Postcrash Health Hazards from Burning Aircraft Composites

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ABSTRACT

The release of toxic combustion products from advanced composite materials in aircraft fires presents an unusual health risk to the various emergency response personnel. There is concern among the aviation fire fighting, rescue, and recovery and investigation groups that a health hazard is posed by the combination of various combustion products. This paper provides a review of the current scientific literature on the potential hazards from inhalation exposure to airborne carbon fibers and the combusted resin residues which are released when there is a crash impact, fire, and explosion involving advanced composites materials. Data collected from fire tests and crash-site investigations suggested that a small fraction of the fibers released in fires and during recovery operations were of respirable size and can be inhaled deep into the lung. However, most of the carbon fibers were 2-10 times larger than the critical fiber size generally associated with asbestos toxicity. The concentration of carbon fibers was well below the OSHA recommended levels for chronic exposure. Based on current published studies, no direct and conclusive linkage can be made between human exposure to the airborne carbon fibers alone with any long-term diseases. At issue, however, are the toxicological effects of the adsorbed combustion products generated in composite fires. Chemical extraction analyses have shown that a large number of toxic organic compounds are adsorbed on the fibers, several of which are known carcinogens in animals. Detailed toxicological studies are needed to assess the long-term health effects from exposure to single high dose of fibrous particulates and any synergistic interactions with the organic chemicals.

INTRODUCTION

Aircraft mishaps involving advanced composite materials present unique safety, environmental, and potential health hazards due to the disintegration of materials in postcrash fire, explosion, and high energy impact. There is growing concern regarding the potential health risks encountered by the civilian and Airport Rescue and Fire Fighting (ARFF) personnel when there is a postcrash fire associated with an advanced composite aircraft. The health concerns center around exposure to the fragmented composites and fibers which, are liberated as the resins burns off, and may splinter in to particles that are small enough to be inhaled and retained in the lungs. Such health risks from a single, acute exposures to combustion products of advanced composite materials are largely unknown. In recent years, a number of incidents have been reported on the toxic effects of fibrous matter and aerosols on personnel responding to the crash site [1]. Incident reports vary concerning the nature and severity of short- and long-term adverse effects on the responding crews, ranging from eye and skin irritation to severe respiratory problems with chronic post-exposure symptoms including forced breathing and reduced exercise capability. In certain instances, response teams equipped with enhanced protective clothing have suffered from penetration by strands of needle-sharp carbon fibers resulting in infected wounds [2-4].

The burning of polymeric materials generates heat and combustion products that consist of a complex mixture of gaseous and solid particulates from incomplete combustion, collectively referred to as smoke. Combustion involves complex chemical/physical processes in which the nature of products formed varies greatly with the composition of the material(s) and the burning conditions. The composition and the concentration of combustion products are dependant upon ventilation i.e., the amount of available oxygen and the resulting fire growth rate. At any stage of the fire development, the smoke stream contains a mixture of evolved gases, vapors, and solid particles. Aerosols constitute the visible component of smoke and are comprised of aggregates of solid particles mixed with combustion vapors and gases. Airborne particles vary widely in size from submicron to many microns. Smaller particles stay suspended in air longer and are more likely to adsorb chemical vapors from the smoke. The physiological effects of human exposure to fire effluent depend upon the size distribution, solubility characteristics, and chemical composition of the aerosols, which determine the depth of penetration in the lungs and the degree of absorption inside the body [5].

Firefighters are routinely exposed to harsh and uncontrolled conditions, with partial products of combustion constituting the major source of chemical exposure. They are frequently exposed to extremely high concentrations of a wide array of chemical and particulate matter. There have been various studies on the health hazards posed to firefighters from various individual chemicals in typical fire scenarios such as residential fires, industrial fires, and wildland forest fires. In a recent review, Lees [6] has described the various chemical species, particulate matter, and their concentrations frequently encountered by firefighters.

However, little has been published describing the combustion products that are generated from burning composites and the health hazards they might pose to the firefighting and rescue personnel. In view of the current and projected use of composites in commercial aircraft, an extensive literature survey was undertaken to determine what has been done by researchers to address the hazards related to composite materials. The primary objective was to compile information on health effects caused by single acute exposure to various pollutants including micron-sized fibers that become airborne during the burning and explosion in fiber composites on impact. This study presents results of the literature review. The paper describes the general nature of hazards due to fiber inhalation, and the potential hazards specific to particulate matter with associated chemicals released during aircraft composite fires. Characteristics of fibers released from burning composites and their size distribution are described. This review also examines some of the toxicological data available to assess the potential inhalation hazard of carbon fibers.

POLYMER MATRIX COMPOSITES

Composites are generally classified according to their matrix phase. There are polymer matrix composites, ceramic matrix composites, and metal matrix composites. These materials are commonly referred to as advanced composites because they combine the properties of high strength and high stiffness, low weight, corrosion resistance, and in some cases special electrical properties. The combination of such properties makes advanced composites very attractive functional substitutes for metallic structural parts. The original impetus for development of advanced composites was the performance improvement and weight savings for aerospace systems and military aircraft and subsequently in the field of commercial aviation.

Polymer matrix composites are very lightweight with a superior strength-to-weight ratio and offer high fuel efficiency over the lifetime of the aircraft. There has been a steady increase in the use of composites in both military and commercial transport aircraft. Until recently, the use of composite materials in commercial transports was limited to non-load or low-low carrying structural parts. However, with the modern technology, composites are increasingly used for primary, load-carrying structural parts. There has been a three-fold increase in the structural weight of composite parts used in Boeing 777 aircraft compared to the previous generation airplanes. In Boeing 777, the vertical and horizontal tail sections as well as major wing sections were made with toughened carbon fiber-reinforced epoxy composite [7]. Given the lightweight, low cost, and performance advantages of advanced composite materials, their use in future aircraft will continue to grow. Boeing estimates that the average structural weight fraction of polymer composites in their commercial airplanes will increase from about 7 percent currently to about 20 percent over the next 15 years [7-8]. Already, smaller business aircraft and helicopters are now being produced with entire aircraft structure made from composite materials [9].

Polymer matrix composites are engineered materials comprised of continuous, high-strength fibers impregnated with a polymer matrix to form a reinforced layer (ply), which is subsequently bonded together with other layers under heat and pressure to form an laminate. The resin acts to hold the fibers together and protect them and to transfer the load to the fibers in the fabricated composite part. The strength and stiffness of the laminate are determined by the orientation of the fibers with respect to the loading direction and their volume fraction in the composite. For a typical polymer matrix composite, fibers comprise about 55-60 volume percent of the laminate with the polymer resin being the remainder.

Resins

There are two main classes of polymer matrix composites depending upon the type of resin used, thermosets and thermoplastics. Thermoset resins are the predominant type in use today with epoxies and phenolics by far being the most dominant resins in commercial aircraft applications because they are relatively tough, easy to process, and require moderate forming temperature. Composite panel materials used in aircraft cabin interiors are required to comply with strict heat release rate regulations. Epoxies are highly flammable and thus cannot be used in composites for large surface area, interior panels such as partitions, stowage bins, galley walls, and ceilings. Phenolics are currently the thermoset resin of choice for aircraft interiors because of their low heat release rate.

Thermoplastic resins have found limited use as matrix resins in aircraft interior and structural composites because they require high forming temperatures in manufacturing. Unlike the thermosets, the thermoplastics can usually be reheated and reformed into another shape, if required. Thermally stable engineering thermoplastics, such as polyetheretherketone and polysulfone, are used as resin tougheners in commercial and military applications [8]. The development of high-performance thermoplastic resin systems is an area of evolving research that holds great promise for future applications of polymer matrix composites.

Carbon/Graphite Fibers

Continuous carbon fibers are the most commonly used reinforcement materials because of their high strength-to-weight ratio. Fibers are used alone or in combination with other fibers (hybrids) in the form of continuous fiber fabrics, tapes, and tows or as discontinuous chopped strands. Common raw materials, also known as precursors, for carbon and graphite fibers are polyacrylonitrile (PAN), rayon, and petroleum pitch. The synthesis process involves controlled pyrolysis at 1000-2000°C for carbon fibers while graphite fibers require pyrolysis temperatures of 2000-3000°C and contain 93-95 and 99 percent carbon atoms, respectively [8]. Typical carbon fibers used as reinforcement material in composites are 6-8 μm in diameter.

HAZARDS FROM INHALATION EXPOSURE

The assessment of fiber toxicity is complex process that generally requires substantial epidemiological data along with long-term exposure studies for the health effects on humans. This is because it a long time for the biological processes to manifest following the exposure. The gestation period for physiological changes in humans may be as long as 20-30 years depending upon the severity and duration of the exposure.

There are two major routes to exposure from fibers – dermal and inhalation. Dermatitis results from mechanical or chemical irritation or sensitization of the skin. This condition is a typical response to surface abrasion and puncture by sharp, needle-like fibers of diameter greater than 4-5 μm. The breakage of stiff carbon fibers into smaller fragments and rubbing against exposed skin may increase severity of the exposure and infection of the affected area. Such irritation effects are generally not permanent. However, the inhalation exposure from fibers poses the greatest potential for adverse health effects.

Asbestos is the most widely studied fiber for its health impact on humans. Extensive epidemiological data combined with animal studies have been done to study the pathological impact of this silica-based fiber [10-14]. Inhalation of asbestos fibers in the lungs initiates an inflammatory response in that region [11]. The lung’s efforts to repair this damage manifests as progressive scarring in the lung walls. This interstitial scarring effect caused by the deposition of fibers is called pulmonary fibrosis, a condition in which scar tissue forms in the connective tissues that support the alveoli in the lungs. Scarring can be a reaction to a large number of diseases and conditions. The induction of fibrosis retards the process of fiber clearance resulting in longer fiber retention. Extended chronic exposure to asbestos is known to result in bronchogenic carcinoma or lung cancer, and may also lead to mesothelioma – a cancer of the pleural cells lining the lungs. The causal relationship between asbestos exposure and onset of lung cancer has been demonstrated in numerous epidemiological studies [12-14].

The framework of information on asbestos and fiberglass has been applied for the study of health effects from new, organic fibers such as kevlar and carbon and to delineate the contributing factors in fiber toxicity. Using the animal models in studies with asbestos, researchers have identified the important characteristics that describe a given material's fiber toxicity. By definition, a particle is considered a fiber if it has a length-to-diameter ratio (L/D) of greater than 3:1.

It appears that fiber size and geometry and its durability are the most important factors in fiber toxicity. Fiber dimension determines whether the fiber can be inhaled deep into the lungs that lie below the larynx, tracheal conducting airways which constitute the upper respiratory tract. Only those fibers with dimensions smaller than the bronchial airways' size can penetrate the deep lung (alveolar) region. Generally, fibers larger than 10 microns (μm) in diameter can not penetrate deep enough into the alveoli to cause disease [12].

However, the respirability of fibers is not entirely governed by their physical dimensions. The respirability or the extent fibers are deposited in the deep pulmonary region and the alveoli is primarily determined by their aerodynamic equivalent diameter (D_{ea}). The parameter D_{ea} reflects the way a particle behaves when airborne. For a fiber, D_{ea} refers to the diameter of an equivalent spherical particle having the same terminal velocity as the fiber. The number of deposited fibers increase significantly when D_{ea} lies between 2-3 μm and falls off to 0 when the D_{ea} is between 7 and 10 μm. Long and thin, aerodynamic fibers line up straight in an airstream and are more likely to penetrate deeper into the lungs. Studies on size analysis of fibers in human lungs exposed to asbestos fibers have shown that the upper limits of respirable fibers are either 3.5 μm in diameter or 200 μm in length [10].

The aerodynamic character of the fibers (D_{ea}) also determines the manner in which the fibers are deposited in the lung tissue. There are five different modes of fiber deposition in the respiratory airways. In the human lung, the airways region consists of a series of branching airways called bronchi and bronchioles that become progressively smaller. The multiple division of the bronchi greatly increases the total cross-sectional area of the airways available for fiber deposition. Fibers aligned vertical to the airway flow stream are primarily deposited by interception at each successive bifurcation. The probability of interception increases when the fiber length is greater than 10 μm. The larger airway bifurcations are the primary sites of fiber deposition and lung cancer in humans from mineral fibers [14]. In smaller airways where the airflow velocity becomes very small, sedimentation is the primary mode of fiber deposition. Three other mechanisms of fiber loading in lungs are interception, diffusion, and electrostatic deposition. The durability of fibers inside the body depends on the response of the local cell tissues in the lungs. Warheit [13] has shown that fibers can be cleared from the pulmonary region via dissolution in lung fluids or through an internal, pulmonary self-defense mechanism. Cells known as alveolar macrophages that are present on the outer walls of the lungs facilitate removal of these fibers. The primary function of these cells is to remove bacteria, dead cells, and foreign particles and fibers by ingestion [13]. Hesterberg [15] has given a detailed description of the biological mechanism in the clearance of fibers by the macrophage cells.

Carbon Fiber Toxicity

Compared to asbestos and other mineral fibers, very little work has been done on the inhalation toxicology of carbon fibers. Few studies have been published on the health effects related to chronic exposure from carbon fibers and dusts in the manufacturing environment. Two conferences [16-17] brought together experts from the aerospace and composites industries and government agencies to address the health implications of exposure to carbon fiber-reinforced composites. These proceedings primarily focussed on the hazards related to exposure from carbon fibers and dusts during the machining and handling of fiber composites. In a review of the to date toxicology research on carbon fibers, Thomson [18] concluded that there are no long-term health risks associated with exposure to PAN-based carbon fibers alone under occupational conditions. The health effects are limited to temporary irritations of the skin and upper respiratory tract since given that exposure under occupational conditions is limited to relatively large-diameter, nonrespirable fibers (nominal diameter ~ 6-8 μm).

In a separate review of studies that included some consideration of the health effects of exposure to composites during various stages of manufacturing, Luchtel [19] concluded that, "carbon fibers and composite dusts should be regarded as more hazardous than the so-called nuisance dusts, and present a low health risk." The author noted that the pulmonary effects of the composite materials are not in the same class as asbestos in terms of toxicity, however adequate respirable protection should be used to minimize the occupational exposure.

One consistent shortcoming of the previous studies is the lack of complete information about the characteristics of the material being studied, i.e., the size distribution of fibers, their D_{ea}, multiple dosages, if used, and the type of resin matrix. In addition, these studies used unequal time periods for the animal exposure and post-exposure recovery. Today, standard design requirements for the toxicological evaluation in a lifetime inhalation study with rats call for an exposure time of at least 2 years and a post-exposure evaluation period of 2-3 years [20]. A post-exposure recovery period allows evaluation of reversibility of effects. In the studies reviewed by Luchtel, the exposure times used by all the researchers were very short compared to the required 2 years. Similarly, post-exposure times for recovery were too short compared to the current standard guidelines.

Further studies are needed to assess the carbon fiber toxicity in the presence of surface contaminants from the combustion environment. Fibers and other small particles, with high surface-to-volume ratio, generated in fires can carry with them a diverse package of chemical species with potentially harmful effects. It has been suggested that adsorbed chemicals may enhance the pathology of inhaled particles similar to the example of diesel soot [6, 21]. In the case of inert fibers such as carbon, the presence of fire-caused surface contaminants might affect fiber retention in the lung.

COMBUSTION PRODUCTS FROM COMPOSITE FIRES

Fiber Size Characterization

Characterization of fiber dimensions is an important requirement in any toxicology study in order to determine their respirability. Bell [22] described an extensive series of tests conducted by the National Aeronautics and Space Administration (NASA) to ascertain the extent of carbon fiber release during an aircraft crash. In one series of tests conducted at the Naval Weapon Center (NWC), China Lake, CA, full composite sections of a Boeing 737 spoiler and an F-16 fuselage were subjected to flames for 4-6 minutes in 15.2 m pool of JP-5 jet fuel to simulate aircraft fires. Fibers released during the fire were collected through adhesive coated papers 20x25 cm located on an elevated platform 0.3 m above the ground. However, this sampling procedure yielded very low amounts of single fibers. The massive smoke plume that reached a height of ~1000 m carried the majority of the single fibers away from the test location to distances beyond the instrumentation limit of 2000 m. 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 [23]. A second series of large-scale fire tests were conducted at the U.S. Army's Dugway Proving Ground, UT to measure the concentration of single carbon fibers. Carbon-epoxy composite parts weighing about 45 kg were burned in 10.7 m diameter JP-4 jet fuel pool fires for 20 minutes. The fire-released fibers were collected using an array of filters suspended inside the smoke plume at a height of 40 m. The filters consisted of stainless steel canisters with stainless steel mesh to trap the fibers carried in the smoke plume. Collected fiber samples from these tests were analyzed for fiber count and size distribution by optical and electron microscopy.

The results showed that fibers were released in several forms ranging from single fibers to large fiber clumps and fragmented pieces of composite laminate [23]. Single fibers constituted less than 1 percent of the carbon fiber mass initially present in the composite. Under certain conditions involving thin composites with turbulence (e.g., air blast or explosion) the total number of single fibers released from burning composite parts increased significantly. There was a threefold increase in the total mass of collected single fibers under the turbulent fire conditions [22-23]. Microscopic fiber analysis revealed that fiber diameter was significantly reduced in the fire due to fiber oxidation and fibrillation.

Overall, the collected fibers had a mean diameter in the range of 4.2 μm versus 7 μm for the virgin fibers. At extreme flame temperatures (> 900°C) and under oxygen-rich test conditions, large amounts of fibers were completely consumed through oxidation. The fiber diameters were reduced drastically inside the flame after the fibers were released from the composite. Sussholz [24] determined that reduction in the fiber diameter in fires occurred due to partial surface oxidation and fibrillation effects–splitting of fibers into smaller, finer fibrils due to surface pitting and or surface flaws. The main reasons for fibrillation of carbon fibers were found to be the presence of sodium impurities and morphological flaws such as voids in the fiber structure. Elemental analysis of the carbon fibers confirmed the presence of sodium impurities. The surface oxidation effects were significantly more pronounced in the regions of low crystalline density.

Considering the potential health implications from inhalation of micron-sized fibers, NASA conducted a scanning electron microscopy (SEM) study for physical characterization of the fibers. Seibert [25] summarized the results of the SEM analysis for respirable fibers (diameter <3 μm, length <80 μm) which constituted less than 24 percent of the total fibers released from burning composites. The respirable fibers had an average diameter of 1.5 μm and were 30 μm long. Overall, the fiber sizes spectrum ranged from ≈ 0.5 to 5 μm in diameter. To quantify the concentration of respirable fibers and determine the potential exposure levels, Sussholz [35] estimated that an aircraft fire involving fiber composites would release 5×10^{11} respirable fibers per kilogram of carbon fibers released (or five percent by weight). This quantity corresponds to an estimated peak exposure of 5 fibers/cm^3 within the smoke plume. This exposure is only half the permissible OSHA limit [26] for time-weighted average (TWA) over an 8-hour period for asbestos fibers.

The fiber concentration was also measured directly via sampling of fibers from the smoke plume in large-scale tests conducted at Dugway Proving Grounds [22]. All fibers with an L/D ratio greater than 3 were counted and fiber concentrations were determined for the 20-minute burn time. The results indicated an average fiber concentration of less than 0.14 fibers/cm^3. This is ten times lower than the OSHA mandated permissible exposure limit (PEL) of 1.0 f/cm^3 for short term exposure, averaged over a sampling period of 30 minutes [26]. Lacking evidence of any known pathological effects, the authors concluded that carbon fiber exposure should be treated in the same manner recommended by NIOSH for fibrous glass [27].

The U.S. Coast Guard (USCG) conducted a series of tests to characterize the graphite fibers emitted from burning graphite/epoxy composites [28]. The study primarily focused of on the size distribution of fibers released during small- and large-scale burn tests with advanced composites. The laboratory-scale tests were conducted using the Cone calorimeter at 50 and 75 kW/m^2 on composite parts from an HH-65A helicopter. A modified sampling system was used in the cone calorimeter to maximize the collection of fibers after the epoxy resin was completely burned. The fiber size distribution was determined through SEM analysis. The study revealed that 23 percent (by weight) of the fibers generated were in the respirable range. Overall, the fiber diameter ranged between 0.5-9 μm and the length was between 3-210 μm. The mean fiber diameter and lengths were 2.5 and 52 μm, respectively.

In a separate test series, USCG burned 48x48 cm^2 sections of graphite/epoxy composite in heptane pool fires [28]. The fiber sampling system consisted of a cascade impactor placed inside the exhaust duct. Analysis of the fiber size distribution indicated that the diameters ranged between 0.5-5.0 μm with a mean diameter of 2.4 μm. The scatter in the fiber lengths was much greater in pool fire data, and ranged between 5-900 μm with a mean fiber length of 77 μm. Results from both the Cone calorimeter and large scale tests indicate that fibers are significantly oxidized during the burning process, with fiber diameters reduced from 7 μm originally to an average value of less than 3 μm. The US Coast Guard studies did not include toxicological evaluation of combustion products.

Additional data on the characteristics of the airborne carbon fibers have come from recent aircraft postcrash investigations. Mahar [29] measured fiber concentration (fibers/cm^3) and aerodynamic diameter of the fibers collected at a military jet crash site. Fiber samples were collected from the personal respirator filters worn by the investigators fitted with 25-mm cassettes containing 0.8-μm mixed cellulose ester filters. Mahar reported that there is a significant increase in the particulate levels during cleanup operations with the disturbance of the aircraft wreckage. Less than 20 percent of the collected fibers were found respirable with aerodynamic diameter smaller than 10 μm. Microscopic analysis revealed that respirable fibers were approximately 2 μm in diameter and 7-8 μm long. The total concentrations of the fibers collected from breathing air zones ranged from 0.02-0.06 fibers/cm^3. The Navy guidelines limit exposure to a time-weighted average of 3.5 fibers/cm^3 of air and a maximum of 10 fibers/cm^3 over a 40-hour workweek [29].

Recent Studies

The Civil Aviation Authority [30] in the United Kingdom investigated the toxic nature of combustion products of composite materials used in structural components of a public transport aircraft and a helicopter. Samples were subjected to a flaming heat source at a temperature of 1150°C ± 50°C in a combustion chamber. The chemical analysis of the combustion products via gas chromatography and mass spectroscopy revealed several organic chemicals, the exact composition of which was not reported. Although no fibers were found in the soot filters, visual inspection of the burnt samples indicated evidence of surface pitting and fiber fibrillation. In further investigations of various air crashes in England in past 10 years, the Defense Evaluation and Research Agency (DERA) [30-31] found that typically 35-50 % of the free fibers still attached to the wreckage pieces and which could be released during handling were smaller than 1 mm in length. These fibers could cause significant skin and eye irritation, and irritation of upper respiratory tract, they are unlikely to be inhaled deep into the lungs. There were however a small fraction of airborne carbon fibers and some still attached to composite parts with signs of intense fire, which showed tapering and surface pitting. These results are consistent with the previous NASA test results showing reduction in fiber size to smaller diameters and could pose a risk of deep lung penetration depending on their lengths.

The US Air Force Toxicology Division conducted a series of tests [32] for evaluating combustion toxicity of advanced composite materials used in military aircraft. Preliminary studies focused on the morphology and chemical composition of organic compounds associated with particulates carried in the smoke from burning composites. The test materials consisted of carbon fiber impregnated in a modified bismaleimide resin [32]. The SEM analysis did not reveal the presence of any fiber-shaped particles i.e., $L/D > 3$. Forty percent of the particles were of respirable dimension with aerodynamic diameter ≤5 μm. These particles are small enough to penetrate deep below the tracheobronchial airways. Approximately 15 percent of particles had an aerodynamic diameter ≤1 μm, which can be deposited in the alveoli. The study did not report the fiber length measurements. The study did however identify a large number of organic species that were adsorbed on the particulate matter. Lipscomb [33] confirmed 90 different chemicals which can be broadly classified as polycyclic aromatic hydrocarbons, nitrogen-containing aromatics such as aniline, and phenol-based organic compounds. Several of these chemicals, e.g., aniline, quinoline, and toluidine, are known to induce carcinogenic and mutagenic effects in animals [33].

RISK MITIGATION

It is apparent from the above discussion that the health risks associated with carbon fibers are not clearly understood. There is a lack of scientific studies which conclusively link exposure to airborne carbon fibers and combusted resin residues to severe health impact on personnel, or that risks of inhalation are similar to other known pathogenic and carcinogenic fibers such as asbestos. However, it is prudent for safety personnel engaged in various stages of an aircraft mishap response to take precautionary measures.

The US Air Force Advanced Composites Program [34] has developed guidelines establishing minimum safety and health protection requirements for firefighters, investigators, and cleanup crews in accidents involving aircraft with advanced composite materials. These guidelines were established to prevent acute inhalation and dermal exposure to various pollutants including respirable fibers. All personnel working in close proximity to a crash-site are required to wear self-contained breathing apparatus, chemical protective clothing, leather gloves, and neoprene coveralls to minimize exposure to all airborne species. Once the fire is extinguished, the scattered debris is sprayed with a fixing agent such as polyacrylic acid or liquid floor was mixed with water to agglomerate the loose fibers and frayed edges of composite parts. Personnel working in close proximity to crash location and engaged in recovery and removal of fragmented composite parts should wear NIOSH approved half-mask respirators with cartridges for organic vapors and fumes, and carbon fibers and dusts. All personnel also wear leather gloves and impermeable Tyvek or equivalent coveralls.

CONCLUSIONS

Aircraft fires involving advanced composite materials present hazardous conditions during the fire fighting, rescue, and investigation and recovery operations in a postcrash situation. Release of a mixture of gaseous, particulate, and other combustion products of unknown composition poses unique protection problems. A small fraction of carbon fibers released from burning composites are of respirable size and contaminated with a diverse range of chemicals including polycyclic aromatic hydrocarbons, nitrogenous aromatics, and phenolics. There have been both anecdotal and a few cited reports [1-4] indicating that firefighters and rescue people responding to such aircraft fires have suffered adverse health effects ranging from skin irritation, puncture, and sensitization to severe respiratory problems from inhalation of fiber particulates.

Data available from research on exposures during manufacturing of carbon fibers and during machining, milling, and sawing of composite materials, indicate that no adverse health effects occur from inhalation of carbon fibers. However, the previous studies were focused on the short-term, chronic workplace exposure to airborne carbon fibers and composite dusts, not on the long-term health effects from a single high exposure to airborne fibers which is expected in aircraft crash and rescue situations. The long-term health outcomes due to inhalation of micron-sized carbon fibers contaminated with an array of organic chemicals generated in aircraft fires are largely unknown. No epidemiological data are available on the extent of personnel exposure to such combustion products from burning composites. Similarly, no animal studies have been conducted with the required post-exposure duration to assess the toxicology of the carbon fibers generated in a fire scenario. Synergistic interactions between the solid, vapor, and gaseous combustion products remain to be identified. Detailed toxicological studies are needed to assess the toxicity implications of combustion products from advanced composites. Efforts to fill these gaps in our knowledge of these recently recognized hazards, both in the United States and England, are still at a preliminary stage.

Until adequate assessments are made, use of personal protective equipment (PPE) can mitigate the dangers encountered by crash rescue personnel. In the absence of complete PPE ensemble, particle filtration masks may provide some measure of protection. Guidelines, developed by the USAF for adequate protection of the various response personnel during handling and disposal of composite wreckage, should also be made available to civilian and airport fire fighting and rescue personnel that are often the first to respond to a postcrash fire. It is equally important to document the on-site exposure among the personnel responding to the crash site to establish specific protective-gear requirements and adequate requirements for fire fighting effectiveness.

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