structure or component as solid waste in a landfill must be approved by environmental authorities.

Regardless of the destruction method, personnel and equipment need to be protected from dust, fiber, or fly exposure. Personnel should double bag the composite material while using the appropriate hazard controls. Identification labels should be placed between the double bags to document the type of waste inside. Carbon fiber wastes should be regarded and labeled as "Industrial Wastes"

Fully cured composites declared to be waste are considered industrial waste, not hazardous waste. They must be disposed in accordance with applicable regulations, but are typically disposed in a landfill and should not be disposed by incineration. Incineration of composites causes the resin system to burn and release known carcinogenic by-products in addition to a potentially large amount of fly and dust. Contaminated clothing, shop rags, and filters should be double bagged and disposed of in the same waste stream as reinforcement fibers and composite structures.

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