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# Composite Materials in Aircraft Mishaps Involving Fire: A Literature Review

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# NAVAL AIR WARFARE CENTER WEAPONS DIVISION

## FOREWORD

When Navy aircraft are involved in crash incidents, firefighters must be aware of hazards presented by airframe composite-material construction. Composite matrices may be combustible, contributing to the aircraft fuel load and burning hazard. Additionally, fibers released from burning composites may present a respiration hazard to firefighters. Current Navy and military doctrine recognize these hazards; cautionary guidance is provided for composite materials reinforced with carbon/graphite fibers and boron/tungsten fibers. The Naval Air Systems Command (NAVAIR), which provides technical guidance for aircraft fire safety, was concerned that hazards presented by new composite materials and greater quantities of composites may not be adequately addressed in current firefighting and guidance. The objective of this project was to perform a literature search to identify any existing "gaps in knowledge" concerning the role of composite materials in a fire mishap involving an aircraft having composite construction materials. With these "gaps" identified, future actions can be identified, prioritized, and performed.

This report was reviewed for technical accuracy by T. L. Boggs.

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## ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| μm | micrometer |
| ACM | Advanced Composite Material |
| ACO | Advanced Composites Office (USAF) |
| AED | aerodynamic equivalent diameter |
| AFFF | aqueous film forming foam |
| AFIERA | Air Force Institute for Environment, Safety, and Occupational Health Risk Analysis |
| AHR | airway hyperreactivity response |
| AR | airway reactivity |
| ARFF | Aircraft Rescue and Firefighting |
| ASC/FBAE | Aeronautical Systems Center/Environmental Safety and Health Program |
| DOD | Department of Defense |
| ESOH | Environmental, Safety, and Occupational Health |
| FAA | Federal Aviation Administration |
| HAMMER | Hazardous Aerospace Material Mishap Emergency Response |
| HEPA | high-efficiency particle arrestor |
| IFSTA | International Fire Service Training Association |
| IPT | Integrated Product Team |
| $kW/m^2$ | kilowatt per square meter |
| MFRI | Maryland Fire and Rescue Institute |
| mm | milimeter |
| NASA | National Aeronautics and Space Administration |
| NATO | North Atlantic Treaty Organization |
| NATOPS | Naval Air Training and Operating Procedures Standardization |
| NAVAIR | Naval Air Systems Command |
| NAWCWD | Naval Air Warfare Center Weapons Division |
| NFPA | National Fire Protection Association |
| NIOSH | National Institute for Occupational Safety and Health |
| NIST | National Institute of Standards and Technology |
| NSWC | Naval Surface Weapons Center |

| | |
|---|---|
| PKP | potassium bicarbonate |
| PPE | personal protective equipment |
| PVC | polyvinyl chloride |
| RAF | Royal Air Force (U.K.) |
| SCBA | self-contained breathing apparatus |
| STEL | short-term exposure limit |
| TWA | time weighted average |
| USAF | United States Air Force |
| USN | United States Navy |

# SECTION 1

# INTRODUCTION

Composite materials are a combination of linear elements of one material (e.g., fibers) in a matrix of another material (e.g., plastic). Fiber-reinforced plastics are widely used in the aerospace industry because of their high strength-to-weight ratios. Military aircraft, including Navy aircraft, are constructed using considerable amounts of composites.

When Navy aircraft are involved in crash incidents, firefighters must be aware of hazards presented by airframe composite-material construction. Composite matrices may be combustible, contributing to the aircraft fuel load and burning hazard. Additionally, fibers released from burning composites may present a respiration hazard to firefighters. Current Navy and military doctrine recognize these hazards; cautionary guidance is provided for composite materials reinforced with carbon/graphite fibers and boron/tungsten fibers. The Naval Air Systems Command (NAVAIR), which provides technical guidance for aircraft fire safety, was concerned that hazards presented by new composite materials and greater quantities of composites may not be adequately addressed in current firefighting and guidance. The objective of this project was to perform a literature search to identify any existing "gaps in knowledge" concerning the role of composite materials in a fire mishap involving an aircraft having composite construction materials. With these "gaps" identified, future actions can be identified, prioritized, and performed. The focus of the literature search was in the following areas:

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

A brief background on composite fire history and materials is presented, followed by a detailed discussion of each of issue. Based on this analysis, recommendations for future actions are presented.

The focus of this effort was from the perspective of the initial crash rescue firefighting response to a composite aircraft mishap. The adequacy of current Navy doctrine for response to composite aircraft mishaps to protect response personnel was considered. Potential differences between ship flightdeck and shoreside response operations were also considered. Post-fire-extinguishment crash procedures for scene restoration were contemplated but were not the primary emphasis of the evaluation.

## SECTION 2

## BRIEF HISTORY OF COMPOSITE FIRE INCIDENTS AND DEVELOPMENT OF FIREFIGHTING GUIDANCE

In the late 1970s, waste carbon composite fibers were burned in an incinerator, resulting in an electrical short that temporarily disabled a local utility substation. This event initiated a research effort to determine electrical effects from carbon composite fibers released from fires. This program, called CORKER, showed that aircraft fires involving composite materials had only a very small chance of causing significant electrical failure. After obtaining the results from CORKER, the U. S. Air Force (USAF) decided not to pursue additional research on the hazards of composite materials at that time. In the late 1980s, B-2 and C-17 aircraft were designed with much larger amounts of advanced composite material than previous USAF systems. In the late 1980s, the USAF Advanced Composites Office (ACO) was formed. ACO developed guidelines for mishap recovery crews. After a T-3 Class A mishap involving the crash and burning of composite-containing aircraft, the ACO became concerned whether mishap response procedures were adequate.

Fire/rescue, cleanup, and investigation personnel are faced with many hazards at the site of an aircraft mishap, including fire, smoke, potential explosions, and sharp edges from wreckage. In the case of an incident involving an aircraft having composite materials, additional hazards may be created by the presence of these materials. In addition to normal combustion products, personnel can be exposed to airborne fibers that may be released from the burning of composite materials. These released fibers have the potential to be inhaled, causing respiratory irritation. A second hazard is from fibers that become exposed along the broken edges of composite wreckage at the mishap site. These exposed fibers may be sharp and needle-like, and may puncture the skin of responding personnel if brushed against. Skin puncture from exposed composite fibers causes irritation and sensitization. Exposure to these composite-material hazards has been documented at several mishaps over the past two decades. The following are examples of incidents involving composite materials.

A few days after working at the scene of an F-18 crash, two members of the recovery team complained of markedly reduced exercise capacity (Reference 1). These men were working at the scene between 8 and 11 hours after the initial crash. Since the men were on site well after the incident, they were exposed only to crash debris (including graphite composite) and a small amount of smoldering aircraft parts. Low-flying helicopters were also present at the scene, causing some stirring of the crash debris. Both men were tested using standard respiratory-related tests. From the results of these tests, it was concluded that one of the individuals was likely to have been affected by his exposure to the pyrolized graphite and other debris from the F-18 wreckage site. He experienced reduced exercise capacity for approximately 5 months. Results were inconclusive for the second man. It is important to note that the exposure received by these men was during the "overhaul" phase of the incident-response team.

Another incident occurred at the 1990 crash of a Harrier GR5 in Denmark (Reference 2). The Royal Air Force (RAF) Aircraft Recovery and Transportation Flight Team was dispatched to the site containing a considerable amount of shattered and charred carbon composite fiber. Since the team was aware of the composite materials, they attempted to reduce the hazard by using diluted car underseal to contain the dust. They also wore facemasks and goggles. After a few days on the site, the team experienced increasing discomfort, including sore eyes, throats, and chests. The site was evacuated until improved safety measures could be identified and implemented. When the team returned using PVC coveralls, service respirators, and ventilated helmets, the previous symptoms disappeared and did not recur. Cordoning off the crash site and decontamination procedures also helped to prevent these symptoms.

A third incident involved the crash of an F-117 Stealth Fighter at a Baltimore air show (References 3 and 4). The accident investigation team determined that the cause of the crash was due to structural failure of the support assembly in the left wing. Sources also reported that there were no consistent guidelines for dealing with mishaps involving composite materials. A wax-like material was sprayed on the fire debris to contain the materials. It was reported that firefighters and others near the crash became ill from the fumes emitted by the fire. It was believed that some of these fumes resulted from the burning of the resin in the composite materials.

Based on incident data, fundamental guidance on the hazards of composite materials has been included in U.S. Navy (USN) technical manuals. This guidance includes basic data on the combustibility and respiration hazards of composite materials.

The composite exposure concerns that developed during the T-3 Class A mishap resulted in the formation of a team to address the hazards of an aerospace mishap response. The integrated project team (IPT) was called Hazardous Aerospace Material Mishap Emergency Response (HAMMER) IPT. The HAMMER burn studies were facilitated by the USAF Institute for Environment, Safety, and Occupational Health Risk Analysis (AFIERA) under the Industrial Hygiene Branch. The organization within the Air Force attempting to inventory the hazards within an aircraft is the Aeronautical Systems Center/Environmental Safety and Health Program (ASC/FBAE). The goals of the project are to identify and inventory all hazardous aerospace materials on USAF weapon systems and ensure that procedures are in place to protect personnel from safety/health hazards associated with aerospace vehicle mishaps. While the program is geared towards the Air Force, the Navy obtains feedback on the effort through PMA 251, the NAVAIR Aircraft Launch and Recovery Equipment Office. The Navy can leverage data/information developed under the HAMMER project for possible incorporation into Navy doctrine, guidance, and training.

## SECTION 3

## COMPOSITE MATERIAL BACKGROUND

Aircraft manufacturers have been using ever-increasing amounts of advanced composite materials in their designs since research began on these types of materials in the 1940s. As of 1997, the structural weight fraction of composite in subsonic commercial aircraft produced by Boeing was approximately 7%. Boeing stated that this fraction is expected to increase to approximately 20% by 2012 (Reference 5). The Airbus A320 currently contains over 9,000 pounds of composite materials, and the C-17 has more than 15,000 pounds of composite materials (Reference 6). Advanced composite material (ACM) provides many advantages over more traditional aircraft materials such as aluminum and steel. Lightweight and extremely strong, ACMs possess a larger strength-to-weight ratio than these metals. They also possess a greater resistance to corrosion and mechanical fatigue.

A typical modern ACM is constructed of a fiber and resin matrix. In general, they consist of "woven" sheets of fibers that are layered and bound together by the resin matrix. The percentage of resin in the ACM varies depending on the engineering design and the properties of the fibers and resin. The range is typically 25% to 40%. Examples of fiber types are carbon, glass, aramid (Kevlar™), graphite, boron, ceramics, and hybrids (References 7 and 8). The most common resins are epoxies; however, some ACMs use other resin materials such as bismaleimides, polyimides, phenolics, vinylesters, and polyesters (References 8, 9, 10, and 11). These fibers and resins are typical of those used in the general composites industry. They are used in many applications in addition to aircraft manufacture.

Advanced composite materials are used in many different locations in both commercial and military aircraft. Typical areas of usage include engine cowlings, flaps, floor panels and beams, undercarriage doors, leading edges, trailing edges, gunpacks, stabilizers, nosecones, rudders, wing skins, ailerons, ducting, landing gear doors, and radomes (References 7 and 12). Figure 1 shows an AV-8B Harrier with composite material locations identified (Reference 13).

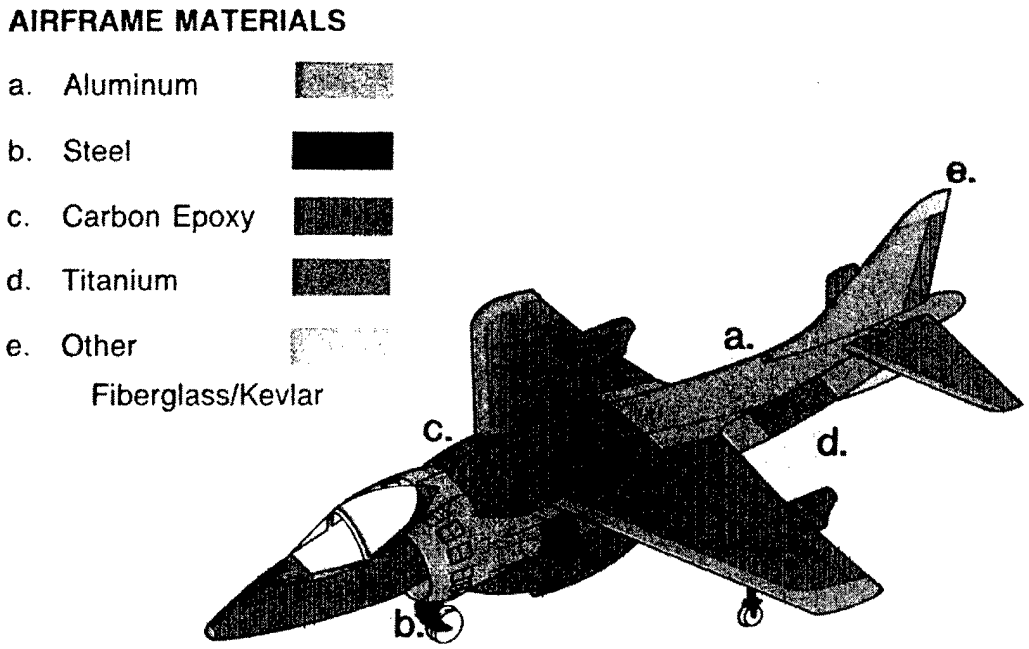


FIGURE 1. Composite Locations on an AV-8B Harrier.

The USN and the USAF have compiled lists of aircraft emergency rescue information, which include composite material locations on various aircraft. USN NAVAIR 00-80R-14-1 (*NATOPS U.S. Navy Aircraft Emergency Rescue Information Manual*, Reference 13) and USAF Technical Order 00-105E-9 (*Aircraft Emergency Rescue Information*, Reference 14) are the manuals containing this information. Table 1 lists representative USN aircraft from these manuals that contain composite materials (References 13 and 14). Note that these two manuals provide only general composite locations and types. A detailed list of USN aircraft composite materials with material properties was not identified. Table 2 presents some other examples of military and commercial aircraft that contain composites, including the composite percentage of the weight of the aircraft (References 7, 8, 15, and 16). As seen in the Table 2, amounts of composite material can vary greatly. Newer designs also tend to contain larger amounts of composite materials.

TABLE 1. Representative U.S. Naval Aircraft With Composite Types Listed in USN 00-80R-14-1 and/or USAF T.O. 00-105E-9.

| Aircraft | Fiberglass | Carbon epoxy | Graphite epoxy | Kevlar | Boron |
|---|---|---|---|---|---|
| Attack | | | | | |
| AV-8 Harrier | X | X | | | |
| Fighter/Strike Fighter | | | | | |
| F-5 Tiger II | No composites indicated | | | | |
| F-14 Tomcat | X | | | | X |
| F/A-18 Hornet | X | | X | | X |
| Patrol/Anti-Submarine | | | | | |
| P-3 Orion | X | | | | |
| S-3 Viking | X | | | | |
| Electronic/Special Purpose | | | | | |
| E-2 Hawkeye | X | | | | |
| E-6 Mercury | X | | | | |
| EA-6B Prowler | No composites indicated | | | | |
| Cargo/Transport | | | | | |
| C-2 Greyhound | X | | | | |
| C-9 Skytrain | X | | | | |
| C-20 Gulfstream IV | | | X | | |
| C-130 Hercules | No composites indicated | | | | |
| Training | | | | | |
| T-2 Buckeye | X | | | | |
| T-34 Mentor | X | | | | |
| T-39 Sabreliner | X | | | | |
| T-44 King Air | X | | | | |
| T-45 Goshawk | X | X | | | |
| TA-4 Skyhawk | X | | | | |
| TE-2C Hawkeye | X | | | | |
| TP-3A Orion | X | | | | |
| Utility/Miscellaneous | | | | | |
| UC-12B Huron | X | | | | |
| Rotary Wing | | | | | |
| V-22 Osprey | X | X | X | | |
| H-1 Huey | X | | | | |
| H-3 Sea King | X | | | | |
| H-46 Sea Knight | X | | | | |
| H-53 Sea Stallion | X | | | | |
| CH-53 Super Stallion | X | | | X | |
| TH-57 Sea Ranger | X | | | | |
| H-60 Seahawk | X | | X | X | |

TABLE 2. Military and Commercial Aircraft With Composite Materials.

| Aircraft | Service | Percentage composite (by weight) |
|---|---|---|
| F-15 | Military – USAF | 2 |
| C-17 | Military – USAF | 8 |
| F/A-18 | Military – USN | 10 |
| H-53E | Military – USN | 10 |
| F-16 | Military – USAF | 13 |
| A320 | Commercial | 16 |
| H-60 | Military – USN/USAF | 17 |
| CH-46E | Military – USN | 22 |
| AV-8B Harrier (Navy) | Military – USN | 26 |
| MD11 | Commercial | 30 |
| Harrier GR5 | Military – RAF | 32 |
| B-2 | Military – USAF | 37 |
| F-22 | Military – USAF | 38 |
| EuroFighter | Military – NATO | 70 |
| V-22 Osprey | Military – USN/USAF | 70 |

Many other commercial and military aircraft also make use of composite materials in their design. Although no specific indication was given to weight percentage, several other sources (References 6, 12, and 17) identified other aircraft as containing composites as indicated in Table 3.

TABLE 3. Other Composite Containing Aircraft.

| Commercial | |
|---|---|
| ATR 42 | Boeing 777 |
| ATR 72 | Embraer EMB 120 |
| Boeing 727 | Embraer EMB 135 |
| Boeing 737 | Embraer EMB 145 |
| Boeing 747 | SAAB SF340 |
| Boeing 767 | SAAB SF2000 |
| **Military** | |
| A-10 | F-117 |
| ATF | KC-10 |
| B-1 | KC-135 |
| C-5 | T-3 |
| C-141 | V-12 |

In addition to exterior and structural locations of composite materials, commercial aircraft also contain various types of composite materials in the interior of the aircraft. Items such as

seats, overhead luggage bins, and interior walls are frequently constructed using composite materials.

As indicated, the USN and USAF have aircraft emergency rescue information in NAVAIR 00-80R-14-1 and Technical Order 00-105E-9 (References 13 and 14, respectively). Additionally, both the USN and USAF have specific emergency-response procedures for aircraft mishaps involving composite materials. The USN procedure is contained in NAVAIR 00-80R-14 (*NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual*, Reference 18). Note that NAVAIR 00-80R-14-1 and NAVAIR 00-80R-14 are separate documents. The USAF procedure is contained in Technical Order 00-105E-9 (Reference 14). These response procedures are discussed in Section 8.

# SECTION 4

# COMPOSITE COMBUSTION AND FIBER RELEASE CHARACTERISTICS

Unlike traditional airframe materials such as steel and aluminum, composite materials are combustible. To best understand the threat of composite materials in an incident involving an aircraft constructed with these materials, it is first important to characterize the behavior of these materials in a fire environment. The typical combustion products, actual release of fibers from the fire, and burning modes were identified so that the hazards could be better understood. The information provided in this section applies generally to composite materials, including those used in aircraft.

## COMBUSTION PRODUCTS

As indicated previously, a composite is made up of two basic components: a resin matrix and fibers arranged in some set pattern. The fibers themselves are typically made of inert materials such as carbon, graphite, glass, or boron. However, the materials used to create the resin matrices are usually various types of plastics including epoxy, phenolic, and bismaleimide, which are combustible to differing degrees. These resins constitute the primary fire fuel load for composite materials. Typically, products of combustion released from burning composites are not especially toxic within the spectrum of fire products present at an aircraft mishap (Reference 19).

Species such as soot, carbon monoxide, carbon dioxide, water vapor, hydrogen chloride, and hydrogen cyanide are examples of combustion products released by composite materials as they burn. The amounts of combustion products released are also similar to other combustibles. Burn data from representative composite materials and some typical solid combustibles are shown in Table 4. Note that the carbon monoxide yield and soot yield fall within the same range as some typical fuels such as wood and plastics. Table 4 also shows that the heats of combustion for these composite materials are in the same range as other fuels.

TABLE 4. Comparison of Combustion Characteristics Between Composite Materials and Other Typical Fuels.

| Material | Carbon monoxide yield, g/g | Soot yield, g/g | Heat of combustion, kJ/g |
|---|---|---|---|
| Phenolic fiberglass[a] | 0.03 | 0.05 | 22 |
| Phenolic graphite[a] | 0.03 | 0.10 | 25 |
| Phenolic Kevlar[a] | 0.09 | 0.13 | 19 |
| Epoxy Kevlar[a] | 0.09 | 0.19 | 11 |
| Epoxy fiberglass[a] | 0.11 | 0.19 | 11 |
| Red oak[b] | 0.004 | 0.015 | 17 |
| Kerosene[b] | 0.012 | 0.042 | 43 |
| Polystyrene[b] | 0.060 | 0.164 | 39 |
| Polyester[b] | 0.080 | 0.089 | 32 |

[a]Reference 20.
[b]Reference 21.

## RELEASE OF FIBERS FROM FIRE

Several experimental series have been conducted over the past two decades to characterize the release of composite fibers from burning composite materials. Fibers released from burning aircraft composites generally appear in various forms, including single fibers, clumps of fibers and fragmented composites debris. In the late 1970s, NASA began an experimental carbon-fiber source program to study the potential for the release of conductive carbon-fibers from burning composites. This program was started as a result of concerns about damage to electrical and electronic equipment resulting from the release of conductive fibers. As a result of this program, a number of experimental studies were performed at various facilities, including the U.S. Army (USA) Dugway Proving Ground, Naval Air Warfare Center Weapons Division (NAWCWD) at China Lake, Naval Surface Weapons Center (NSWC) shock tube at Dahlgren.

Tests ranged from laboratory scale to large scale. Laboratory-scale tests were conducted to determine the relative importance of several parameters influencing the amounts of single fibers released. Large-scale aviation tests were performed to confirm data gathered during the laboratory-scale tests. Table 5 summarizes the tests performed as part of the NASA experimental carbon-fiber source program.

TABLE 5. NASA Composite Material Tests.

| Facility/test | Objective(s) | General results |
|---|---|---|
| Naval Surface Weapons Center—Dahlgren Chamber Tests (Reference 22) | Expose electrical equipment to carbon-fibers released by burning composites. Tests included burn only, burn/explosion, burn/disturbance, and burn of honeycomb pans | Burn/Explosion<br>1. Amount of single fiber released varied.<br>2. Length ranged from 1.8-6.5 mm.<br>3. Average single fiber mass released was approximately 5.6% of the original mass of fibers. |
| | | Burn/Disturbance – Amount of single fiber released varied for the different disturbance conditions, which included airflow, air blasts, external impact, and internal disturbances. Fiber releases are presented as a percentage of the original mass of fibers in the sample.<br>1. Airflow (both during and after burning) released between 0.2% and 1% single fiber, respectively.<br>2. Air blasts released the greatest amount of single fiber (2.5-4%).<br>3. External disturbances resulted in less than 0.25% single fiber released.<br>4. Internal disturbances (including twisting and flexing) released approximately 0.08-0.18% of single fiber. |
| | | Burn Only<br>Small amounts of single fibers released (0.01-0.2%). |
| AVCO Fire Test Facility (Reference 22) | Fundamental study of variables important in the potential release of carbon-fibers from burning composites. | 1. Oxidation of fibers was studied.<br>2. Fibers lost weight through oxidation at higher temperatures.<br>3. Fibers oxidized faster in an oxygen rich environment. |
| TRW Outdoor Tests China Lake (Reference 22) | Large-scale out doors tests conducted to release carbon-fibers from burning composites. Objectives were used to verify results of closed chamber tests (Dahlgren Chamber Tests). | 1. Quantities of single fibers released by mass 0.008-0.010%.<br>2. Number of single fibers over 1 mm in length was less than the amounts observed in the laboratory-scale tests (Dahlgren).<br>3. The low number of fibers counted was determined a result of inadequate sampling procedures. |
| Dahlgren Shock Tube Tests (Reference 23) | Prior tests studied the effects of raw carbon-fibers on electrical equipment. This test studied the effects of fire-released fibers, using a moderate sized JP-1 fuel fire. | 1. Electrical equipment failed near the expected fiber exposure levels, which were predicted using test data for raw carbon-fibers.<br>2. An average of 0.75% of the initial carbon-fiber mass was released as single fiber.<br>3. The mean length of collected fibers was 2.12 mm. |
| Dugway Proving Ground Tests (Reference 23) | Large-scale (outdoor) tests that determined the amounts of carbon-fiber released during the burning of large amounts of composite materials. Tests were also conducted to determine the dispersion of fibers into the environment. | 1. Consistent results for varying conditions (wind conditions).<br>2. Approximately 0.23% single fibers released. |

The research in the NASA program was focused on the potential effects to electrical equipment from a release of composite fibers from a fire. These tests did not account for fibers released that were less than 1 mm in length because they were not believed to be a threat to electronic equipment. The general conclusion from the NASA tests was that the release of conductive fibers from composite materials posed a negligible threat to electronic equipment.

Several other tests of fiber release from burning composite materials have been conducted since the NASA tests. Since the hazards to electrical equipment were found to be very small, these tests focused on the potential health hazards to humans when exposed to burning composite materials. Table 6 lists this additional research involving composite materials, focusing on fiber release.

TABLE 6. Other Studies of Composite Material Fire Hazards.

| Facility | Objective(s) | General results |
|---|---|---|
| TRW Defense and Space Systems Group (for NASA) (References 22 and 24) | The primary objective was to determine the amounts of potentially respirable fibers generated during burn and burn/explosion tests of graphite composites. A secondary goal was to investigate the size reduction of fibers in a fire. This investigation used records of the fibers collected in the NASA tests listed in Table 5. | 1. 60% of the fibers released fall within the reported respirable range of D<3 μm and L<80 μm. (Corresponds to approximately 24% by mass)<br>2. Average fiber sizes were D=1.5 μm and L=30 μm.<br>3. 70% of fibers collected from burn tests were less than 1mm in length.<br>4. 98% of fibers collected from burn plus explosion tests were less than 1mm in length.<br>5. Size reduction of carbon-fibers in fires can be attributed to surface oxidation and fibrillation.<br>6. Metal impurities and surface defects increase fibrillation. |
| Worcester Polytechnic Institute (for U.S. Coast Guard) (Reference 25) | The primary goal was to characterize the fiber emissions from burning composite materials used on the HH-65A helicopter. Tests included cone calorimeter tests and exposure of 48 x 48 cm samples to a heptane pool fire. | 1. The average fiber generation rate for a fully involved burning area of the graphite-epoxy composite is about 0.36g/s-$m^2$, which corresponds to a fiber yield of 0.056 g-fiber per g of composite burned.<br>2. The median fiber length of the fibers released from this burning composite is 31-41μm and the median fiber diameter is approximately 2.3 μm.<br>3. The percentage of fibers in the reported respirable range (<3.5 μm in diameter and <80 μm in length) is 23% to 29% by weight and 69% to 75% by number of fibers. |
| Marine Corps Air Station, Cherry Point NC (Reference 17) | Air samples were collected following the 1988 crash of an AV-8B Harrier II. These samples were from the cleanup/recovery phase of operations. | 1. Total fiber counts for the breathing zones of the recovery personnel were between 0.2 and 0.3 fibers/$cm^3$ as an 8-hour time weighted average (TWA).<br>2. Peak fiber levels as high as 6 fibers/$cm^3$ were recorded.<br>3. Fiber sizing was not recorded. |
| Various Aircraft Crashes (Reference 12) | Some data from aircraft mishap sites has been collected by Navy industrial hygienists, including breathing air sampling for fibers and dusts. | 1. Exposures ranged from 0.011 to 6.998 fibers/$cm^3$.<br>2. Exposures using an 8-hour TWA ranged from 0.011 to 0.56 fibers/$cm^3$.<br>3. Handling/moving and hand searching of the debris created the greatest exposures. |

In addition to the studies presented in Table 6, several sources indicate that fibers exposed to fire tend to break and become thinner (References 12, 17, 24, and 26). The reduction in fiber size (diameter *and* length) is attributed to oxidation of the fibers and longitudinal splitting by fibrillation. One study was identified that suggested that carbon-fibers in particular begin to oxidize and break down at temperatures above 850°C (Reference 17).

## BURNING MODES

The physical combustion of composite materials appears to be similar to other types of solid combustibles. No special combustion characteristics of composite materials, such as very fast flame spread or extreme heat-release rates have been identified in the literature. However, the fire performance of composite materials can vary depending on materials of construction. For example, phenolic-based composites have been found to possess low flame spread and low smoke and toxin emission during burning (Reference 27). Vinylester-based composites, while having superior structural properties to phenolics, have been found to be much poorer in fire performance tests (i.e., more rapid flame spread, greater smoke and toxin production) (Reference 10).

A test series conducted by the USA Materials Technology Laboratory and Factory Mutual Research Corporation assessed the flammability characteristics of composite materials using small-scale experiments (Reference 11). Materials tested included three polyester resin composites, a Kevlar/phenolic-resin composite, and a phenolic-resin composite. Important results from these tests included the following:

1. These materials are all stable below 200°C.

2. Maximum mass loss occurs between 350 and 490°C.

3. From the results of ignition and fire propagation tests, these materials do not have a high degree of self-sustained fire propagation.

4. Pyrolysis rates of these materials were also found to be much lower that that of wood, polypropylene, and polystyrene.

Composite materials also tend to have high thermal capacitance, reducing the threat of fire spread through a barrier. However, the retained heat has been suggested to lead to re-ignition after the fire has been extinguished (Reference 9). Little information is available in the literature regarding this concern. In one test, after a composite specimen was removed from a fire source, thermocouples that were further from the exposed surface continued to rise in temperature. This indicated that some type of internal heat-generation process (smoldering) was occurring. Further smoldering composite tests were conducted and it was concluded that (Reference 28):

1. Smoldering combustion of epoxy composites is not easily characterized.

2. Self-sustained smoldering combustion will not spread to non-preheated areas.

3. Smoldering combustion will not lead to open combustion without the addition of heat.

4. Epoxy composite smoldering combustion is difficult to see and extinguish.

Another source indicated that re-ignition of composite materials from smoldering combustion is not likely (Reference 29). Smoldering of composite materials is typically associated with the core material (balsa, foam, etc.) when they are used in the composite construction. Navy aircraft composite materials generally do not use cored construction, so smoldering combustion should not be of concern.

## ELECTRICAL EFFECTS

One of the objectives of the composite material test series conducted by NASA in the late 1970s/early 1980s was to assess the electrical effects created by airborne carbon-fibers. Through bench-scale tests, full-scale tests, and modeling, NASA concluded that widespread damage to remote electrical equipment from released carbon-fibers was unlikely.

However, electrical equipment near a crash site of an aircraft with carbon/graphite composite construction could be affected. Electrical equipment exposed to the smoke plume from burning composite materials has the greatest chance of being adversely affected. Classified tests were conducted in the late 1980s, which assessed the viability of graphite-fiber bombs as weapons to neutralize electrical installations. These tests successfully met this objective, disabling the targeted electrical equipment.

The electrical effects of fibers released in a composite aircraft mishap may be a locally important factor. The fibers could potentially impact antennas/transmitters on a flightdeck island structure or electronics on downwind aircraft. However from a firefighter response standpoint, the electrical characteristics of released fibers should not affect firefighting or rescue operations. Proper operation of affected electronic equipment would be restored during cleanup operations.

# SECTION 5

# COMPOSITE FIBER TOXICOLOGY

In addition to the hazard created by combustion products such as carbon monoxide, carbon dioxide, and soot, burning composite materials can create two further hazards at an aircraft mishap site. The first is the generation of airborne fibers. Burning composites can produce fibers that are small enough to penetrate deep into the lungs. These small fibers pose a hazard to the respiratory system. The second hazard is exposure to splintered composite fibers. These can be present on the edge of fragmented composite debris at an aircraft mishap site. Since exposed fibers are sharp and needle-like, they have the potential to puncture the skin and cause irritation and sensitization. The information presented in this section applies generally to composite materials, including aircraft composite materials.

## INHALATION HAZARD

A basic understanding of general fiber toxicology is helpful in understanding the potential hazard created by fibers released from burning composite materials. Small particles and fibers can become trapped within the alveoli in the lungs (sedimentation). Once inhaled, the fibers cannot be efficiently expelled from the body. Particles and fibers of this size are often referred to as "respirable." Any time a foreign product is introduced into the respiratory tract, a risk exists of pulmonary scarring or other long-lasting respiratory damage. USAF toxicology studies revealed that particles less than one micrometer (μm) in diameter could be deposited into alveoli in the lungs, resulting in respiratory damage (Reference 6). Because these particles enter where the gas exchange takes place within the lungs, other complications can arise as a result of exposure to the toxic products of combustion. An exposed individual could also possibly suffer an allergic reaction to either the composites themselves, the gases yielded from the composite matrix, or gases from other burning materials (Reference 6).

Extensive studies of natural and man-made fibers, such as asbestos and glass, have been used to identify the size limits of respirable fibers. Respirable fibers are suggested to have a diameter of less than 3 μm, a length between 5 and 80 μm, and a length to diameter ratio of greater than 3 (References 7, 15, 22, 30, and 31). One report indicated that respirable fibers could be as long as 200 μm (Reference 31). Another method to determine the respirability of fibers involves use of the aerodynamic equivalent diameter (AED) (Reference 17).

If the AED is greater than 10 according to Equation 1, then it is respirable:

$$D_e = D_f \rho (0.7 + 0.91 \ln \beta)^{1/2} \quad (1)$$

where $D_e$ is the AED, $D_f$ is the physical diameter of the fiber, $\rho$ is the fiber material density, and $\beta$ is the ratio of fiber length to width.

If the composite fibers released in an aircraft mishap are of respirable size, then several factors can affect their toxicity. These factors include dosage, physical dimensions, retention time in the lung, location of deposition in the lung, and solubility of the fibers in the lung (References 12, 15, 17, and 30). In addition to these characteristics, a combustion environment produces many other toxic products of decomposition. These products have the potential to be adsorbed on the released composite fibers, increasing their pathology (References 30 and 31).

To date, a limited number of studies on the toxicology of inhaled carbon-fibers have been conducted. A few studies have been conducted that relate to exposure from fibers and dusts in the workplace. From these tests it was concluded that no long-term health risks are associated with exposure to raw carbon-fibers under occupational conditions (Reference 30). Some animal studies with raw carbon-fibers and composite dust have also been conducted. It was concluded that carbon-fiber and composite dust are significantly less toxic than crystalline silica dusts and fibers, such as asbestos, although more study was suggested to verify these findings (Reference 30).

NASA/Ames performed a series of tests to determine the toxicity of products of decomposition of epoxy composite using fertile chicken eggs as the test subjects (Reference 28). Two hundred grams of epoxy composite were decomposed under a heat flux of 23 $kW/m^2$ for 20 minutes in a 4 $ft^3$ test chamber. Liver damage was prevalent in three of the chicken embryos. A second test exposed mice to the burning epoxy composite in a similar test setup. Two hundred grams of epoxy composite were decomposed under a heat flux of 25 $kW/m^2$ for 30 minutes in a 4 $ft^3$ test chamber. One of the mice sustained liver damage, and the products of combustion were similar to other hydrocarbons for these conditions. Significant quantities of aniline and aniline compounds were identified in the gas analysis from this test. These types of compounds are extremely toxic, mutagenic, carcinogenic, and known to cause liver damage in humans. This test did not specifically target the toxicity of the fibers themselves, although fibers released from the burning composite were part of the exposure.

An experimental series was conducted by the Naval Health Research Center Detachment (Toxicology) in 2000 to gather information on the lethality and respiratory toxicity from acute exposure to an advanced composite material currently being used on the B-2 Stealth Bomber (Reference 32). This material was a single-ply carbon/graphite/epoxy composite. Laboratory animals (rats) were exposed to the combustion products of various sample sizes of B2-ACM, for either 1 or 2 hours. The sample sizes of B2-ACM were 10, 55, and 100 g. Data on the composition of the smoke included measurements of carbon monoxide, carbon dioxide, oxygen, oxides of nitrogen, silicon dioxide, hydrogen cyanide, particulate fraction, and smoke aerosol size distribution. Some of the reported smoke values are indicated in Table 7. Fibers are mentioned as a part of the smoke aerosol particle makeup, although no specific mention of the size distribution of the fibers themselves is given.

TABLE 7. Reported Smoke Values from B2-ACM Tests.

| Smoke property | Value |
|---|---|
| Peak $CO_2$ concentration | 2.28% |
| Peak CO concentrations | 630 ppm to 3750 ppm |
| Minimum $O_2$ concentration | 18.7% |
| Peak $NO_x$ concentration | 33 ppm to 202 ppm |
| Peak $SO_2$ concentration | 52 ppm |
| Peak smoke aerosol concentrations | 0.84 $g/m^3$ to 4.4 $g/m^3$ |
| Mass median aerodynamic diameter of smoke aerosols | 1.5 μm to 1.8 μm |

The experimental animals that survived the exposure underwent a thorough battery of pulmonary function tests 2, 7, and 14 days after the exposure. Several animals were sacrificed immediately following each exposure for collection of blood samples. The combustion of the B2-ACM (performed in a furnace) did not result in flaming ignition of the samples, so the exposure is actually of smoldering composite combustion products.

The conclusions from this study are that a 2-hour exposure to smoke, combustion gases, and airborne fibers generated from burning B2-ACM at a rate of approximately 2.6g/min can be lethal. Those exposed for 1 hour to B2-ACM smoke generated at a rate as low as 2.15g/min suffer from pulmonary dysfunction indicative of an early inflammatory response and diffuse pulmonary edema often associated with smoke exposure. It is unknown if these reactions are likely to progress into more severe and lethal lung diseases, such as Acute Lung Injury and Acute Respiratory Distress Syndrome.

Subsequent studies have shown that non-visible smoke from B2-ACM can lead to an airway reactivity response severe enough to cause convulsions (Reference 33). A significant fraction of sensitive individuals (estimated at 10 to 20%) may be at an increased risk of severe, possibly lethal, acute airway reactivity (AR) or related airway hyperreactivity responses (AHR). These responses (similar to asthmatic symptoms) could be elicited by exposure to very low concentrations of combustion products from the combustion of advanced composite materials. A second test was conducted by the Naval Health Research Center Detachment (Toxicology). The objective was to test laboratory animals (guinea pigs) for potential AR responses when exposed to B2-ACM smoke and attempt to identify a concentration at which there was no observable effect (Reference 33).

Diluted smoke from the combustion of as little as 5 grams of B2-ACM was found to elicit AR responses after a brief exposure. Exposure to larger amounts (from a 100-gram sample) caused severe bronchospasms, which led to convulsions. A minimum threshold sample size was proposed as 2 grams for minimal response. The smoke was not visible at this concentration, and removal of particulate matter from the smoke did not significantly alter responses. Two conclusions were proposed. The dilute smoke from burning B2-ACM can cause AR reactions in sensitive individuals. It was also theorized that sensitization of individuals may occur, greatly increasing the chance of AR or AHR upon subsequent exposure. More research is suggested in this area.

Some exposure guidelines were identified for fibers released at the site of an aircraft mishap. Based on a review of the available data at the time (1985) one set of guidelines was as follows (Reference 31):

1. Exposures should not exceed 3 fibers/$cm^3$ of air as a time weighted average (TWA) over a 10-hour work day or 40-hour work week.

2. The largest exposure should never exceed 10 fibers/$cm^3$ of air, while maintaining the 3 fibers/$cm^3$ of air TWA.

3. The total airborne material exposure should not exceed 3.5 mg/$m^3$ of air (TWA).

4. The recommended short-term exposure limit (STEL) should not exceed 7 mg/$m^3$ of air and should not be greater than 15 minutes in duration. The STEL can occur up to four times in a workday, but each exposure must be separated by at least a 60-minute interval. The STEL must also adhere to the 3.5 mg/$m^3$ of air TWA.

A similar set of guidelines from the USN limits exposure to a TWA of 3½ fibers/$cm^3$ of air and a maximum of 10 fibers/$cm^3$ of air during a 40-hour work week (Reference 6).

## DERMAL PUNCTURE HAZARD

The second specific hazard associated with composite materials at the site of an aircraft mishap is the puncture and irritation of the skin from exposed fibers on fragmented composite debris. Skin irritation is possible because fragmented composites often have sharp, needle-like edges that can easily penetrate the skin. Fibers that puncture the skin can also act as carriers for deposited combustion products, causing increased irritation (Reference 7). Sensitization of the skin is another possible effect from composite fiber puncture. If a person should sustain a puncture, a composite splinter will tend to crumble, break apart, and stay below the surface of the skin. Composite splinters tend to fester and cause sores, often disintegrating when attempts are made to remove them from the skin (Reference 6). Splintered fibers are also suggested to increase in irritability with increasing diameter (Reference 17). Fibers that pose an irritation/penetration hazard are larger in diameter and length than respirable fibers (Reference 30).

Exposed fibers from fragmented boron composites are suggested to present the most severe dermal puncture hazard. This is because the boron fibers are much larger in diameter (100 to 140 μm) than other fibers such as carbon fibers (Reference 17). When fragmented, boron fibers also tend to form long, sharp needle-like structures. Concern is that boron fragments could possibly enter the bloodstream, thus lodging in vital internal organs; however, evidence does not exist to support these concerns (Reference 6).

No studies were identified that address the toxicology of skin puncture by exposed composite fibers at an aircraft mishap. Health effects of skin puncture from composite fibers are based on reports from composite aircraft mishap sites.

# SECTION 6

# CURRENT RESEARCH

Two research programs were identified in the literature that address the role of composite materials in aircraft mishaps. These are the HAMMER project being conducted by the USAF and the "Fire Safe Materials" program currently underway at the Federal Aviation Administration (FAA). These programs are described briefly here.

## HAZARDOUS AEROSPACE MATERIAL MISHAP EMERGENCY RESPONSE (HAMMER)

The HAMMER project was chartered by the Deputy Assistant Secretary of the Air Force for Environmental, Safety and Occupational Health (ESOH) (References 15, 34, and 35). The main working group for the program is the Industrial Hygiene Branch of the USAF Institute for ESOH Risk Analysis.

The Institute for ESOH Risk Analysis, tasked to ensure consistency in all matters related to mishap emergency response, initiated the HAMMER program. Hazardous aerospace materials are defined as "materials and systems integrated into aerospace vehicles that can present a safety and health hazard to response and recovery personnel," including composites, radioactive materials, metallic alloys, and coatings. Mishap emergency response is defined as "that portion of an emergency response performed at the mishap location after a mishap has occurred." The goals of the HAMMER project are to identify and inventory all hazardous aerospace materials on USAF weapon systems and ensure procedures are in place to protect personnel from safety/health hazards associated with aerospace vehicle mishaps. The test program includes full-scale fire testing of composite materials for toxicology and expected exposure to response personnel.

To date, numerous composite-containing aircraft have been identified and documented. The list includes composite-containing aircraft from the USAF, USN, U.S. USA, NATO, and commercial fleets. A copy of the most current list of specific composite material locations on aircraft from the HAMMER project is attached as Appendix A, taken from Reference 36.

Two large-scale composite burns were completed in September 2000. Two damaged aircraft wing boxes made with approximately 100 pounds of carbon-fiber epoxy were burned over a pool of JP8 fuel. These tests were used to determine the extent of composite fiber and chemical exposure levels during simulated aircraft recovery operations (post-fire operations). Chemical exposures were found to be generally low, and fiber concentrations were similar to those measured during actual mishap recovery operations (Reference 37). HAMMER personnel indicated that a recent review of these tests showed significant smoldering carbon-fiber combustion. The smoldering was found in interior layers of the composite material, below the

outer layer of char (Reference 38). HAMMER IPT members witnessed carbon-fiber combustion lasting for 30 to 40 minutes after flaming combustion ceased (Advanced Composites Office (AFRL/MLS-OL)). The surface temperature of the composite wing box dropped to room temperature while the internal layers continued to burn at 1400°F, producing a bright red glow.

Toxicology studies are currently underway. The goal of these studies is to assess the toxicological effects and products of combustion from burning composite materials. Additionally, fiber and chemical sampling kits were distributed to the Bioenvironmental Engineering office at various USAF bases for use in actual composite aircraft mishap recovery operations. These kits will help to further clarify conditions present during the recovery phase of a composite aircraft mishap. Appropriate protective equipment requirements for recovery personnel can then be refined.

## FIRE-SAFE MATERIALS

The FAA reports that 40% of all passengers who survive a crash subsequently perish in the post-crash fire. The Fire Safe Materials program was initiated with the goal of reducing this statistic by eliminating burning cabin materials as a cause of death in aircraft accidents. The focus of the research is in the reduction of heat release rate of burning cabin materials. The research is basic in nature and focuses on composite material synthesis, characterization, modeling, and processing. The research effort is organized by the FAA, and performed by various groups as indicated in the lists below (References 39 and 40). An overview of each area is presented here.

### Synthesis

1. Evaluation of polybenzoxanies to demonstrate fire/thermal properties of low-cost thermoset polymers with broad chemical design flexibility (Case Western Reserve University & Schneller)
2. Molecular design of fire-safe polymers/composites for interior applications using computational and synthetic chemistries (University of Massachusetts)
3. Synthesis of hybrid polymers for various aircraft applications—thermally stable resins, low-viscosity liquid crystalline materials, etc. (Dow Corning)
4. Evaluation of the effects of pre-ceramic polymers on the flammability of organic polymers (National Institute of Standards and Technology [NIST])
5. Development of a new class of fire-safe polymeric materials containing no halogens or heteroatoms (University of South Carolina)

### Characterization

1. Heat-release-rate study of burning polymers using thermal analysis, bomb calorimetry, fire calorimetry, and mechanistic pyrolysis kinetics to develop a simple analytic model of flammability that relates ignitability and heat-release rate to material properties (FAA Technical Center).

2. Study of the mechanical properties and fracture behavior of carbon-fiber reinforced primary and secondary aircraft composites at ambient and elevated temperatures (Rutgers University)

**Modeling**

1. Development of a physics-based computational model that describes thermal degradation behavior of a variety of linear and network polymers and predicts thermal stability of polymers, trends of crosslink formation, and relative heat release rate from polymer burning (NIST)
2. Development of a physics-based computational model that describes intumescent char formation in fire conditions, which is also useful for design/optimization of intumescent char formation to reduce the flammability of polymers (NIST)

**Processing**

Development of polymer-silicate nanocomposites for electrical wire jacketing and connectors, molded parts and composites fabricated by inserting bulk polymers into surface-modified, nanometer-thick layers, including a study of the thermal stability enhancement by the molecular-level reinforcement and its relationship to flammability (Cornell University)

## SECTION 7

## TRAINING COURSES FOR COMPOSITE AIRCRAFT MISHAP RESPONSE

The next task was to identify any training courses that had specific emphasis on the response to incidents involving composite aircraft materials. Note that this exercise was a simple preliminary identification. Actual audits of the training courses were not conducted.

As indicated previously, the USN and the USAF doctrines for response to composite aircraft mishap are contained within NAVAIR 00-80R-14 and Technical Order 00-105E-9, (References 18 and 14, respectively). These documents are supposedly part of the aircraft rescue and firefighting (ARFF) training courses that both military branches teach, but this was not confirmed. USN personnel indicated that potential composite materials hazards at an aircraft mishap site are briefly mentioned in naval firefighter training but are not a focus point (Reference 41). USAF personnel were unable to give specific information on the inclusion of composite material hazards in the ARFF training program used by the USAF (References 42 and 43). However, Technical Order 00-105E-9 is currently under review for updates, which will include new information on composite-material hazards at an aircraft mishap site. Depending on new content added to the manual, training procedures might be changed to reflect the new information on composite material hazards.

In addition to USN and USAF training, the Department of Defense (DOD) conducts an ARFF course at the DOD Firefighter School. This school conducts firefighter training for all U.S. military branches and is located at Goodfellow Air Force Base in San Angelo, Texas. Discussion of composite-material hazards in the ARFF course at this facility is unknown. Randy Moore at the DOD Firefighter School should be contacted for further information (915-654-4832).

The FAA conducts ARFF training at various regional centers. Discussion of composite material hazards appears to vary between regional training centers. These hazards are briefly highlighted (2 hours of course time) at the International Center of Emergency Response Training Academy (Reference 44), but are not covered at the Fayetteville Fire/Emergency Management Training Division (Reference 45). Discussion of composite material hazards at other regional ARFF training centers is unknown. The FAA should be contacted for further information (http://www.faa.com).

Two non-military/non-government courses were identified that highlight composite material hazards at aircraft mishap sites. The first is located at Butte College in Oroville, California. Butte College is a multi-discipline community college that offers firefighting training at its Fire Science Academy. An 8-hour course covering response to aircraft mishaps involving fire is included in a series of courses on "Fire Service Principles and Procedures." Approximately 40% of the 8-hour course is devoted to the complications that composite materials create in these

incidents. The remainder of the course focuses on aircraft anatomy, typical aircraft hazards, special considerations of military aircraft, and response tactics (Reference 46). For further information, the Fire Science Department at Butte College should be contacted (http://www.cin.butte.cc.ca.us).

The second course is offered by the Maryland Fire and Rescue Institute (MFRI), a fire service extension of the University of Maryland. According to MFRI staff, the offered ARFF training courses include information presented in the ARFF manual published by the International Fire Service Training Association (IFSTA) (Reference 47). The latest edition of this manual includes content on composite hazards at aircraft mishap sites (Reference 48). MFRI should be contacted for additional information about its ARFF courses (www.mfri.org).

# SECTION 8

# RESPONSE GUIDELINES FOR COMPOSITE AIRCRAFT MISHAPS

As discussed in Section 4, fibers released from burning aircraft composites appear in various forms, including single fibers, clumps of fibers, and fragmented chunks of composites. These fibers present potential health hazards to those responding to an aircraft mishap. Smaller size fibers (diameters less than 3 μm and lengths less than 80 μm) have been determined to be respirable and pose a potential hazard to the lungs. Larger sized fibers pose a potential risk of penetrating the eyes or skin. Because of the potential hazards associated with these fibers in the event of a composite aircraft mishap, guidelines and tactics have been established to reduce the risk of exposure.

This section describes recommended procedures at a mishap involving aircraft composite materials, including suggested personal protective equipment, initial response, containment of fiber, and cleanup/disposal of composite wreckage. The recommended procedures described here are representative of combined information from multiple sources. Both USN and the USAF have developed guidelines that specifically address composite materials at an aircraft mishap involving fire and are available in NAVAIR 00-80R-14 (Reference 18) and Technical Order 00-105E-9 (Reference 14), respectively. A brief comparison of these specific guidelines is presented at the end of this section. Incident response checklists have also been developed by various groups for response to incidents involving aircraft composite materials. These checklists are not discussed here but are available in Appendixes B, C, D, and E.

## PERSONAL PROTECTIVE EQUIPMENT

Various types of personal protective equipment (PPE) have been recommended for personnel responding to aircraft incidents involving composite materials. Some recommendations are specifically directed to firefighters, while others apply to all responding personnel, including other emergency responders (police, medical, etc.), clean-up crews, investigators.

### Head/Respiratory Protection

For initial response to an incident involving the crash and burn of an aircraft containing composite materials, most sources recommend that firefighters wear self-contained breathing apparatus (SCBA) and a standard protective helmet (References 1, 6, 7, 14, 16, 17, 18, and 31). Other recommendations for firefighters included flash hoods (Reference 7) or fume capable filters in place of SCBA (Reference 1). Headgear for additional heat protection may also be used for firefighting and rescue operations. This type of protection is described by National Fire

Protection Association (NFPA) Standard 1976, the standard on protective clothing for proximity firefighting (Reference 49). Naval Safety Center personnel indicated that USN ARFF protective gear conforms to the standards described in NFPA 1976 (Reference 41). The USN recognizes that the nature of shipboard aircraft mishaps and the non-availability of this safety equipment may prevent shipboard firefighting personnel from wearing appropriate respiratory protection (Reference 18).

After the fire has been extinguished and other personnel are permitted to enter the crash site, the recommended protection is generally a full-face respirator (References 6, 14, 15, 16, 18, 19, 31, 50, and 51) or a half-mask respirator with safety goggles (References 6, 12, 19, and 31). Some specific suggestions regarding this equipment have been NIOSH-approved equipment (Reference 19), half-face air-purifying respirators (with N, R, or P100 filters) (Reference 12), and HEPA filters for respirators (Reference 6).

**Body Protection**

Standard protective clothing worn by firefighters (as described by NFPA 1971 (Reference 52) and NFPA 1976 (Reference 49) is thought to be adequate to protect them from the fire hazards and airborne composite fibers present at a composite aircraft mishap (Reference 31). One source suggests increased firefighter safety through the use of aluminized proximity suits (Reference 6). No documentation has been identified that specifies the puncture resistance to thin fibers of typical turnout or proximity gear worn by firefighting personnel. NFPA Standards 1971 and 1976 do not have a requirement that specifically addresses puncture of protective clothing from thin fibers. The Navy Clothing and Textile Research Center also indicated that current naval firefighter protective clothing is not required to pass a fiber-puncture test (Reference 53).

Disposable coveralls were suggested as the minimum level of body protection for non-firefighting personnel at crash sites during the mid-1980s (Reference 31). Hazards have become better understood since that time, and current recommendations include the use of fiber-resistant coveralls. Several sources recommend Tyvek® coveralls with hoods, which are manufactured by DuPont (References 6, 12, 14, 16, 17, 18, 19, and 51). Taping of the seams between gloves/boots/etc. and the coveralls is also recommended (References 6 and 16). Tyvek® Type 1422 is specifically identified for good performance as a fiber barrier (Reference 17). Type 1422 is made of spunbonded olefin and is a unique DuPont material that offers high strength and provides an excellent barrier to many dry particulates, including asbestos, lead dust, and radioactive dusts down to sub-μm size. Laboratory tests have shown Tyvek® to hold out >99% of asbestos fibers. DuPont notes that garments of Tyvek® spunbonded olefin are not flame resistant and should not be used around heat, flame, sparks, or in potentially flammable or explosive environments (Reference 54). Therefore, any fires present at an aircraft crash site must be mitigated before personnel can enter the site wearing these garments.

### Hand/Foot Protection

Hand and foot protection recommendations are the same for both firefighting personnel and other response personnel. Puncture-resistant gloves are suggested to consist of an inner nitrile layer and a tough outer leather layer. However, the USAF Technical Order 00-105E-9 recommends that firefighters not wear the nitrile inner gloves because they could possibly melt (Reference 14). Steel-tipped, hard-soled work boots are also recommended (References 6, 12, 14, 17, and 19). In cases where boron composites are expected to be present, steel-shanked work boots are suggested for use (References 12 and 14). The steel shank is recommended because of the greater puncture hazard of exposed boron fibers, as described in Section 5.

The USN does not list *specific* hand or foot protection for firefighters or rescue personnel in its composite aircraft mishap procedures (Reference 18). USN ARFF protective gear meets the requirements of NFPA 1971 and 1976 (which include hand and foot protection), and therefore protection from fire hazards at the composite aircraft mishap site should be adequate. However, hand and foot protection from thin-composite-fiber puncture may not be adequate. As stated, these NFPA standards do not address thin-fiber puncture.

## INITIAL RESPONSE PROCEDURES

The three major elements for response to aircraft crashes are (1) initial response, (2) containment, and (3) disposal/cleanup. The first of these elements, the Initial Response, establishes the procedures required during early response to an aircraft emergency. These procedures are summarized below:

1. Firefighting and rescue operations should commence as soon as possible. The primary concerns are victim rescue, prevention of weapons cookoff, and fire control/extinguishment. A secondary consideration is the cooling of composite materials. Cooling of the composite materials is important to extinguish any potential smoldering combustion. Firefighters equipped with SCBA should be the only personnel in the immediate area of the burning/smoldering mishap site, until the area is determined safe by the fire chief or officer in charge. If possible, precautions should be taken to avoid high-pressure water breakup and dispersal of composite materials (Reference 14). These ARFF operations should be ongoing while the remainder of the initial response procedures are conducted.

A series of tests were performed to determine the optimum extinguishing agents and firefighting techniques for flaming composite aircraft fires (Reference 28). Several small-scale tests were performed to screen potential extinguishants, including water, aqueous film forming foam (AFFF), $CO_2$, potassium bicarbonate (PKP), and others. AFFF and PKP were found to be the most effective from these tests and were used in subsequent full-scale tests of an aircraft fuselage and wing mockup. The wing of the mockup had an epoxy composite panel embedded in it. The exposure fire was a 2000-gallon, 48-foot-diameter pool of JP-5. These large-scale tests concluded that the AFFF was the most effective extinguishant. The best firefighting technique found was to extinguish the pool fire first, followed by the burning composite. A continuous

application of AFFF (3 minutes minimum) was necessary to extinguish the smoldering combustion. The lower surfaces of the wing needed to be directly hit with the agent to effectively complete extinguishment. PKP was not found to be effective in extinguishing the smoldering combustion of composite materials.

Another composite test series was conducted with the goal of determining the overall performance of compartments constructed of composite when exposed to fire insults ranging from 50 to 6900 kW (References 55 and 56). One of the specific objectives of these tests was to determine fire-extinguishment requirements for the burning composite material. These tests concluded that the burning composite materials could be readily extinguished using typical shipboard fire-suppression agents such as water or AFFF.

2. The fire chief should perform an initial survey of crash area, to determine the following (References 14 and 19):

a. Amount of fire-damaged composites
b. Presence of loose/airborne fibers
c. Weather conditions/wind direction
d. Degree of site exposed to fire/impact/explosions
e. Local/proximal equipment/asset damage and hazards
f. Level of safety precautions that should be implemented during response and cleanup

In addition, an aircraft specialist should be contacted to determine composite-materials and other potential hazards associated with the aircraft. Composite-material information is available in NAVAIR 00-80R-14-1 (Reference 13) for various USN aircraft. However, this information is generic in nature as it typically gives only the overall location and the general type of composite material.

3. Areas in the immediate area of the mishap should be evacuated as much as possible. This procedure may not be practical on a ship flightdeck. Unprotected personnel should be kept from assembling downwind of the mishap, and required personnel should be kept to a minimum. Easily mobile and critical equipment should be moved from areas affected by direct and dense fallout from the smoke plume (References 14, 16, 18, and 19). If a large amount of smoke is present, in-place evacuation of downwind buildings is suggested. Exterior doors, windows, HVAC air intakes, and similar openings should be closed in buildings exposed to the smoke plume (Reference 6).

4. Ground/flight operations should be prohibited to a range of 500 feet above ground level and 1000 feet horizontally in all directions. This is especially important for helicopter operations, which have the greatest potential to disturb loose composite material fibers (References 6, 14, 18, 19, and 49).

5. The wreckage site should be cordoned off and a single point of access established (References 6, 7, 14, and 50). Personnel must be adequately protected before entering the

cordoned off area. They should also be adequately protected in the peripheral area of the wreckage site. Entry/exit from the wreckage site should be monitored.

6. Some suggestions for the setup of cordoned zones around the wreckage site have also been made (Reference 49). These zones include the incident site itself (where the wreckage is located), the casualty clearance area (upwind of the incident zone for prioritizing of victims), and the ambulance loading zone. Individual incident control points for firefighting operations, law enforcement, and medical services are recommended. The incident zone should be divided into inner and outer zones, which are roped/taped off with an indication of Hazard to Health Zone and clearly marked entrance and exit points. Entry into the inner zone would require donning of appropriate safety equipment suggested in Section 8 under Personal Protective Equipment. This equipment should be donned in the outer zone. Persons exiting from the inner zone should pass through decontamination to clean clothing by disposing of it in plastic bags or cleaning fibers with a vacuum cleaner with sealed electric motors and HEPA filters. All other equipment should be carefully cleaned as well.

7. If possible, personnel should collect samples of the materials present at the wreckage site for later characterization. Recommended equipment is summarized in Table 8 from Reference 12). Sampling should occur during post-fire debris handling.

TABLE 8. Equipment Recommended for the Collection of Composite Materials.

| Item collected | Collection equipment |
|---|---|
| Inhalable particulate | IOM Sampler or 5.0-μm PVC filters mounted in a 37-mm cassette. |
| Respirable particulate | Respirable dust cyclone such as the 10-mm nylone cyclone or the aluminum cyclone. Aerosols should be collected on 5.0-μm PVC filters mounted in a 37-mm cassette. |
| Fibers | 0.8-μm mixed cellulose ester filter mounted in a 25-mm cassette containing a black anti-static cowling. |
| Area samples | These samples should be taken in the same way for personnel exposure, but at the various locations around the site, particularly downwind of the accident site. |

## CONTAINMENT OF FIBER

When the fire has been extinguished at the crash site of a composite-containing aircraft, steps should be taken to reduce the dispersion of composite fibers at the site. The most common method of containment is spraying burned/fragmented composite materials with polyacrylic acid or acrylic floor wax and water (References 6 and 14 through 19). When the solution dries, it provides an effective barrier to fiber disturbance. If generic acrylic floor wax is used, the recommended mixture ratio is 10 parts water to one part wax (References 6 and 14). Diluted car underseal was used at the crash site of a Harrier aircraft in an attempt to contain fibers but was found to be ineffective (Reference 2). Canvas bags, sheets, and tents are also suggested as methods to contain fibers for larger pieces of composite wreckage (References 6, 7, 14, 15, and 18). Plastic is not recommended because of issues and the lack of puncture resistance.

If composite fibers/wreckage is on soil or sand, agricultural soil tackifiers may be applied to hold materials to these surfaces (References 6 and 14). Examples of tackifiers are "Polychem," "J-Tack," or "Tera Tack." These should be applied by spraying the ground, using approximately 0.5 gallon per square yard. Hard surfaces, such as asphalt or concrete, should be cleaned with HEPA vacuums and the effluent should be collected for disposal (Reference 14).

## CLEANUP/DISPOSAL OF COMPOSITE WRECKAGE

The final response element involves the cleanup/disposal of the advanced composite materials (References 14, 18, and 19). Material disposal is required to be conducted in accordance with local, state, federal, and international guidelines. If hazardous materials are present, they should be properly sealed and disposed. Crash debris not needed for investigative purposes, coveralls, and gloves should be disposed of and appropriately labeled. All response equipment and clothing should be decontaminated as soon as possible, using HEPA vacuums and plastic disposal bags. Portions of aircraft and other downwind equipment subjected to smoke/debris should be properly cleaned. Personnel should carefully decontaminate clothing and shower as soon as possible after leaving the hazard zone (References 13, 14, and 46).

## COMPARISON OF U.S. NAVY AND U.S. AIR FORCE COMPOSITE AIRCRAFT MISHAP-RESPONSE PROCEDURES

This section provides a direct comparison of the procedures outlined by USN and USAF in response to an aircraft mishap involving composite materials. As indicated previously, these procedures are located in NAVAIR 00-80R-14 (USN) and Technical Order 00-105E-9 (USAF) (References 18 and 14, respectively). The comparison of procedures is listed in Tables 9 through 12. Items with quotation marks in the Tables are used to indicate actual wording used in the response procedures. A detailed line-by-line comparison is not made here because the tables are intended for general informative purposes.

However, two important differences between the response procedures exist. First, the USAF procedures are more detailed than the USN procedures. For example, the USAF makes specific recommendations for personal protective equipment and site survey, whereas the USN procedure does not. The other difference between the procedures (although not shown well by the tables) is the structure of the documentation. The USAF procedure is logical and well organized into four distinct sections (personal protective equipment, initial-response steps, fiber containment, and fiber cleanup). In contrast, the USN procedure is not well organized. Recommendations for personal protective equipment are scattered in different sections, and the only differentiation made for ship flightdeck and shoreside flightline operations is in the Cleanup section of the document. Separate sections for ship flightdeck and shoreside flightline procedures could be warranted, depending on the number of differences between the procedures. Further review is needed to make this determination.

TABLE 9. Required Personal Protective Equipment Needed for Response to an Aircraft Mishap Involving Composite Materials as Indicated by USAF T.O. 00-105E-9 and USN NAVAIR 00-80R-14.

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 1. "Burning or smoldering composites"<br>a. "Self Contained Breathing Apparatus (SCBA)" | 1. "Firefighting and rescue personnel"<br>a. Non-specific breathing apparatus – "appropriate respiratory protection" to be selected based on the "quantity of composite materials present at the site as well as the duration of the potential exposure." Specific guidance to be given by the "local cognizant industrial hygienist or medical department representative." |
| b. "Full protective clothing (NFPA Standards 1971 and 1976)" | b. Full protective clothing (via NFPA 1976) (Reference 39) |
| c. "Do ***not*** use rubber gloves" | c. No glove restrictions specified |
| 2. "Broken or splintered composite"<br>a. "Full-face respirator with dual cartridge (high-efficiency particulate air (HEPA) and organic dust/mist) filters" | 2. "Cleanup/Investigation personnel"<br>a. "Full-face high-efficiency particulate air/organic vapor combination respirator" (identified as potentially appropriate for early cleanup/investigation or areas of heavy contamination)<br>(1) "Dust-fume-mist filter respirator" (identified as potentially appropriate for later stages of cleanup/investigation)<br>(2) "Safety glasses with side-shields" should be worn when not using a full face respirator |
| b. "Coated, hooded Tyvek™ suit with booties" | b. "Disposable coveralls and shoe covers" |
| c. "Leather work gloves (outer)" with "inner nitrile gloves (rubber)" | c. "Leather palm gloves" |
| d. "Hard soled work boots (steel toe and shank recommended)" | d. No footwear guidance is given |
| 3. "Peripheral area composite exposure"<br>a. "Battle Dress Uniform (BDUs) or long sleeve work uniform" | |
| b. "HEPA filter respirator" | |
| c. "Safety glasses with side shields" | |
| d. "Leather work gloves (outer)" with "inner nitrile gloves (rubber)" | |
| e. "Hard soled work boots (steel toe and shank recommended)" | |

TABLE 10. Response Guidelines to an Aircraft Mishap Involving Composite Materials as Indicated by USAF T.O. 00-105E-9 and USN NAVAIR 00-80R-14.

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 1. Initial survey/assessment for:<br>a. "Signs of fire damaged composites" and "presence of loose/airborne fibers and particulate" | 1. Initial survey/assessment for:<br>a. Presence of relative amount of airborne fibers caused by impact, fire, explosion, or a combination of all three. The Amount of fibers released into the atmosphere is suggested to increase respectively. |
| b. "Prevailing weather conditions/wind direction" | b. Although not specifically mentioned in the composites section, weather and wind condition checking is a suggestion in the general NATOPS ARFF procedure in 00-80R-14. |
| c. "Degree of site exposed to fire/impact/explosion" | c. Degree of site exposed to fire/impact explosion is covered in a. |
| d. "Local/proximal equipment/asset damage and hazards" | d. In the event of fire followed by explosion, "immediate action" is suggested to "prevent damage to downwind electronic/electrical equipment and facilities." |
| e. "Exposed personnel." | e. Survey for exposed personnel is not specifically identified. |
| 2. "Establish site control." | 2. Establishment of site control is not specifically addressed. |
| 3. "Evacuate areas in the immediate vicinity of the mishap site affected by direct and dense fallout from the fire/explosion generated plume."<br>a. evacuate personnel | 3. Evacuation procedures (not specifically identified as such):<br>a. "All personnel not directly involved in firefighting operations should remain upwind and at a safe distance from the mishap." |
| b. "evacuate easily mobile and critical equipment" | b. The scene should be approached from an upwind and uphill (ashore) position, if possible. ("Uphill" is specified in the general NATOPS ARFF procedure in 00-80R-14) |
| c. "restrict all unprotected personnel from assembling downwind of the site" | c. "If afloat, the ship should be maneuvered to direct smoke and debris away from parked aircraft, the island structure, and the ventilation inlets." |
| d. Warning of adjacent aircraft/ships is not specified, although a 'no-fly zone' is established in 5). | d. If afloat, "warn adjacent aircraft/ships that the smoke may contain hazardous electrical contaminants" (specified in "Cleanup (afloat)" section) |
| 4. "Extinguish fire and cool composites to below 300°F (149°C)" and "avoid high pressure breakup and dispersal of composites," if possible. | 4. "Extinguish the fire as quickly as possible." Cooling with a spray of AFFF is recommended in the "Interim Containment" section. |
| 5. Restrict ground or flight operations within "500 feet above ground level" and "1,000 feet horizontally." | 5. Helicopters should not be involved in the firefighting effort or allowed to hover at "altitudes less than 500 feet" over the site. No direction is given as to the horizontal distance restriction. |
| 6. "Cordon off the mishap site and establish a single entry/exit point." Only "sufficiently protected individuals" may enter. (cordon should be 25' away from any damaged composites as a guide) | 6. No suggestions are made for site cordoning. |

TABLE 10. (Contd.)

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 7. "If personnel other than those at the accident site have been directly and significantly exposed to material and smoke hazard," consult medical staff for consultation and tracking. Notify public safety officials if necessary to relay the following information:<br>a. "Remain indoors"<br>b. "Shut external doors and windows"<br>c. "Turn off forced-air intakes"<br>d. "Await further notification" | 7. "The local cognizant industrial hygienist or medical department representative should be consulted for detailed health hazard control guidance, based on the extent of exposure." |
| 8. Access the crash site to conduct a more thorough survey<br>a. "Identify specific aircraft hazards by inspection and consulting with crew chiefs or weapons system manager, reference documents, contractor or aircraft specialists."<br>b. Relay this information to incident commander and response personnel<br>c. "Minimize airborne particulates/fibers by avoiding excessive dust disturbance created by walking, working, or moving materials." | 8. No suggestion is made for a secondary survey. |
| 9. Monitor entry/exit from the entry control point to the site:<br>a. Exiting personnel should use HEPA vacuums, if available, to remove as much composite as possible from outer protective equipment and clothing. If unavailable, as much composite as possible should be brushed or wiped off.<br>b. Sites should be setup for donning/removal of personal protective equipment as practical<br>c. No eating, drinking, or smoking is permitted near the crash site as directed by the incident commander. Showering must be advised to personnel prior to eating, drinking, or smoking. At the very least, personnel should wash hands, forearms, and face prior to these activities.<br>d. "Wrap and seal contaminated protective clothing and dispose of properly."<br>e. Personnel should shower in cool water prior to going off-duty. Portable showers may be necessary.<br>f. Where practical, remove contaminated outer garments of both victims and response personnel at the scene to protect the medical staff. | 9. Since no suggestion of cordoning is made, there is no 'entry/exit' point. However, some similar recommendations are presented in the "Clean-Up" sections of the document.<br>a. "Aircraft/equipment/clothing" that have been "dosed" with debris from the aircraft fire "must be vacuumed and/or washed down prior to further use or before movement into the ship structure" (specified in the "Cleanup (afloat)" section of the document).<br>b. See e. below.<br>c. Suggestions for restrictions on eating, drinking, or smoking are not made.<br>d. Contaminated debris/disposable clothing is suggested to be disposed of using EPA guidelines (ashore) or local solid waste disposal authority guidelines (afloat)<br>e. "Showers and change room facilities should be available after particularly 'dirty' investigation/cleanup operations."<br>f. Suggestions for contaminated garment removal for the safety of medical personnel are not made. |

TABLE 10. (Contd.)

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 10. Ventilation inlets on surface vessels are not a concern with land-based mishaps. | 10. When afloat, "If ventilation inlets are known to be contaminated, take immediate action to verify filtration system is properly operating. If the system is not operating properly, shut down system and provide temporary filtration at inlets leading to compartments with electrical/electronic equipment. |

TABLE 11. Composite Containment Guidelines for Response to an Aircraft Mishap Involving Composite Materials as Indicated by USAF T.O. 00-105E-9 and USN NAVAIR 00-80R-14.

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 1. "Secure burned/mobile composite fragments and loose ash/particulate with:"<br>a. "plastic"<br>b. "firefighting agent"<br>c. "fixant material"<br>d. "tent"<br>Note that the "fire must be completely extinguished and the composites cooled below 300°F (149°C)" before this operation is to be conduced. Plastic sheet/film used for covering composites should also be minimally 0.006 inches (6 mils) thick. | 1. Containment of composite aircraft debris should be accomplished by:<br>a. polyethylene sheeting and tape (specified in "Cleanup" sections)<br>b. firefighting agent<br>c. fixant material (specified in "Cleanup (Ashore)" section)<br>d. tents are not specified for containment<br>"Interim containment of aircraft debris" is recommended to be accomplished with a "spray pattern of AFFF until the debris is cool, more permanent containment is specified, or disposition is directed." |
| 2. Specific aircraft authority and investigators should be consulted before applying fixant, although safety concerns may override any delayed application<br>a. A 'hold down' solution or fixant 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."<br>b. "A heavy coating of the fixant" should be applied to "all burned composite material and to areas containing scattered/settled composite." The coating should be allowed to dry. | 2. No suggestion is made to consult aircraft authorities or investigators before applying the fixant. Suggestions for fixant include:<br>a. The preferred method of containment is wrapping of damaged parts in plastic (polyethylene) sheets with tape or placement in plastic bags (specified in the "Cleanup (Ashore)" section).<br>b. Where the use of plastic sheets/bags is not feasible, "more permanent containment than provided by AFFF can be obtained by using acrylic floor wax" (specified in the "Cleanup (Ashore)" section). A mixture ratio is not specified. Use of acrylic floor wax is only specified for shore-side operations. |
| 3. "Agricultural soil tackifiers may be used to hold materials on sand or soil," if necessary. "Most solutions, including Polychem TM, J-Tack TM, or Terra Tack TM can be sprayed onto the ground at a rate of 0.5 gallons per square yard." | 3. Suggestions for use of agricultural soil tackifiers are not made. |

TABLE 11. (Contd.)

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 4. Contaminated, "improved hard surfaces," such as concrete or asphalt, "should be vacuumed with an electrically protected vacuum." Sweeping should be avoided, as it disseminates the particulate debris." | 4. Specific suggestions for containment of composite debris on fixed surfaces are not made. General containment/cleanup procedures (for both afloat and ashore) are given as:<br>"Use of a high-efficiency vacuum cleaner is recommended whenever possible for cleanup of debris rather than use of systems of lower efficiency. Following the vacuuming process, a thorough detergent/water washdown should be performed to remove any remaining residual material." |
| 5. Fixant-application equipment should immediately be flushed with dilute solvent to avoid clogging. | 5. Suggestions for flushing fixant application equipment are not made. |
| 6. Sharp projections from damaged composites parts should be padded to prevent accidental injury. | 6. Suggestions for preventing accidental injury from sharp composite projections on debris are not made. |
| 7. Firefighting vehicles and equipment must be decontaminated at the accident site by washing with water or through the se of HEPA vacuums. | 7. Suggestions for decontaminating firefighting vehicles and equipment while on-site are not made. |

TABLE 12. Cleanup Procedures for Response to an Aircraft Mishap Involving Composite Materials as Indicated by USAF T.O. 00-105E-9 and USN NAVAIR 00-80R-14.

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| 1. "Conduct material disposal according to local, state, federal, and international guidelines." Disposal procedures should be obtained from the appropriate environmental group, and the Safety Investigation Board (SIB) and Accident Investigation Board (AIB) should have authorized the part for disposal. | 1. If ashore, debris should be disposed of "in accordance with local EPA requirements." If afloat, local solid waste disposal authorities shall be consulted for approved burial sites/techniques for composites or composite-contaminated materials." Debris should be stored "in a remote location" if needed for accident investigation. |
| 2. "Place hazardous waste material in containers and appropriately dispose as hazardous waste." Labels on the containers should read "Composite Waste. Do Not Incinerate. Do Not Sell for Scrap. Composite Waste." | 2. Debris collected in "plastic (garbage) bags" should be stored and disposed (ashore). No container information is specified in the 'afloat' cleanup section. |
| 3. "For open terrain mishap areas, the appropriate soil and surface restoration will be completed." | 3. For ashore mishaps, "decontamination of the immediate area of the aircraft wreckage may require vacuuming, washing down, and /or plowing the debris under." For afloat mishaps, cleanup consists of "washing down [the deck] with saltwater, directing the residue over the side", and "covering the aircraft parts containing carbon-fiber composites, taping securely, and removing wreckage to a safe parking area." Both locations of operation specify: "Use of a high-efficiency vacuum cleaner is recommended whenever possible for cleanup of debris rather than use of systems of lower efficiency. Following the vacuuming process, a thorough detergent/water washdown should be performed to remove any remaining residual material." |
| 4. "If aircraft were subjected to the smoke and debris of the immediately affected area, the following should be undertaken:"<br>a. "Vacuum the air intakes with an electrically protected vacuum cleaner."<br>b. "For internally ingested smoke, visually and electronically, inspect all compartments for debris and vacuum thoroughly."<br>c. "Prior to flying, perform electrical checks and engine run-up" | 4. If aircraft/facilities/equipment/clothing "are dosed with the aircraft debris, they must be vacuumed and/or washed down prior to further use or before movement into the ship structure [if afloat]".<br>An additional caution is added as "Do not put power to or start up dosed aircraft or electrical/electronic equipment until decontamination by vacuuming and/or wash down is completed." |
| 5. "For significantly affected structures and equipment:"<br>a. "Thoroughly clean all antenna insulators, exposed transfer bushings, circuit breakers, etc. Inspect air intakes and outlets for signs of smoke or debris and decontaminate, if necessary." | 5. Affected structures/equipment are covered by no. 4. |

TABLE 12. (Contd.)

| *U.S. Air Force, Technical Order 00-105E-9 Technical Manual – Aircraft Emergency Rescue Information (Fire Protection)* (15 January 2001) | *U.S. Navy, NAVAIR 00-80R-14 NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual* (1 November 1996) |
|---|---|
| b. "Consult more detailed electrical reference material and specific decontamination instructions for more information." | |
| 6. "Continue to monitor affected personnel, equipment, and mishap site." | 6. No suggestions for monitoring affected personnel, equipment, and the mishap site are made. |
| 7. Recommendations for securing aircraft/facilities/equipment along the travel route of uncovered aircraft debris are not made. | 7. For ashore operations, "If wrapping and secure taping of the aircraft wreckage is not possible, transporting the wreckage must be planned, bypassing highly populated and industrial areas. If this is not possible, aircraft parked along the planned route must have their canopies and access doors closed and engine inlet and exhaust covered. In addition, the doors and windows of surrounding building should be closed to minimize the probability of having wind-blown fibers enter areas with electrical/electronic equipment." |

# SECTION 9

# CONCLUSIONS

A thorough literature search was completed to gather information about the role of composite materials in an aircraft mishap. Based on the information gathered, several conclusions were reached.

1. Burn data suggest that the combustion characteristics of composite materials are roughly equivalent to other combustible materials. Combustion products released by burning composite materials are similar to those released from other solid combustibles. Additionally, unusual combustion characteristics of composite materials were not identified in the literature. Characteristics such as very rapid flame spread or excessively large heat release rates do not appear to be a concern for composite materials.

2. Smoldering combustion of composite materials is possible but unlikely to lead to re-ignition. Smoldering of composite materials is typically associated with a core material (balsa, foam, etc.) that is not typically used in naval aircraft composite construction. At a composite aircraft mishap site, smoldering combustion should not be a problem from a response standpoint. Cooling of the burnt composite materials with water or AFFF should eliminate or reduce smoldering combustion and preclude the possibility of re-ignition.

3. The presence of burning composite materials at an aircraft mishap does not affect extinguishing agent selection. Typical aircraft firefighting agents, such as water or AFFF, are adequate to control and extinguish burning composite materials.

4. Burning of composite materials can release fibers that are respirable. These fibers have diameters of $\leq 3$ μm and lengths $\leq 80$ μm. Burning of carbon-fiber composites has the potential of releasing single fibers during a pool fire; however, a very specific set of conditions is needed, and not all fires will produce airborne carbon fibers.

5. Fibers released from burning composite materials can be electrically conductive. This is especially true of carbon and graphite fibers. NASA tests determined that electrical effects of released fibers were not likely to be a widespread problem. From a response standpoint, the electrical conductivity of the fibers should not affect the work of naval firefighters or rescue personnel. The toxicity of combustion products from burning aircraft composite materials currently used does not appear to be exceptional. Types and quantities of combustion products from burning composite materials fall within the same spectrum as other burning combustibles at an aircraft mishap site. Smoke from a burning composite used on the B2 bomber was shown to cause a reaction consistent with smoke inhalation from other typical combustibles.

6. No additional smoke toxicity hazards created by burning composite materials were identified. This is based upon the combustion and toxicity information found in the literature.

7. Respirable fibers released from burning composite materials can penetrate into the lungs, causing respiratory irritation. Factors known to affect the toxicity of these inhaled fibers include dosage, physical dimensions, retention time in the lung, location of deposition in the lung, and solubility of the fibers in the lung.

8. Exposed fibers along the edges of fragmented composite debris present a dermal-puncture hazard. The skin can be irritated and sensitized if punctured by exposed fibers. It is unknown if personal protective equipment worn by naval firefighters is resistant to thin-fiber puncture.

9. The USAF HAMMER project is currently the most relevant ongoing research program relating to composite materials in aircraft mishaps. Studies include full-scale exposure tests from composite materials at a simulated aircraft mishap site, identification and inventory of composite material locations on military and commercial aircraft, toxicology tests of burning composite materials, and review of USAF response procedures to composite aircraft mishaps. HAMMER personnel identified significant smoldering combustion of composite materials during testing of A-6 wings. HAMMER IPT members witnessed significant carbon-fiber combustion (not epoxy smoldering) during a JP8 pool fire of a carbon-fiber epoxy wing box. HAMMER IPT witnessed deep-seated carbon-fiber combustion 30 minutes after the fire went out. During the 2 years since the composite burns of 2000, HAMMER IPT has not met, and ongoing studies have ceased.

10. The degree of instruction on composite materials hazards in USN, USAF, and DOD ARFF training courses is unknown. The FAA has regional ARFF training centers, some of which discuss the hazards of composite materials. Non-military/-government ARFF training courses known to include guidance on composite materials are offered at Butte College and the Maryland Fire Rescue Institute. Auditing of training courses was not conducted.

11. Personal protective equipment recommendations for firefighters responding to composite aircraft mishaps include SCBA, standard firefighter protective clothing and/or proximity suits, and steel-tipped/-shanked boots. USN firefighters are expected to wear breathing apparatus and protective clothing that conforms to NFPA Standard 1976.

12. Personal protective equipment recommendations for recovery and investigation personnel vary. At the minimum, these personnel should wear a half-mask respirator, safety goggles with side-shields, fiber-resistant coveralls, inner nitrile gloves with outer leather gloves, and steel-tipped/-shanked work boots.

13. Based on combustion characteristics and the toxicity of burning composite materials, the current personal protective equipment worn by naval firefighters should be adequate. This assumes that the firefighter wears SCBA and clothing that conforms to NFPA Standard 1976 (protective ensemble for proximity firefighting). The only exception is the lack of information on puncture resistance of protective gear from thin fibers located on the edges of fragmented composite debris.

14. The USN and USAF guidelines for emergency response and cleanup/salvage of composite aircraft mishaps are contained in NAVAIR 00-80R-14 (*NATOPS U.S. Navy Aircraft Firefighting and Rescue Manual*) and Technical Order 00-105E-9 (*Aircraft Emergency Rescue Information*), (References 18 and 14, respectively). NAVAIR 00-80R-14 is structurally disorganized and lacks procedural detail compared to Technical Order 00-105E-9. For example, only generic personal protective equipment recommendations are given. These recommendations are scattered in different sections of the document.

15. A comprehensive list of all composite materials used in USN aircraft was not identified.

16. Aircraft composite material information in NAVAIR 00-80R-14-1 (*NATOPS U.S. Navy Aircraft Emergency Rescue Information Manual*, Reference 13) lacks detail. This document provides only general locations and generic types of composite materials used on USN aircraft.

## SECTION 10

## RECOMMENDATIONS

Based on the conclusions from the literature search, several recommendations for future action can be made. These recommendations are listed in decreasing order of importance.

1. The USN should participate in the USAF HAMMER program. If participation is not possible, the USN should continue to monitor findings from this program. This program is currently the most relevant research study about composite materials in aircraft mishap situations. The USN could glean valuable up-to-date information about aircraft composite materials by participating in this project.

2. The HAMMER program recently conducted full-scale tests of composite A-6 wings in order to simulate exposure to composite materials at an aircraft mishap site. HAMMER personnel indicated that smoldering combustion of composite materials was significant. The final report from these tests should be acquired to verify these results and determine if cooling of composite materials should be further emphasized.

3. The response procedures for composite aircraft mishaps in NAVAIR 00-80R-14 need to be updated. The documentation should be reorganized for clarity, and additional detail should be added. Details should include (but not be limited to) specific personal protective equipment and specific information on the differences between ship flightdeck and shoreside flightline response operations.

4. All USN aircraft composite materials should be identified. A comprehensive list of USN aircraft composite materials should be assembled, including details about material properties and any special hazards. An example of special hazard could be the greater skin-penetration hazard posed by exposed boron fibers.

5. The composite material information contained in NAVAIR 00-80R-14-1 should be updated with regard to more specific composite information. Currently, the information about composite materials for various USN aircraft is vague. In this document, only location and general composite types are listed. In addition to location, updated information should include specific composite material information as well as the approximate weight of composite material contained in each aircraft.

6. The degree and adequacy of instruction related to composite fire hazards at USN training facilities need to be identified. The amount of composite material hazard instruction in Naval ARFF courses is currently unknown. Some naval firefighting training may occur at the DOD ARFF training facility. Therefore, a similar assessment of the degree of composite hazard instruction should be conducted.

7. Lacking is information that identifies the degree to which protective clothing prevents puncture from exposed fibers on composite wreckage. Firefighting turnout gear and Tyvek™ (or equivalent) garments are known to prevent passage of μm-sized particles and fibers; however, their capacity to defend against penetration of fibers from impact is relatively unknown. Studies on the resistance of these garments to thin-fiber penetration are suggested.

## SECTION 11

## REFERENCES


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# Appendix A

## CURRENT HAMMER PROJECT LIST OF COMPOSITE CONTAINING AIRCRAFT

This appendix is a facsimile of a list from USAF Institute for Environment, Safety, and Occupational Health Risk Analysis, Industrial Hygiene Branch report: *Aerospace Vehicles Composite Material*, accessed on the Internet 26 April 2001.

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# Aerospace Vehicles Composite Material

Click here for aerospace vehicle index

# AIRFRAME MATERIALS



1. AIRFRAME MATERIALS

a. Main Rotor Blades ( not pictured) are constructed of stainless steel, aluminum, fiberglass, and nomex honeycomb.

b. Cockpit flooring (not pictured) is constructed of Boron armor.

c. Crew seats (not pictured) are contructed of Kevlar/Boron carbide and nylon.

d. Tail Rotor hub forks (not pictured) are contructed of Titanium.

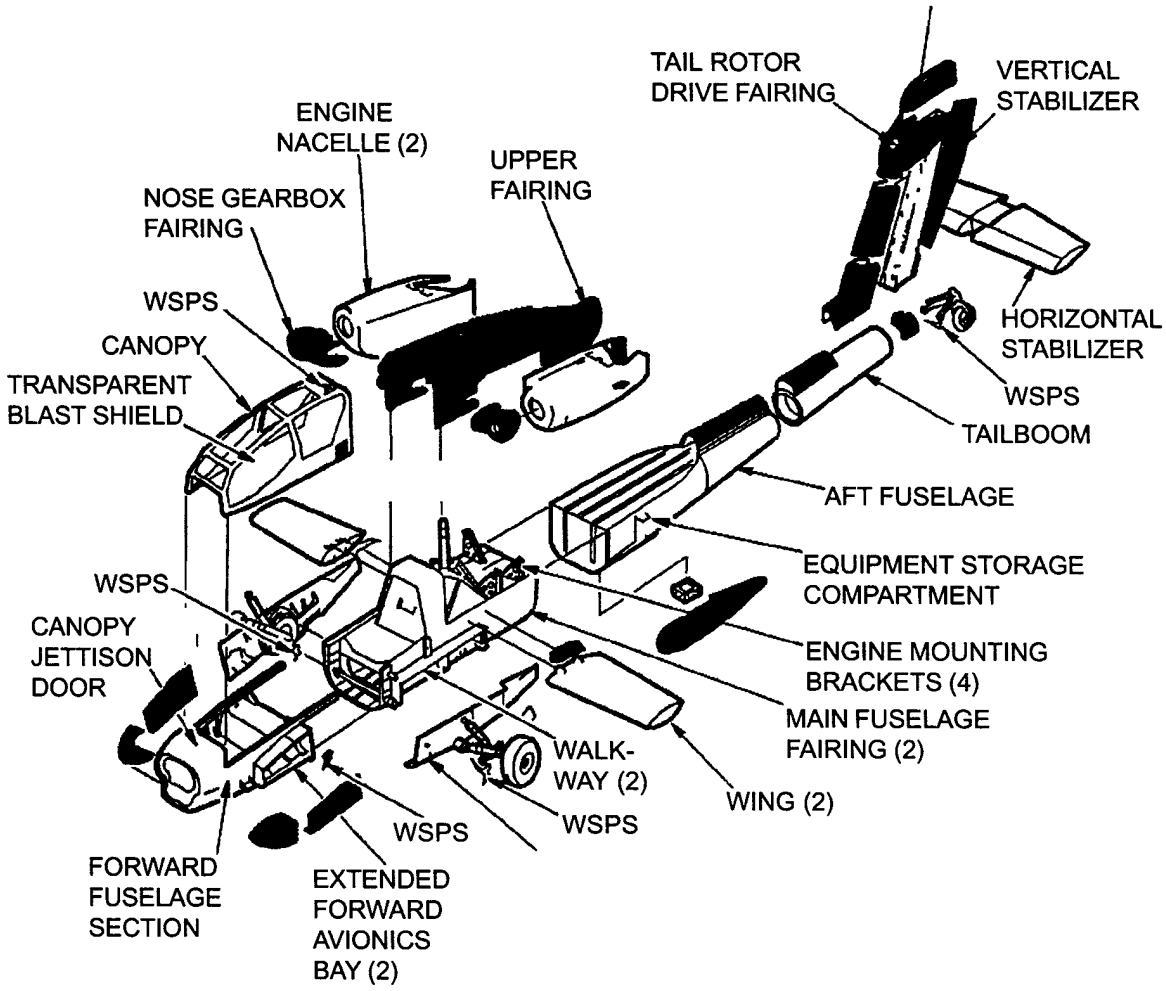
e. Both aircraft engines (T700-GE-701-C) are contructed with Titanium/Carbon/ Nickel Graphite.

f. Battery (not pictured), located on the right side is a Fiber Nickel-Cadmium battery.

LEGEND

■ Graphite Composite

■ Kevlar/epoxy Composite



# AIRFRAME MATERIALS



1. AIRFRAME MATERIALS

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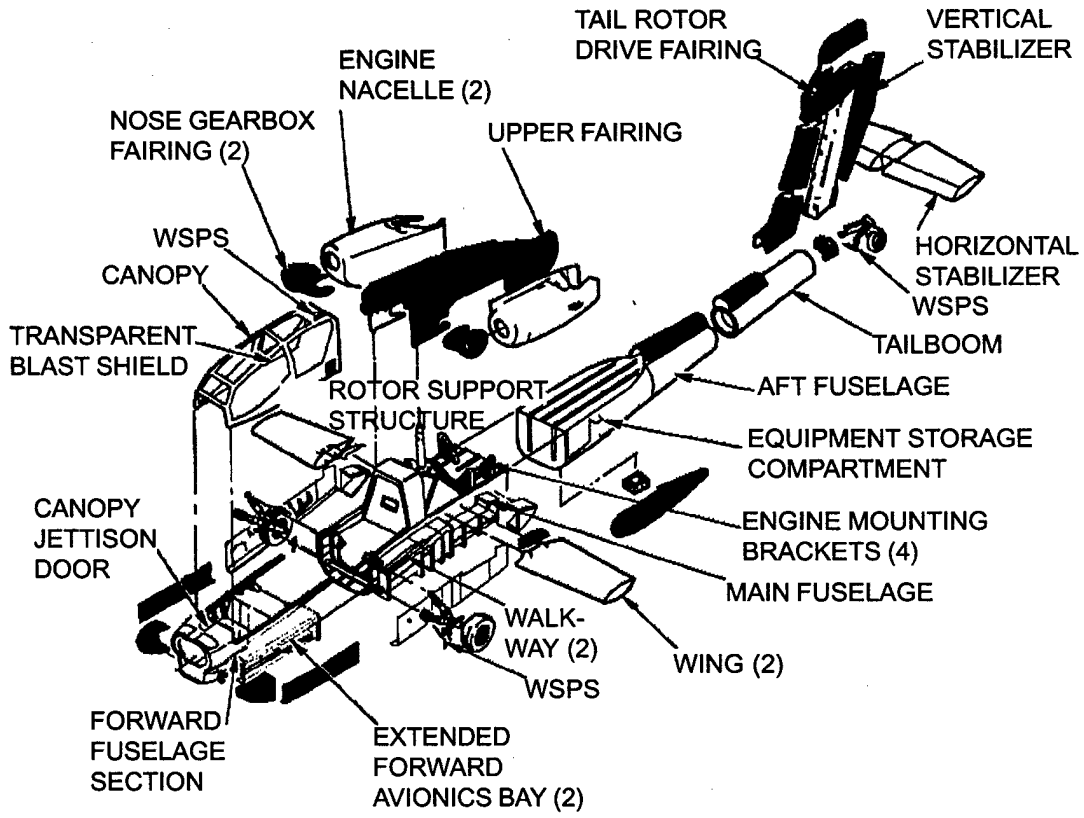
LEGEND

- Graphite Composite
- Kevlar/epoxy Composite



# AIRFRAME MATERIALS





a. Aluminum

b. Carbon/Epoxy

c. Carbon/Kevlar/Epoxy

d. Glass Fiber Reinforced Plastic

e. Kevlar/Foam Core

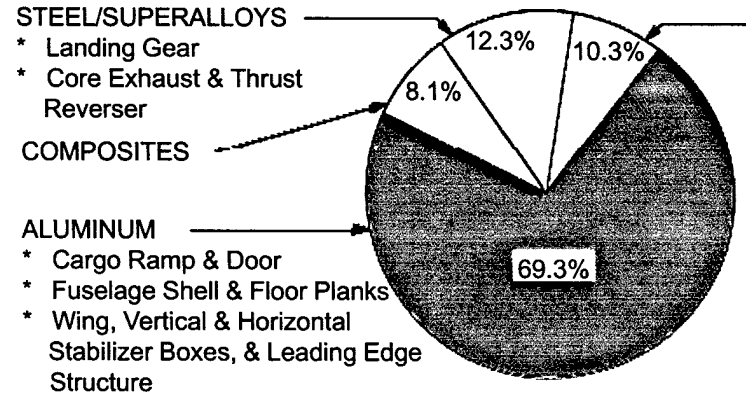
f. Kevlar/Nomex

g. Carbon/Nomex

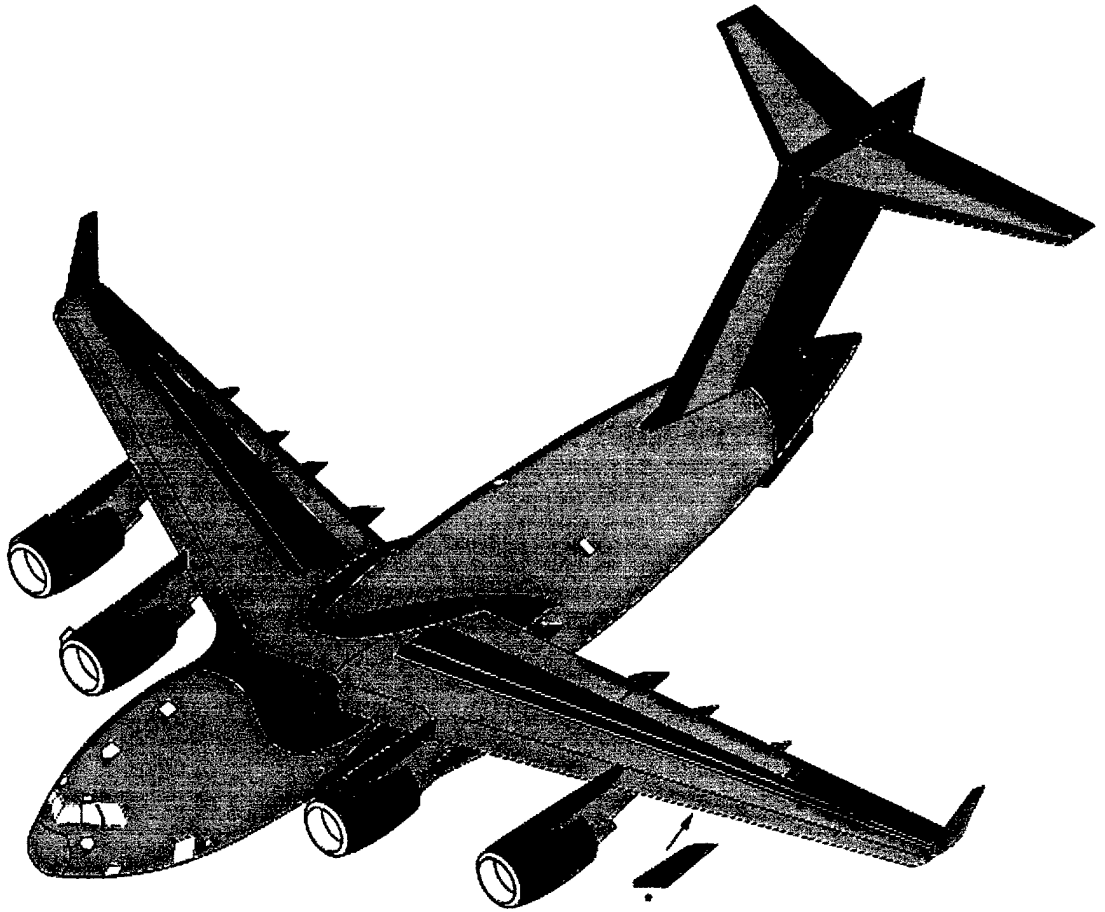
NOTE:
Many interior nonstructural parts (e.g., liners, troop seats) are also made of composite materials.

*NOTE
There are 4 flap track fairings for each wing using Kevlar/Nomex.

NOTE:
The fuselage and wing are constructed primarily of aluminum alloy material. However, aluminum-lithium, titanium, steel, and composite materials are used wherever there are cost-effective advantages in weight, fatigue life, or corrosion resistance.

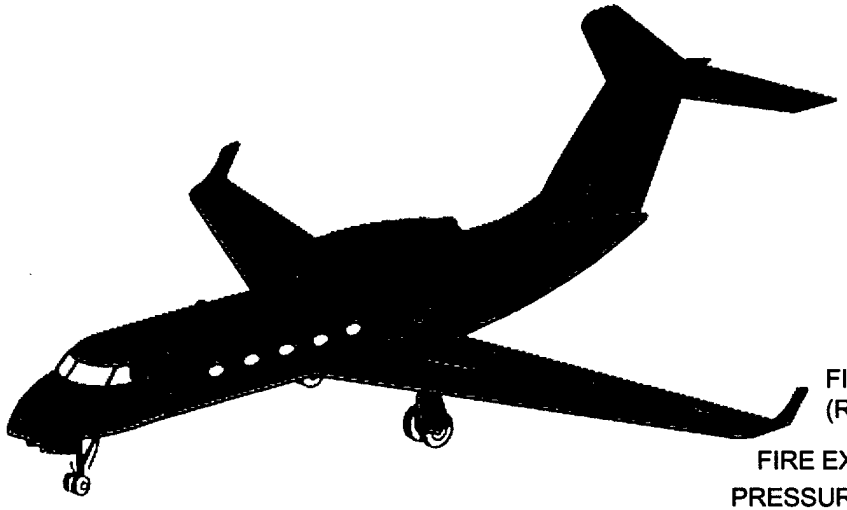



***Structural Material Usage by Weight***



# AIRFRAME MATERIALS, FLAMMABLE LIQUID, AND COMPONENTS

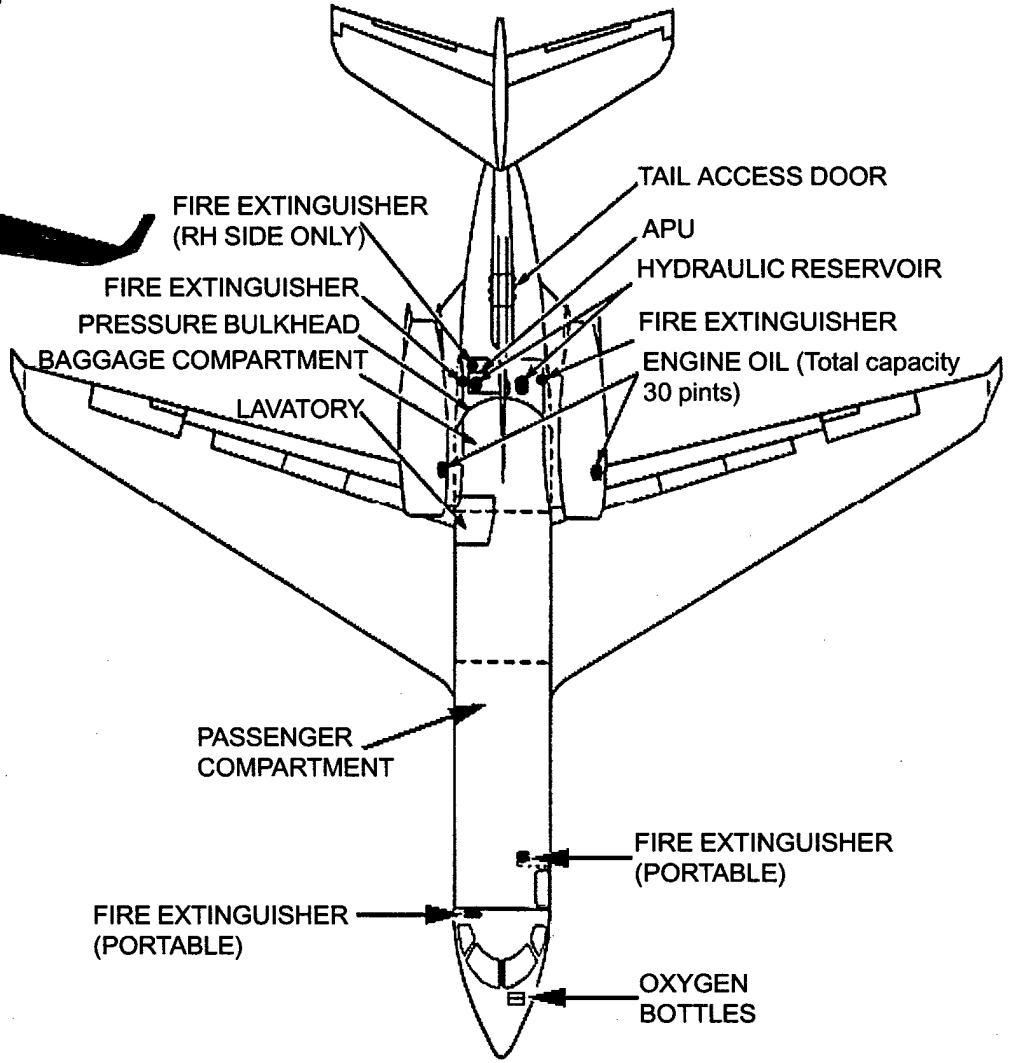




ALUMINUM

STEEL

GRAPHITE EPOXY



# AIRFRAME MATERIALS

STRUCTURE AND COMPOSITES



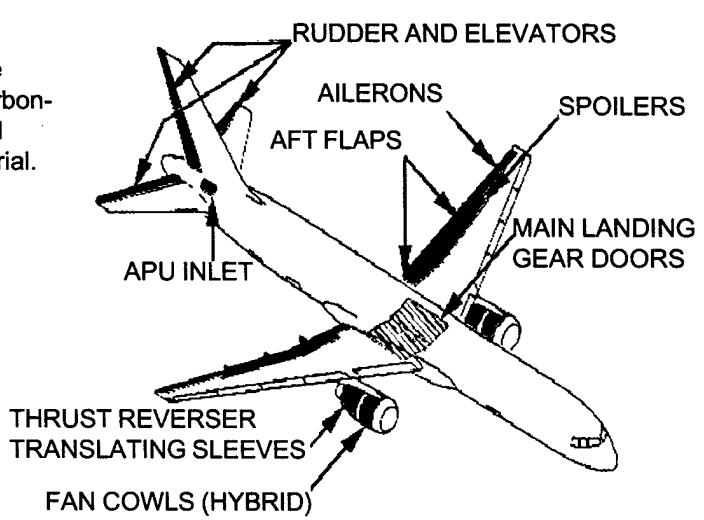
NOTE:

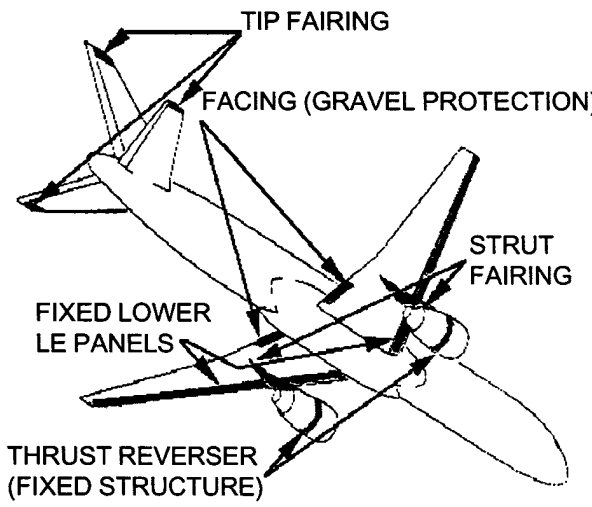
The airframe materials for the C-32A are titanium, titanium alloy, carbon fibre, carbon-reinforced aramid-fiberglass, aramid and carbon epoxy preimpregnated raw material.

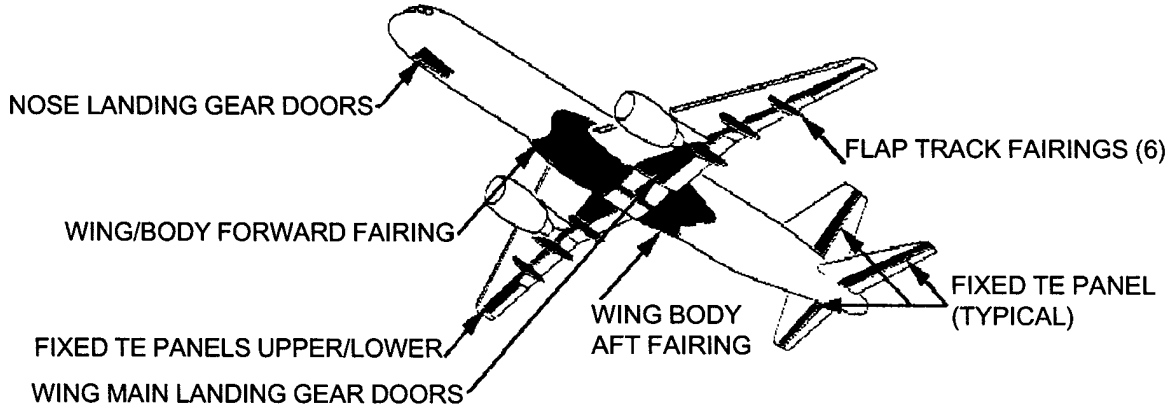
LEGEND:

LE Leading edge
TE Trailing edge

- CARBON-ARAMID (HYBRID)
- ARAMID
- CARBON-ARAMID-FIBERGLASS (HYBRID)



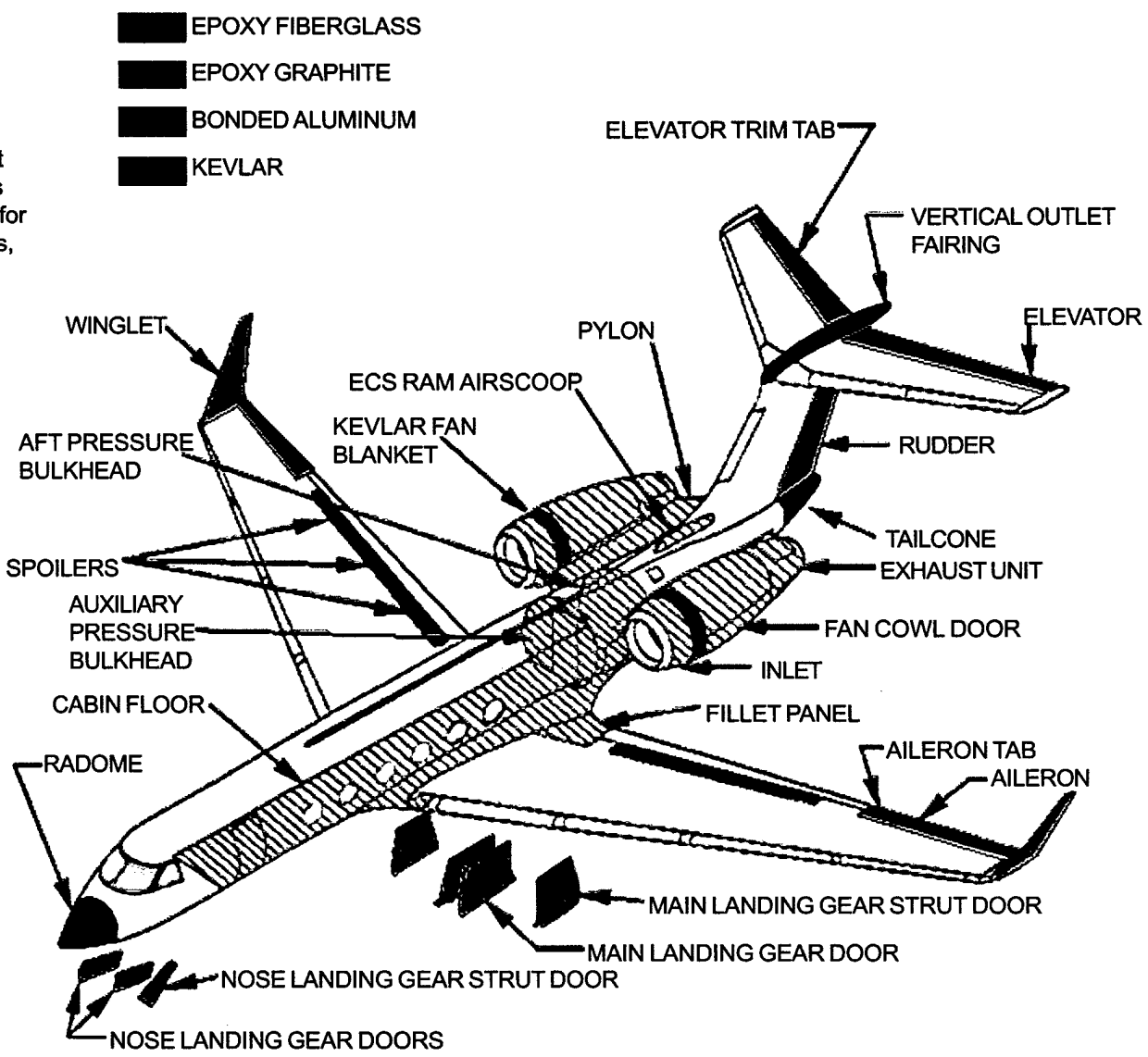



# COMPOSITE MATERIALS



NOTE:
Ailerons on A/C 521 & 542 are metal-riveted sheet metal.

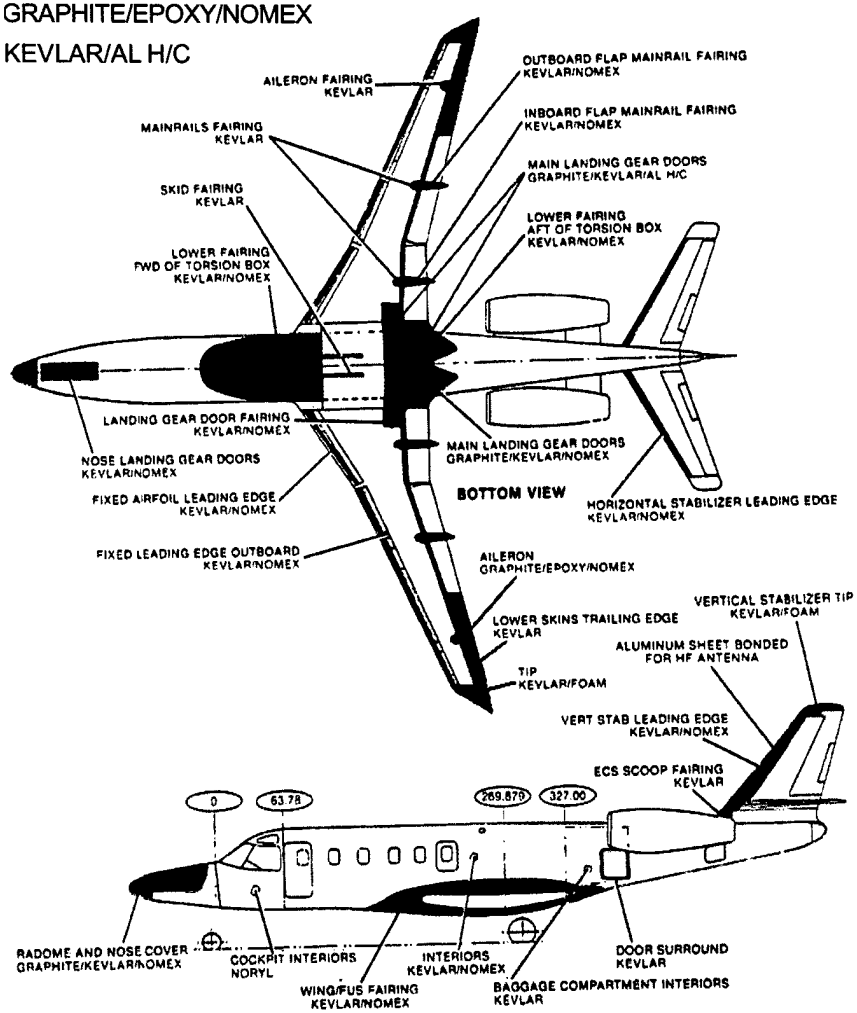
NOTE:
Composite materials are used extensively on this aircraft (Gulfstream V) to save weight and increase strength. Composite materials include metallic and non-metallic structures for bulkheads, doors, flight controls, floor panels, fairings, nacelles, panels, pylons, radome, tailcone, and winglets.

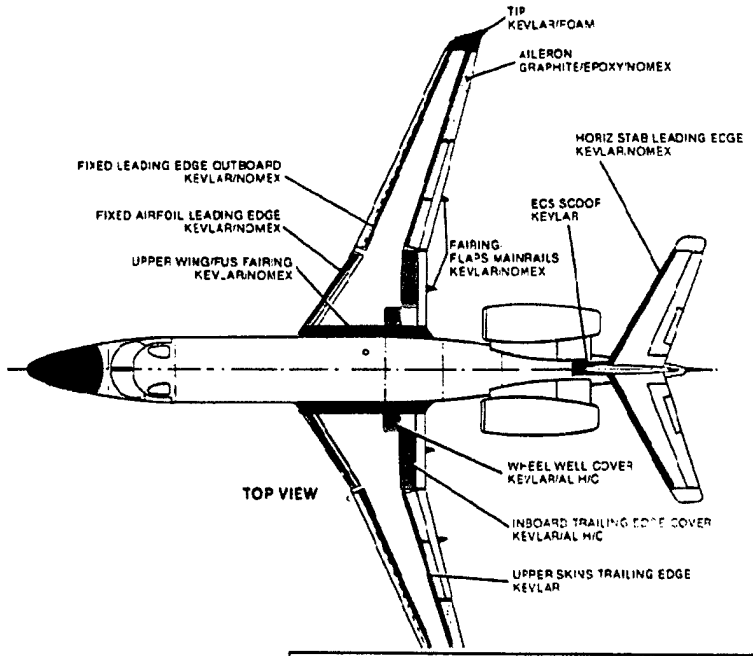


# COMPOSITE MATERIALS

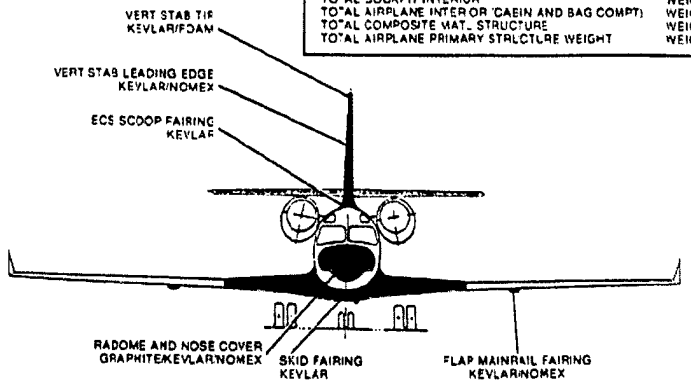


- KEVLAR/FOAM
- ALUMINUM SHEET BONDED
- KEVLAR
- GRAPHITE/KEVLAR/AL H/C
- GRAPHITE/KEVLAR/NOMEX
- KEVLAR/NOMEX
- GRAPHITE/EPOXY/NOMEX
- KEVLAR/AL H/C




| | | |
|---|---|---|
| TOTAL COCKPIT INTERIOR | WEIGHT = | 40 LB |
| TOTAL AIRPLANE INTERIOR (CABIN AND BAG COMPT) | WEIGHT = | 50 LB |
| TOTAL COMPOSITE MAT. STRUCTURE | WEIGHT = | 150 LB |
| TOTAL AIRPLANE PRIMARY STRUCTURE WEIGHT | WEIGHT = | 14,000 LB |



# GENERAL ARRANGEMENT



FOR RC-7B, O-5A, AND EO-5B MODELS

COMPOSITE MATERIALS INTERNAL LOCATIONS:

1) Armor plating located beneath and on the sides of the seats for the pilots and the workstations.

2) Avionics Auxiliary Rack located in the right forward portion of cabin area.

3) The left forward bulkhead in the cabin area.

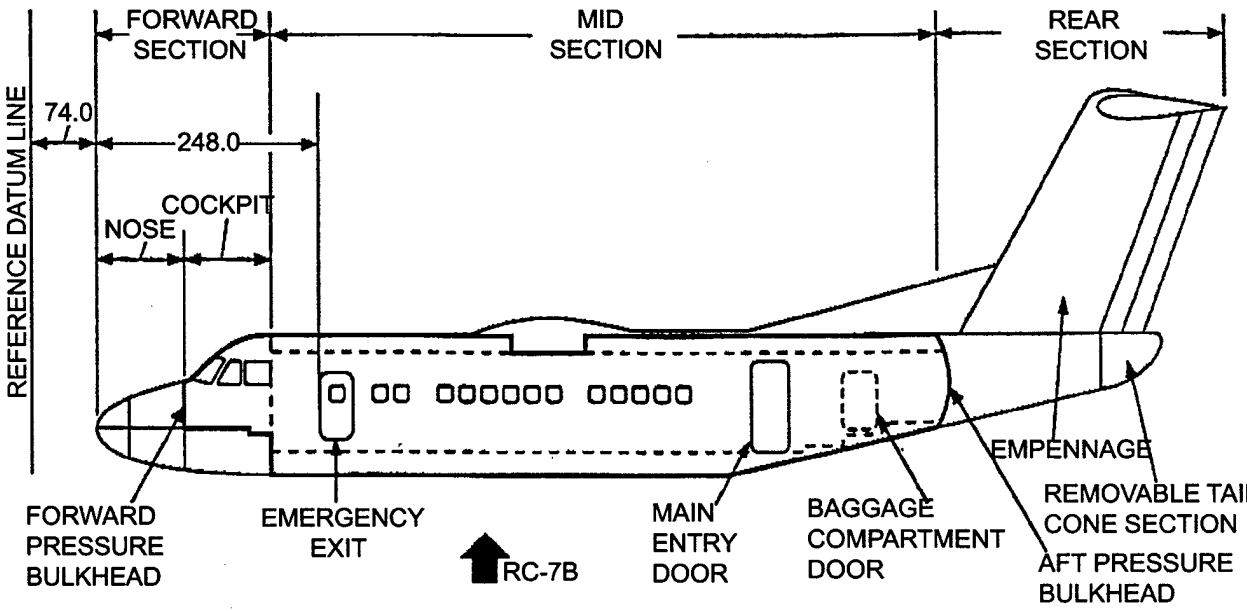
4) Equipment racks within the main cabin area.

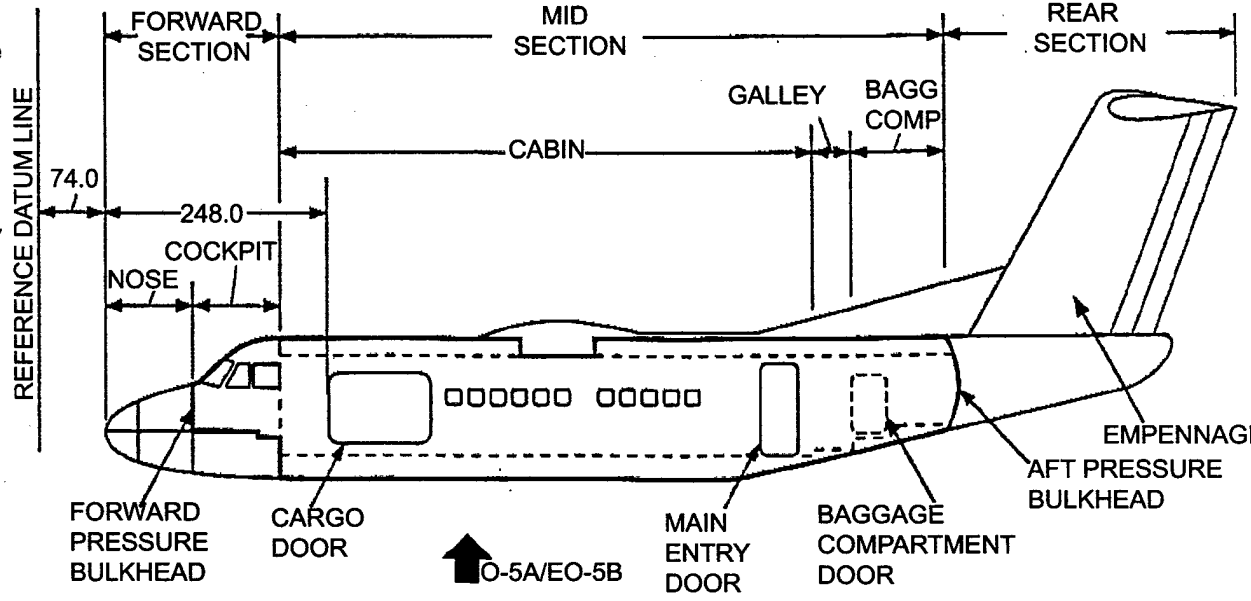
5) For the RC-7B, the wall panels around the portable lavatory.

6) For the RC-7B, the food storage/heating/ cooling unit located in the aft portion of the cabin area (that area normally considered the baggage compartment).

7) For the RC-7B, the spare lavatory tank storage unit located in the aft portion of the cabin area (that area normally considered the baggage compartment).

8) Avionics support structure located in the far aft portion of the cabin area (that area normally considered the baggage compartment).



# AIRFRAME MATERIALS



ALUMINUM

STEEL

OTHER-FIBERGLASS

NOTE:
Skin penetration points are similar to the E-3. See pages E-3 30/35.1, .2, & .3.

# AIRFRAME MATERIALS

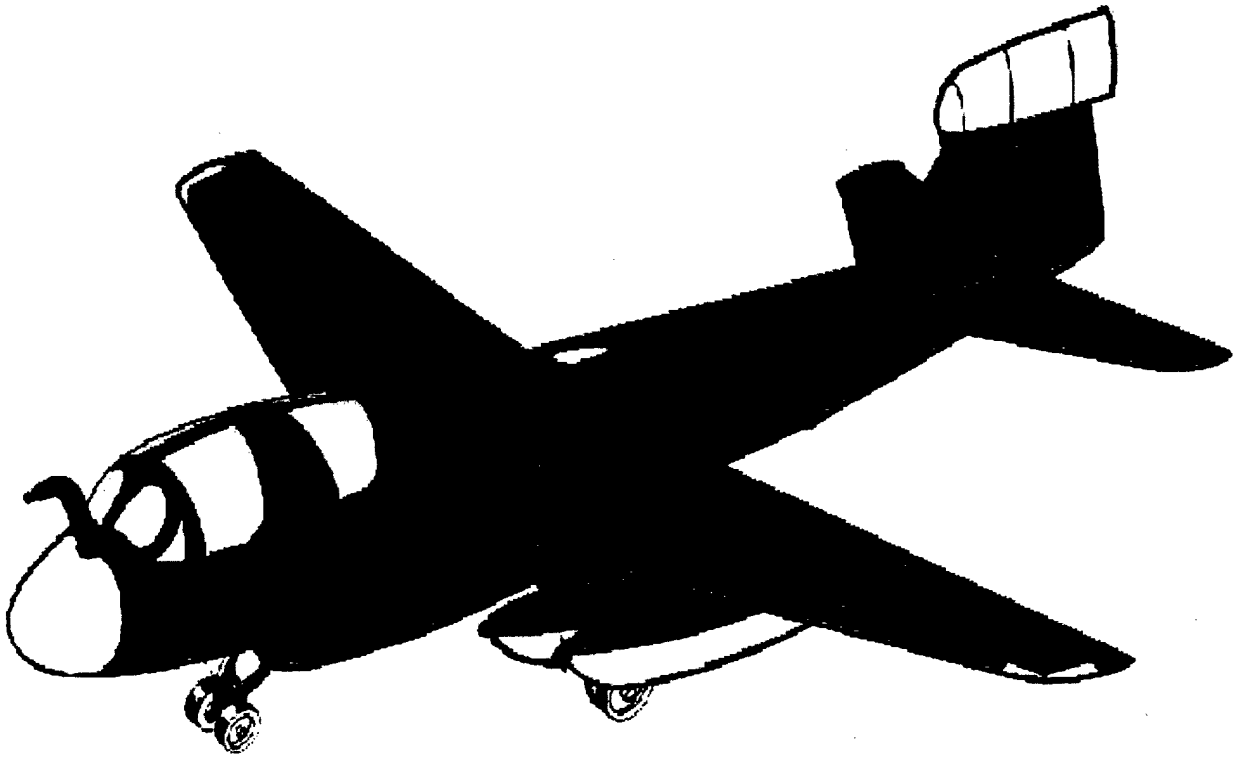


ALUMINUM

STEEL

OTHER

FIBERGLASS



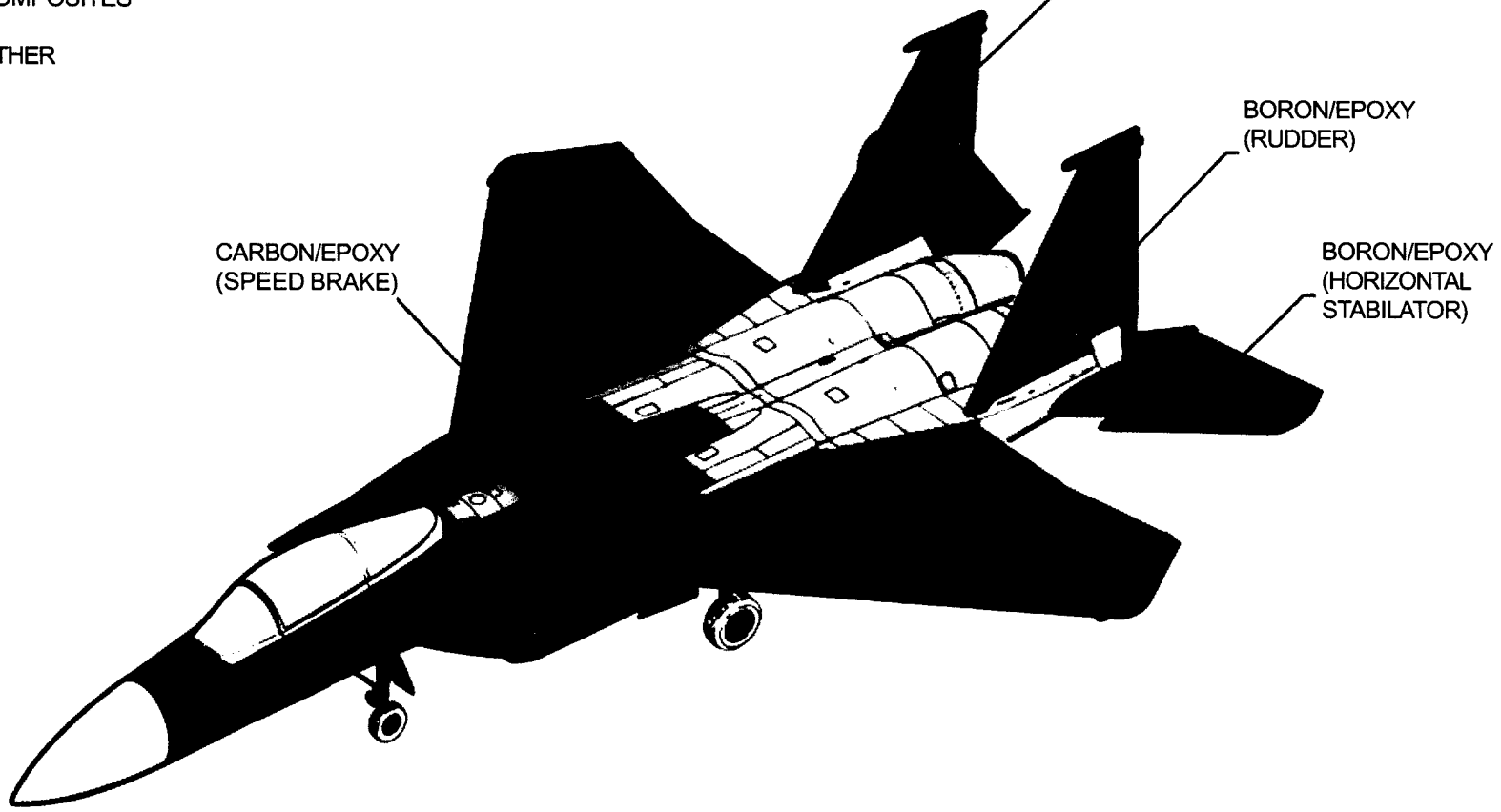
# AIRCRAFT HAZARDS

COMPOSITE APPLICATIONS





- ALUMINUM
- STEEL
- TITANIUM
- COMPOSITES
- OTHER

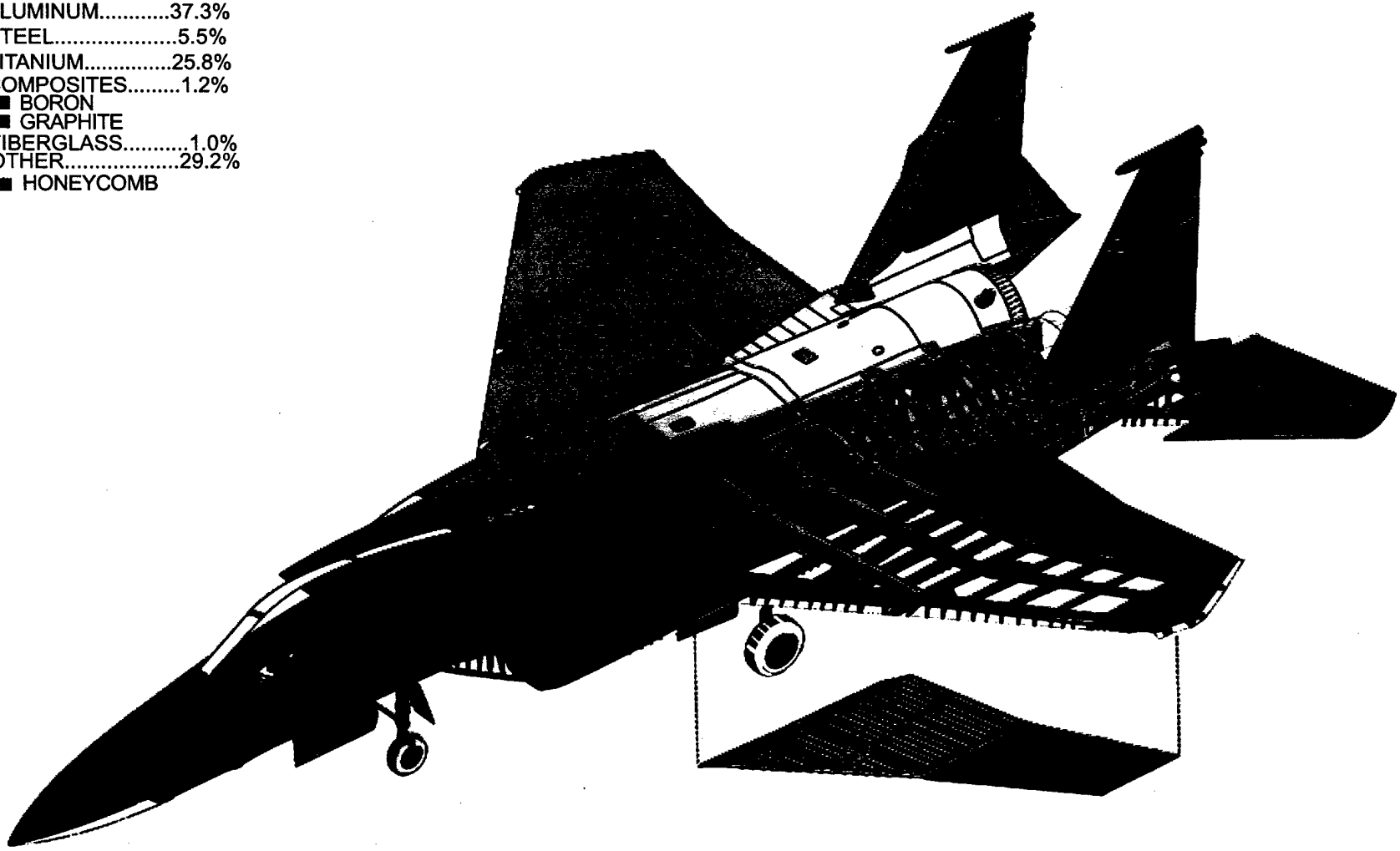


# AIRCRAFT HAZARDS-Continued



COMPOSITE/MATERIAL DISTRIBUTION

- ALUMINUM.....37.3%
- STEEL.....5.5%
- TITANIUM.....25.8%
- COMPOSITES.....1.2%
  - BORON
  - GRAPHITE
- FIBERGLASS.....1.0%
- OTHER.....29.2%
  - HONEYCOMB



# AIRFRAME MATERIALS





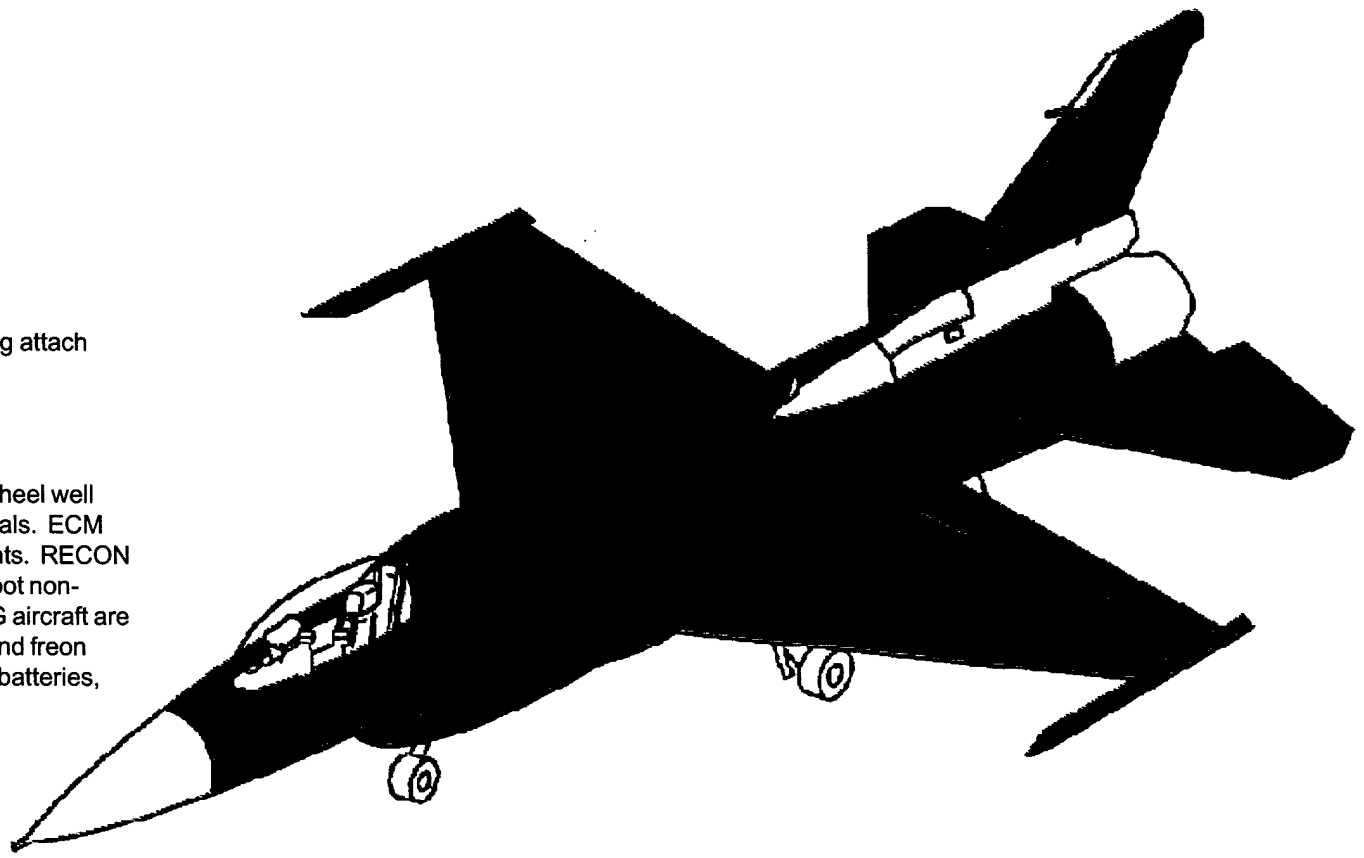
LEGEND

- ALUMINUM
- STEEL
- GRAPHITE/EPOXY
- OTHER/FIBERGLASS

NOTE:
Engine heat shield and lower wing attach fittings are Titanium.

**WARNING**

Latirn pods (2) have no access to wheel well area. Pods have radioactive materials. ECM pods have types of radioactive agents. RECON pod (block 30 aircraft only) are 15 foot non-jettisonable canoe shaped. 95 ANG aircraft are affected. Hazards are electronics and freon type coolant. It has no emissions, batteries, squibs or charges.



# AIRFRAME MATERIALS

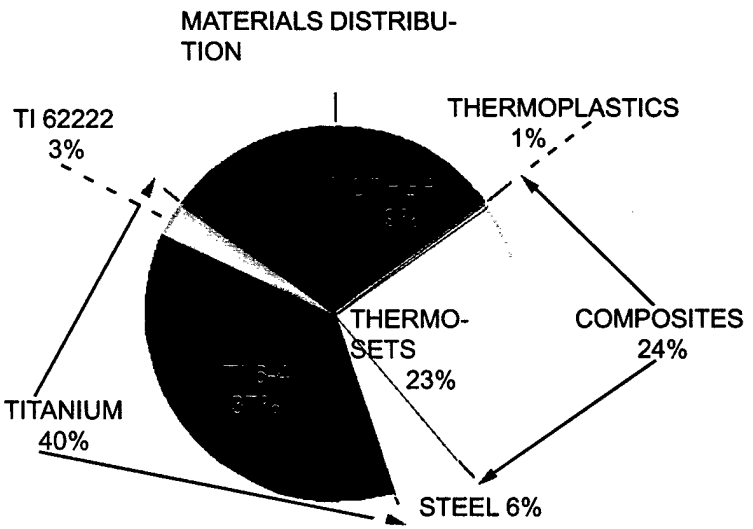




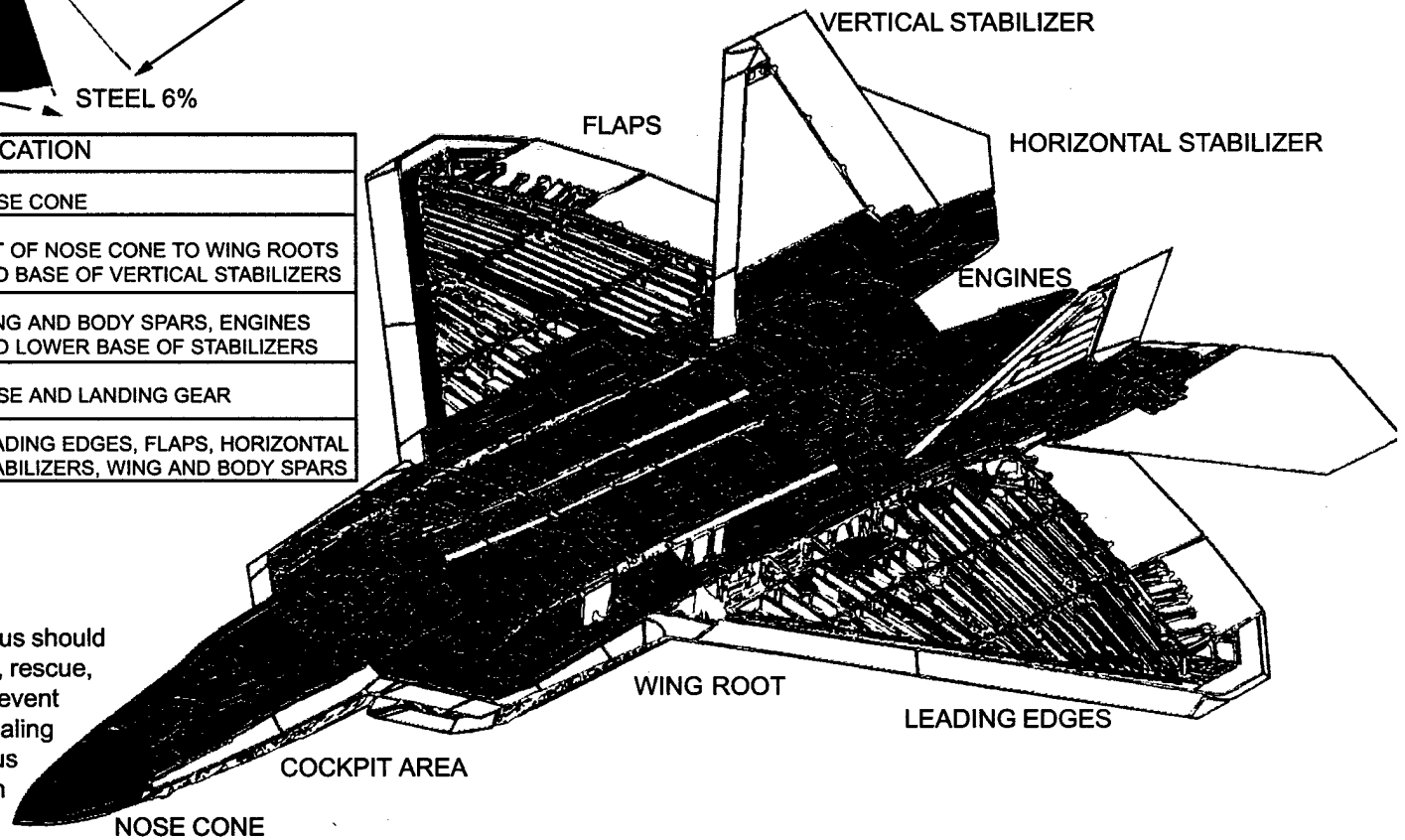


NOTE:

Organic composite structural laminates are made up of stacks of oriented thin lamina that consolidated under heat and pressure. Each lamina consists of a layer of high-strength, high-modulus, low-density reinforcing fibers embedded in a resin matrix. Fibers typically are materials such as carbon, boron, Kevlar 49, or fiberglass. The matrix can be either a thermosetting material such as epoxy, bismaleimide, or polyimide, or a thermoplastic material. If the matrix is thermosetting, a solid material is formed that cannot be reprocessed. Thermoplastic materials, however, can be reshaped by reheating and reforming.




| MATERIALS LOCATION | |
|---|---|
| OTHER | NOSE CONE |
| ALUMINUM | AFT OF NOSE CONE TO WING ROOTS AND BASE OF VERTICAL STABILIZERS |
| TI 6222 (TITANIUM)<br>TI 6-4 (TITANIUM) | WING AND BODY SPARS, ENGINES AND LOWER BASE OF STABILIZERS |
| STEEL | NOSE AND LANDING GEAR |
| THERMOPLASTICS (COMPOSITES)&<br>THERMOSETS (COMPOSITES) | LEADING EDGES, FLAPS, HORIZONTAL STABILIZERS, WING AND BODY SPARS |




**WARNING**

Self Contained Breathing Apparatus should always be worn during firefighting, rescue, and when removing bunkers to prevent respiratory complications from inhaling composite fibers and dust. Serious health problems will result through failure to observe this warning.

# HAZARDOUS/NON HAZARDOUS AIRFRAME MATERIALS AND DIMENSIONS

# F-117A

LEGEND

a. ALUMINUM - MAIN BODY

b. ALUMINUM - TITANIUM - AFT OF WING ROOTS

c. EPOXY FIBERGLASS - EDGES

d. GRAPHITE POLYETHERETHERKETONE (PEEK) - RUDDER, A PLASTIC THAT BURNS @ 600 DEGREES WITH TOXIC SMOKE

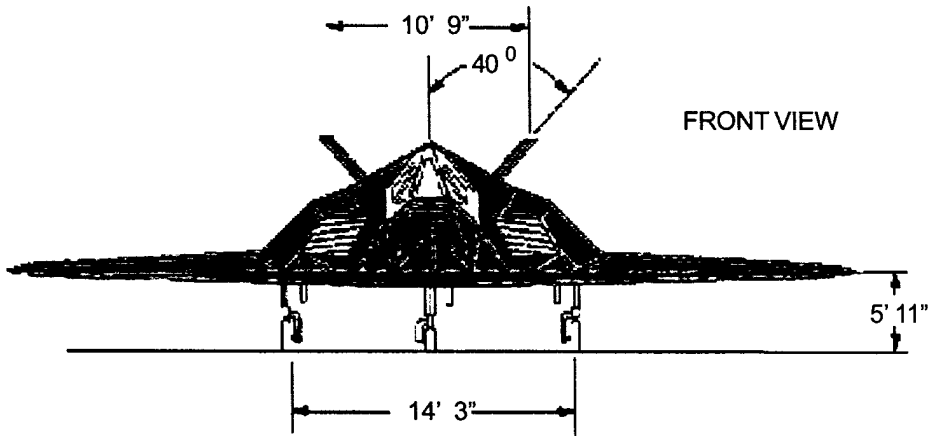
e. GRAPHITE EXPOXY - WEAPONS BAY DOOR

f. POLYIMID - AFT TRAILING EDGE - BURNS AT A HIGHER TEMPERATURE. > 600 DEGREES

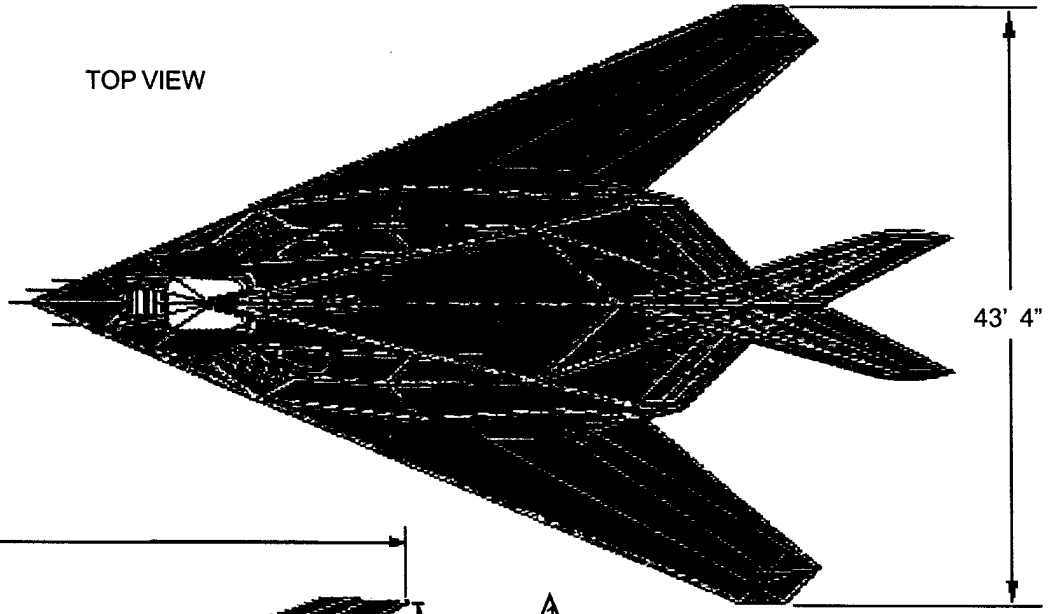
NOTE:
Composites comprise 5% or less of total structure.

NOTE:
Polyurethane plastic - paint coating.

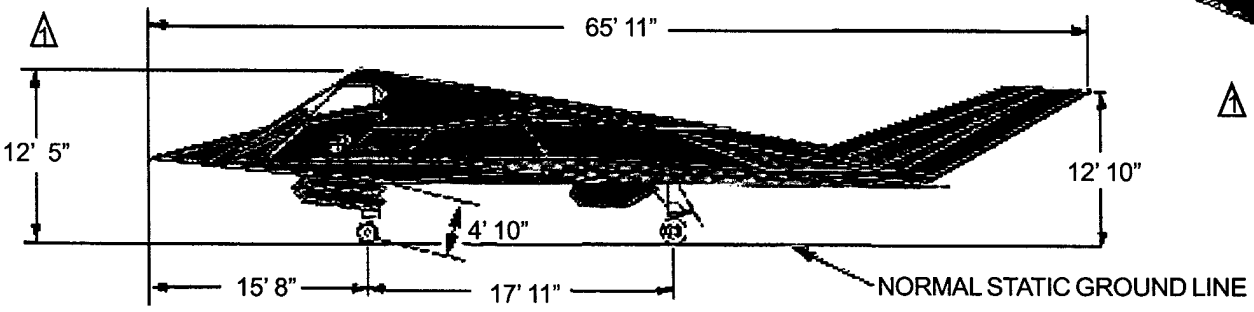
NOTE:
⚠1 Dimension shown (side view) is for nose and main gear struts inflated to 3 inch extension.




TOP VIEW



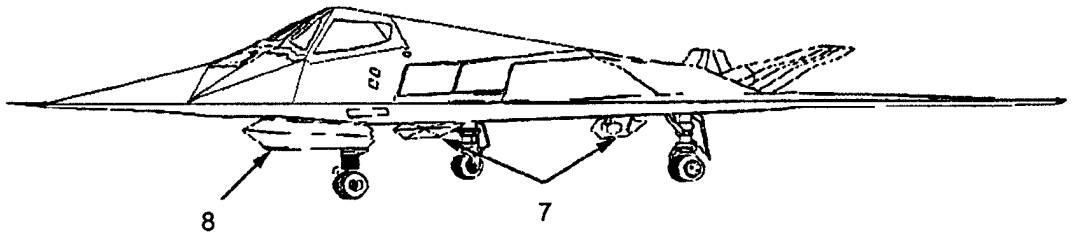

LEFT SIDE VIEW

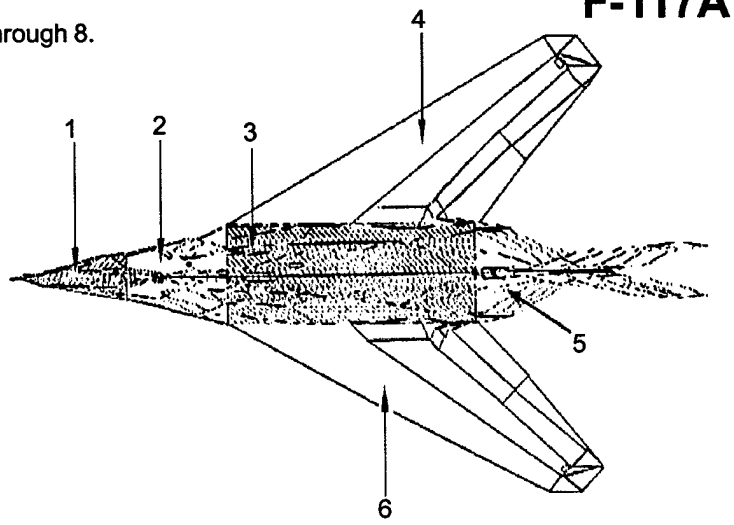


# HAZARDOUS BYPRODUCTS OF BURNING WRECKAGE

NOTE:
Aircraft areas identified by numbers 1 through 8.

**F-117A**



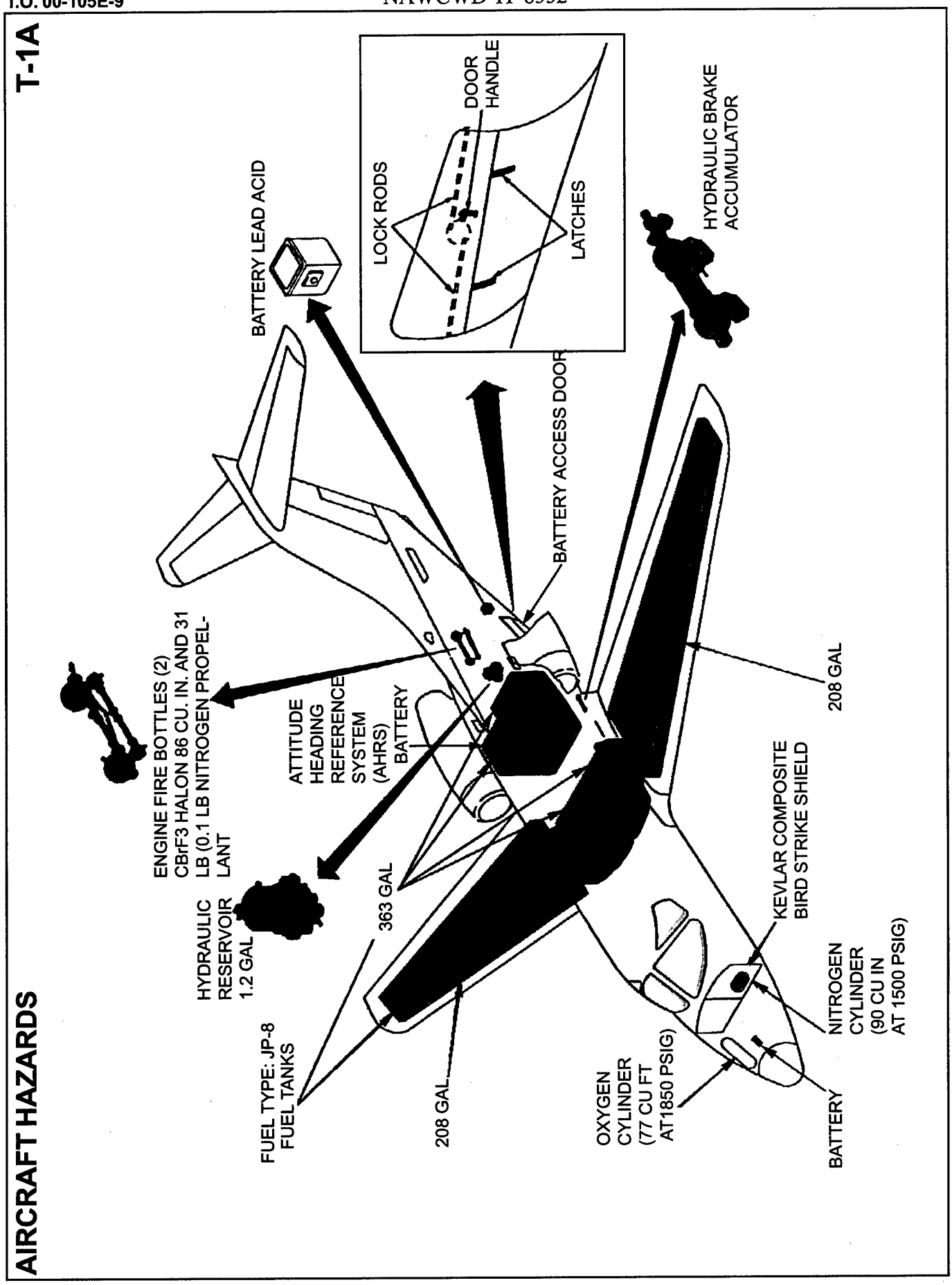

| GENERAL MATERIAL | SPECIFIC MATERIAL | AREA USED ON AIRCRAFT | BYPRODUCT |
|---|---|---|---|
| Fuel<br>Hydraulic fluids<br>Lubricants | Fuel, JP8<br>Oil, low temperature<br><br>Oil, synthetic<br>Molybdenum disulfide<br>Grease, various types<br>Fluid, hydraulic, various types | 3,4,5,6,7,8 | Carbon monoxide<br>Carbon dioxide<br>Sulfur oxides<br>Polynuclear aromatic hydrocarbons<br>Phosphorus oxides |
| Rubber (gaskets and tires)<br><br>Honey comb core<br>Plastics (gaskets, sleeving, electrical and thermal insulations, tubing, canopy, sheets, and parts | Neoprene<br>Chloroprene<br>Silicones<br>Fluorosilicones<br>Nitriles<br>Polyvinyl chloride<br>Nylons<br>Polyolefins<br>Teflons<br>Polyurethanes<br>Acrylic - polycarbonate<br>Viton, Phenolics, Bismaleimides, Epoxies, and Polysulfide | Throughout aircraft | Carbon monoxide<br>Carbon dioxide<br>Polynuclear aromatic hydrocarbons<br>Hydrochloric acid<br>Hydrofluoric acid<br>Nitrogen oxides<br>Hydrogen cyanide<br>Phosgene<br>Formaldehyde<br>Sulfur oxides |

# HAZARDOUS BYPRODUCTS OF BURNING WRECKAGE-Continued





| GENERAL MATERIAL | SPECIFIC MATERIAL | AREA USED ON AIRCRAFT | BYPRODUCT |
|---|---|---|---|
| Fabrics and fibers, natural and synthetic | Wool<br>Kevlar<br>Carbon fibers - epoxy coated<br>Glass fibers - aramid, epoxy, teflon, and polyester coated<br>Polyetherether ketone<br>Polysulfide<br>Cellulose | 1,2,3,4,5,6 | Hydrogen cyanide<br>Nitrogen oxides<br>Sulfur oxides<br>Carbon monoxide<br>Carbon dioxide<br>Polynuclear aromatic hydrocarbons<br>Hydrochloric acid<br>Hydrofluoric acid<br>Phosgene<br>Formaldehyde |
| Metal alloys - structural, fillers, bonding, and welding | Aluminum, Chrome, Copper, Gold, Iron, Steel, Lead, Silver, Tin, Titanium, Zinc, and Trace metals | Throughout aircraft | All may melt and resolidify. No hazardous emissions. |
| Blanket insulation and other ceramics | Fiberfrax, Fused ceramic powders | 1,3,5 | None |
| Adhesives<br>Sealants<br>Paint<br>Coatings | Polysulfides<br>Silicones<br>Flourosilicones<br>Epoxy<br>Polyurethane<br>Buena - N<br>Iron<br>Silver<br>Silicon dioxide<br>Strontium chromate<br>Lead chromate | Throughout aircraft | Hydrogen cyanide<br>Nitrogen oxides<br>Sulfur oxides<br>Carbon monoxide<br>Carbon dioxide<br>Polynuclear aromatic hydrocarbons<br>Hydrochloric acid<br>Hydrofluoric acid<br>Phosgene<br>Formaldehyde |


T-1A
AIRCRAFT HAZARDS
BATTERY LEAD ACID
LOCK RODS
DOOR HANDLE
LATCHES
HYDRAULIC BRAKE ACCUMULATOR
ENGINE FIRE BOTTLES (2) CBrF3 HALON 86 CU. IN. AND 31 LB (0.1 LB NITROGEN PROPEL-LANT
ATTITUDE HEADING REFERENCE SYSTEM (AHRS) BATTERY
BATTERY ACCESS DOOR
HYDRAULIC RESERVOIR 1.2 GAL
363 GAL
208 GAL
KEVLAR COMPOSITE BIRD STRIKE SHIELD
FUEL TYPE: JP-8 FUEL TANKS
208 GAL
OXYGEN CYLINDER (77 CU FT AT1850 PSIG)
NITROGEN CYLINDER (90 CU IN AT 1500 PSIG)
BATTERY

# AIRCRAFT GENERAL INFORMATION



GENERAL INFORMATION FOR ALL MODELS

1. The MD-11 Series and variants: is a medium/long range DC-10 follow on. Seating for 323 two class passengers and a maximum of 410. Two crew flightdeck. Crew door and three passenger doors each side, all eight of which open sliding inward and upward. Two freight holds in lower deck, forward and aft of wing, and one bulk cargo compartment in rear fuselage. Power plant is three Pratt & Whitney PW4460 turbofans or three General Electric CF6-80C2D1F turbofans.

2. MD-11-Combi is a cargo/passenger version. Seating for 168 to 240 passengers and 4 to 10 pallets. Common configuration 214.

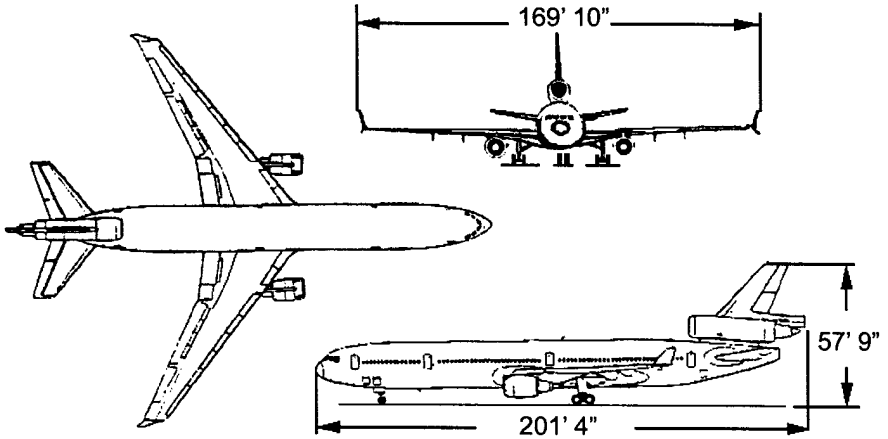
3. MD-11CF is a convertible freighter. Main deck cargo door at front on port side.

4. MD-11F is a all-freighter version.

5. MD-11C&D are tentatively planned for increased capacity.

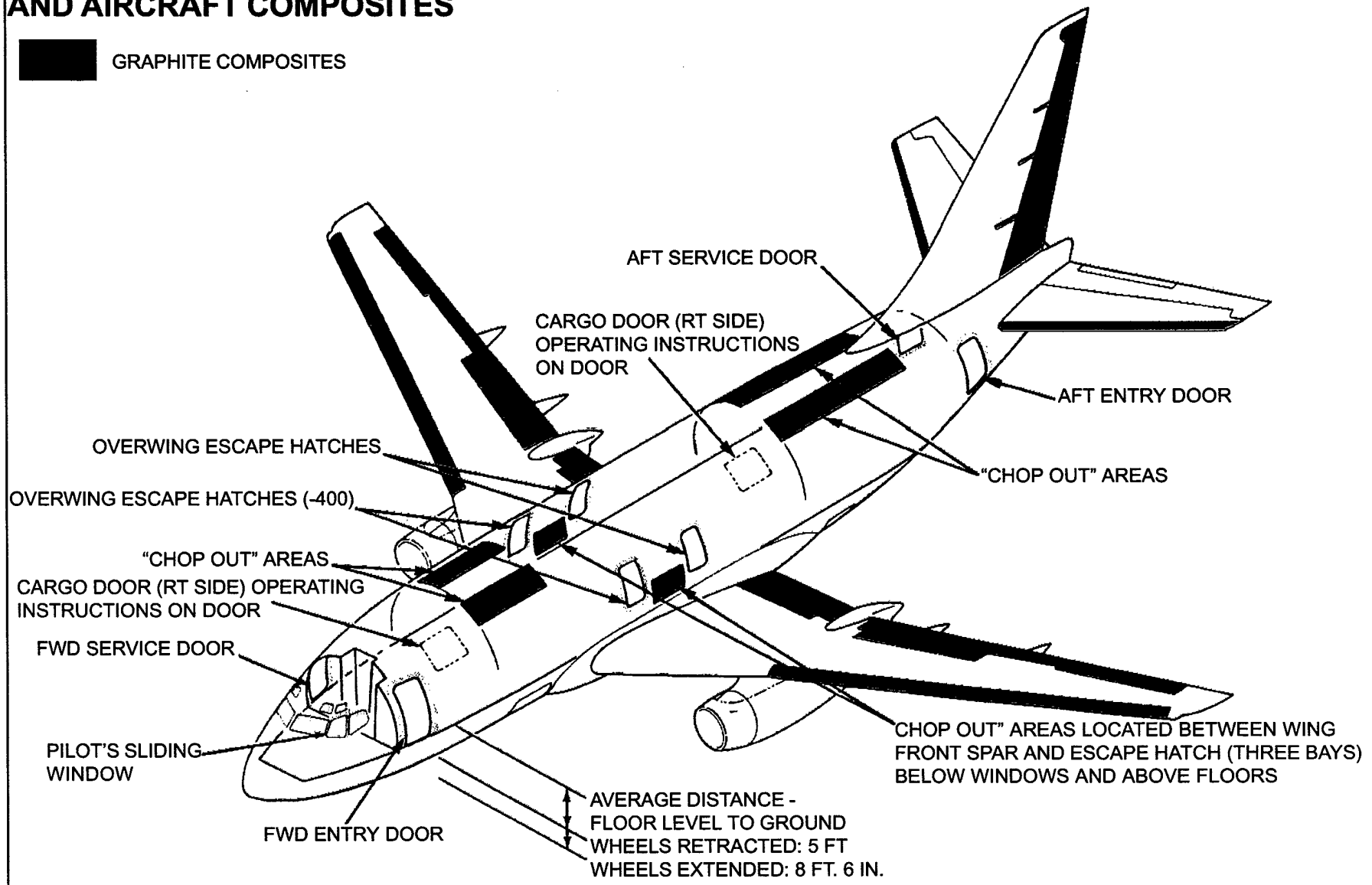
6. AIRCRAFT STRUCTURE
Composites used in virtually all control surfaces, engine inlets and cowlings, and wing/fuselage fillets; wing has two-spar structural box with chordwise ribs and skins with spanwise stifferners; upper winglet of ribs, spars and stiffened aluminum alloy skin with carbonfibre trailing edge; lower winglet carbonfibre; inboard ailerons have metal structure with composites skin; outboard ailerons all composites; inboard flaps composites-skinned metal; outboard flaps all-composites; spoilers aluminum honeycomb and composites skin; tailplane has CFRP trailing edge; and elevators CFRP.

NOTE:
AIRCRAFT DIMENSIONS
Length 201' 4"
Wing Span 169' 10"
Height 57' 9"



# EMERGENCY RESCUE ACCESS AND AIRCRAFT COMPOSITES





# AIRCRAFT COMPOSITE MATERIALS AND LOCATION



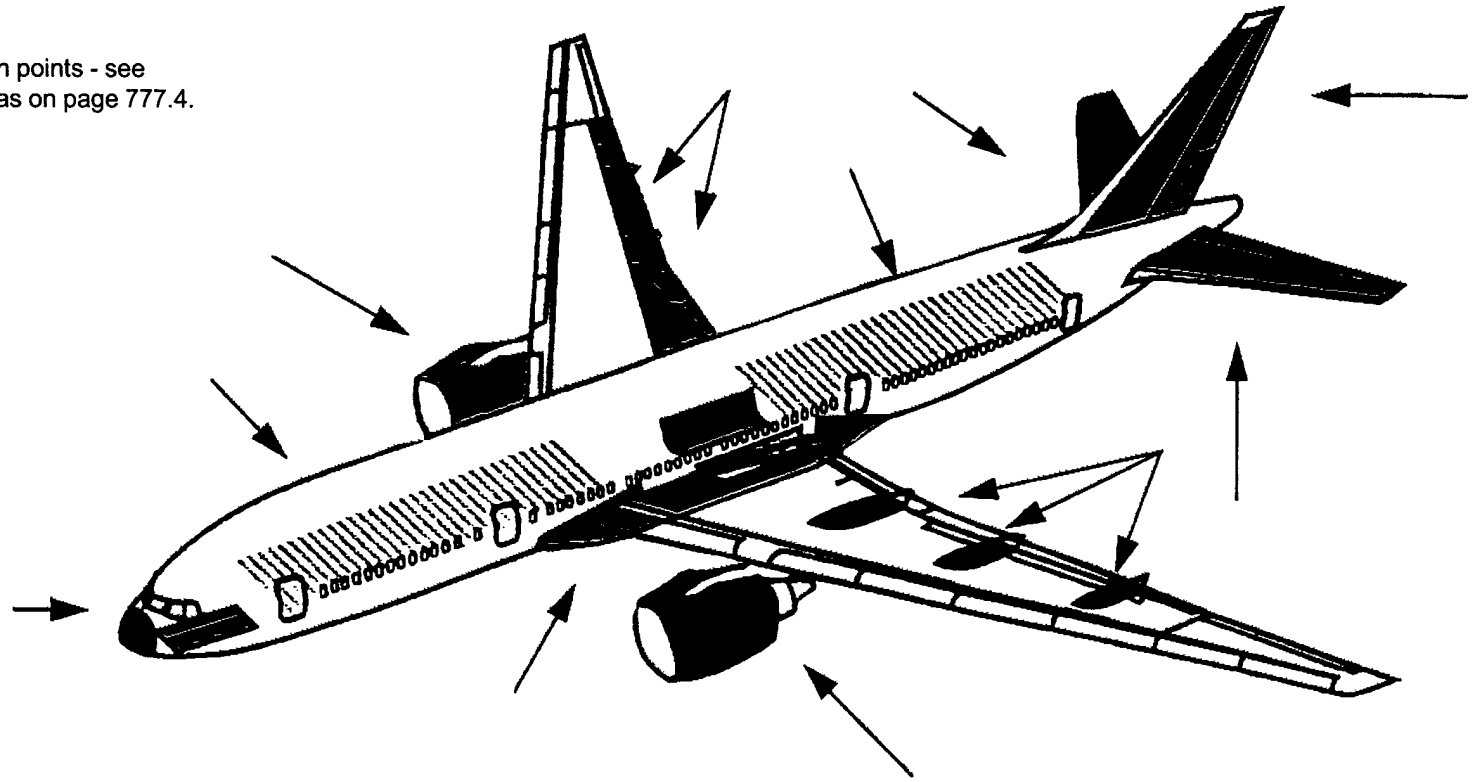
-200A/B & -300

Colored and arrowed areas indicate where the tough, lightweight plastics improve damage resistance and damage tolerance, and resist corrosion and fatigue. Nine (9) % of structural weight is composed of plastic, carbon fibers and graphite epoxy resin. Dust from composites can be a respiratory hazard.

AIRCRAFT DIMENSIONS:
-200 Length 209' 1"
-300 Length 242' 4"
Wing Span 199' 11"
Height 60' 2"
Wing Tip Length 21' 6"

NOTE:
Folding wing tips (optional) are illustrated in down position.

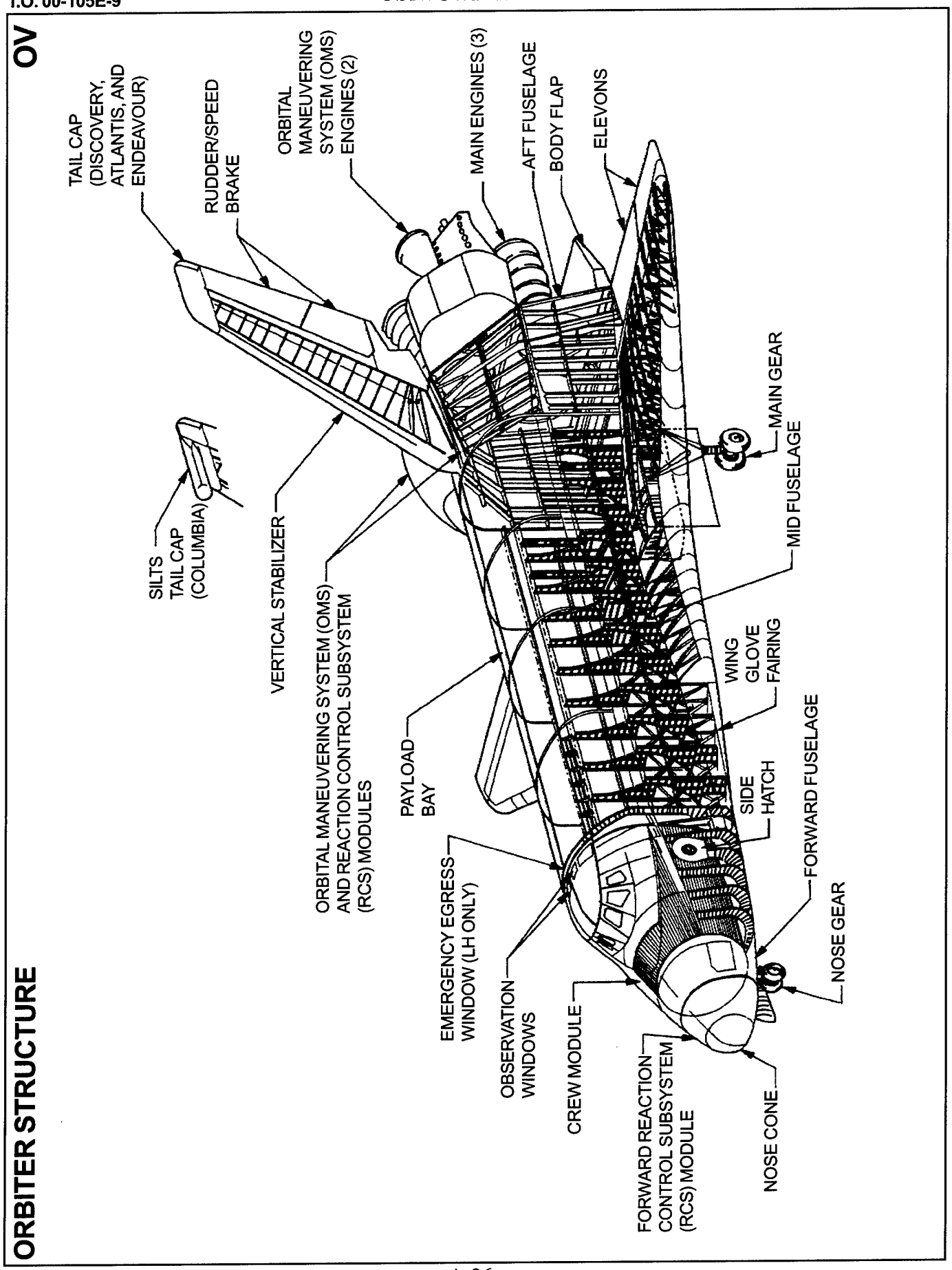
NOTE:
Skin penetration points - see "Chop Out" areas on page 777.4.



# DANGER AREAS/SAFETY PRECAUTIONS
# HAZARDOUS MATERIALS, FLUIDS & GASES



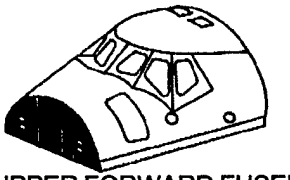
| DANGER AREA | PERSONNEL ACTION |
|---|---|
| CAUTION<br>Monomethylhydrazine ($CH_3NHNH_2$) in contact with metallic oxides or other oxidizing agents can ignite. | Do not park vehicles over metal drains. |
| NOTE:<br>Nitrogen tetroxide ($N_2O_4$) and monomethylhydrazine may be venting through the relief valves unless each system has been safed. | Stay upwind of venting gas. Wear protective clothing and recommended air breathing device. |
| Forward and aft reaction control subsystem (RCS) thruster nozzles and relief valve vent ports. | Stand clear. |
| Main landing gear/tires/wheels could explode. Peak temperatures may not be reached for 45 minutes. | Do not approach from the sides. |
| Main landing gear tire fire. Peak temperatures may be reached 45 minutes after a hard-braking landing which could ignite the rubber tires. | Approach upwind and apply large amounts of water to cool the brakes and to extinguish the burning tires. |
| Metals (composites)<br>Berylium: windshield frames, ET doors, and brake structure<br>Aluminum boron: truss members in the wing feed-through section<br>Epoxy boron: truss members of the main propulsion system thrust structure, aft fuselage<br><br>Although not easily ignited, these metals will burn at elevated temperatures and produce toxic compounds that are hazardous to health. | MET-L-X may be used on brake fires.<br><br>Exercise caution. Although small amounts of water accelerate these types of metal fires, rapid application of large amounts of water is effective in extinguishing these fires because of the cooling effect of water. If water or foam is used, wear complete protective clothing and NIOSH-approved positive pressure breathing equipment. |
| Fluids/gases are flammable and hazardous. | Exercise caution to prevent exposure. |
| External surfaces will be at elevated temperature. | Wear proper clothing to prevent injury. |
| Hydrogen overboard vents, 8-in. fill and drain, and 17-in. Orbiter/external tank (ET) disconnects. Autoignition may result from high surface temperatures. Note that the flame of pure hydrogen is invisible. | Exercise caution. |
| Switches. | Do not operate any switch other than those specifically identified. |
| Emergency egress window that is to be jettisoned (all vehicles). | Move to position out of range of debris. |
| Emergency jettison of the side entry/egress hatch (all vehicles). | Move to position out of range of jettisoned hatch. |
| Inadvertant deployment of drag chute after rollout (all vehicles). | Avoid area 10 degrees left and 47 degrees right of Orbiter centerline and 100 feet aft until pyrotechnic circuits are safed. |


OV
ORBITER STRUCTURE
TAIL CAP (DISCOVERY, ATLANTIS, AND ENDEAVOUR)
RUDDER/SPEED BRAKE
ORBITAL MANEUVERING SYSTEM (OMS) ENGINES (2)
MAIN ENGINES (3)
AFT FUSELAGE
BODY FLAP
ELEVONS
SILTS
TAIL CAP (COLUMBIA)
VERTICAL STABILIZER
ORBITAL MANEUVERING SYSTEM (OMS) AND REACTION CONTROL SUBSYSTEM (RCS) MODULES
PAYLOAD BAY
MAIN GEAR
MID FUSELAGE
WING GLOVE FAIRING
SIDE HATCH
FORWARD FUSELAGE
EMERGENCY EGRESS WINDOW (LH ONLY)
OBSERVATION WINDOWS
CREW MODULE
NOSE GEAR
FORWARD REACTION CONTROL SUBSYSTEM (RCS) MODULE
NOSE CONE

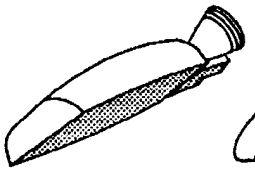
# ORBITER STRUCTURE-Continued

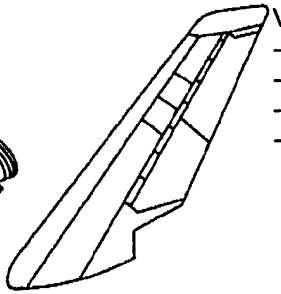




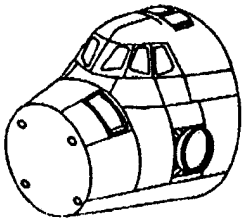


UPPER FORWARD FUSELAGE
- Skin and Stringer

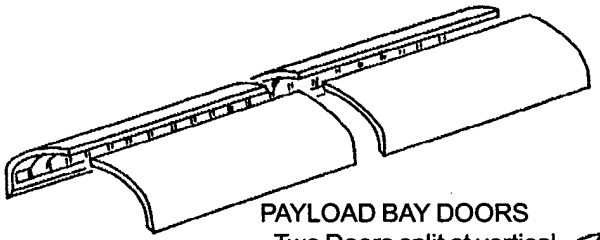




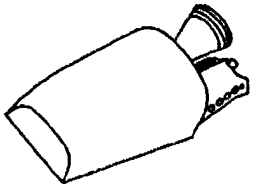
VERTICAL STABILIZER
- Skin and Stringer Fin Covers
- Honeycomb Rudder Cover
- Machined Spars
- Sheet Metal Ribs



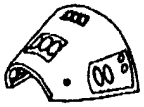
CREW MODULE (CABIN)
- Floating
- Welded Skin



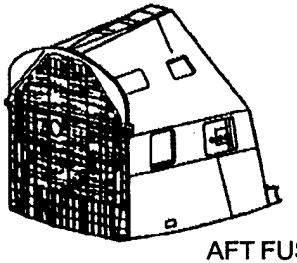
PAYLOAD BAY DOORS
- Two Doors split at vertical
- Graphite Epoxy



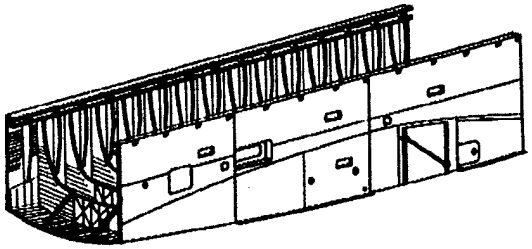
ORBITAL MANEUVERING SYSTEM (OMS)/REACTION CONTROL SUBSYSTEM (RCS) MODULE (TYPICAL)
- Skin and Stringer
- Graphite Epoxy and Milled Skin
- Titanium Thermal Barrier



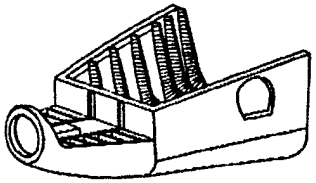
FORWARD REACTION CONTROL SUBSYSTEM (RCS) MODULE
- Skin and Stringer



BODY FLAP

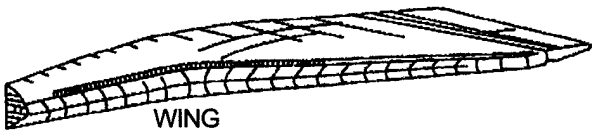


AFT FUSELAGE
- Integrally Machined Skin/ Stiffner Shell
- Titanium/Boron Epoxy Thrust Structure



LOWER FORWARD FUSELAGE
- Riveted Skin and Stringer

MID FORWARD FUSELAGE
- Skin and Stringer Honeycomb Panels



WING
- Skin and Stringer
- Web and Truss Spars

# ORBITER STRUCTURE AND SURFACE TEMPERATURES
# OV 102 COLUMBIA



- RCC- REINFORCED CARBON-CARBON
- HRSI- HIGH TEMPERTURE REUSABLE SURFACE INSULATION
- LRSI- LOW TEMPERATURE REUSABLE SURFACE INSULATION
- FRSI- FELT REUSABLE SURFACE INSULATION (NOMEX FELT)
- METAL OR GLASS
- AFRSI- ADVANCED FLEXIBLE REUSABLE SURFACE INSULATION (QUILTED)

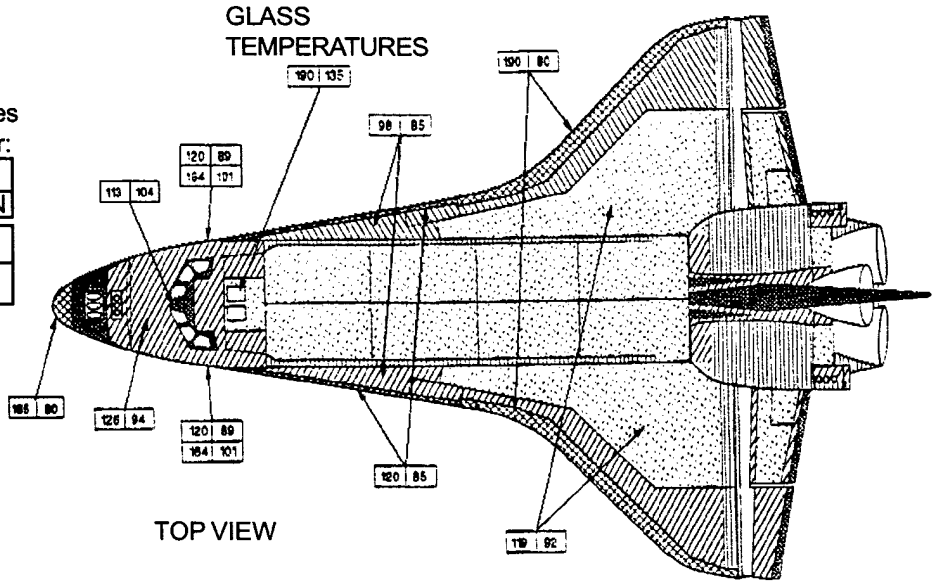
NOTE:

- Post touchdown temperatures of the orbiter are indicated in degrees fahrenheit in the following manner:

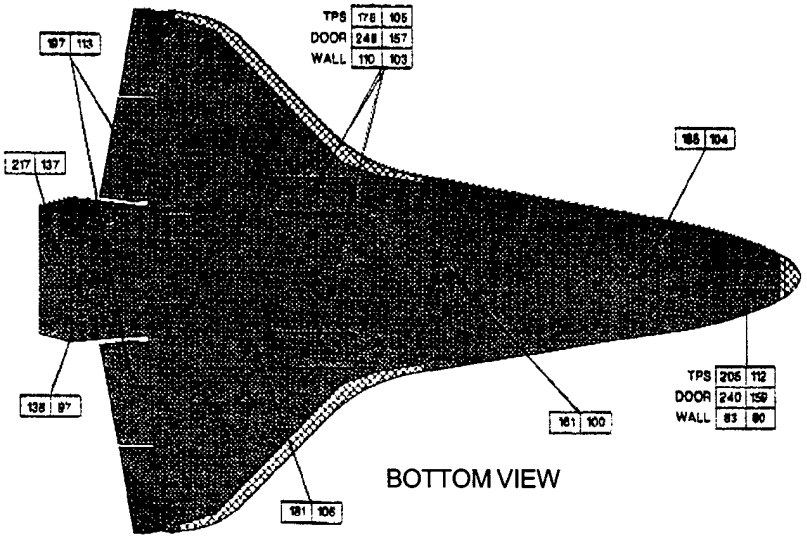
| COMPONENT MEASURED | TOUCHDOWN +4 MIN | TOUCHDOWN +30 MIN |
|---|---|---|
| THERMAL PROTECTION SYSTEM (TPS) - | | |
| STRUCTURE - | | |

- Single-level boxes indicate TPS temperature only.

GLASS TEMPERATURES

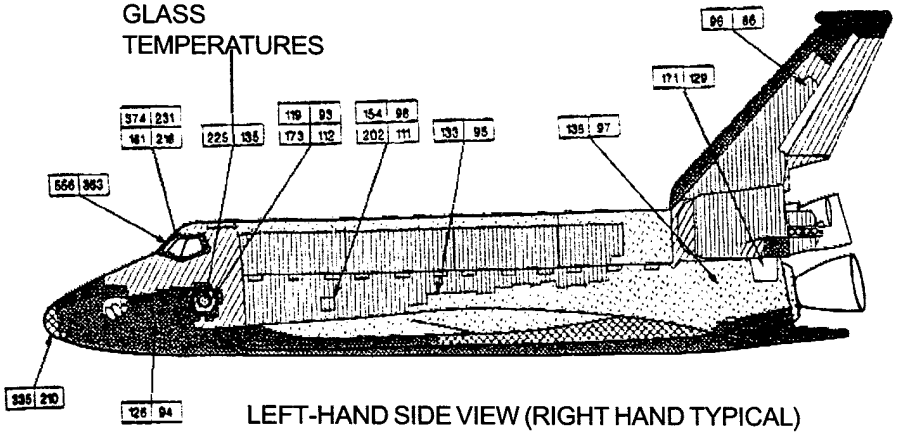



TOP VIEW




BOTTOM VIEW

GLASS TEMPERATURES




LEFT-HAND SIDE VIEW (RIGHT HAND TYPICAL)

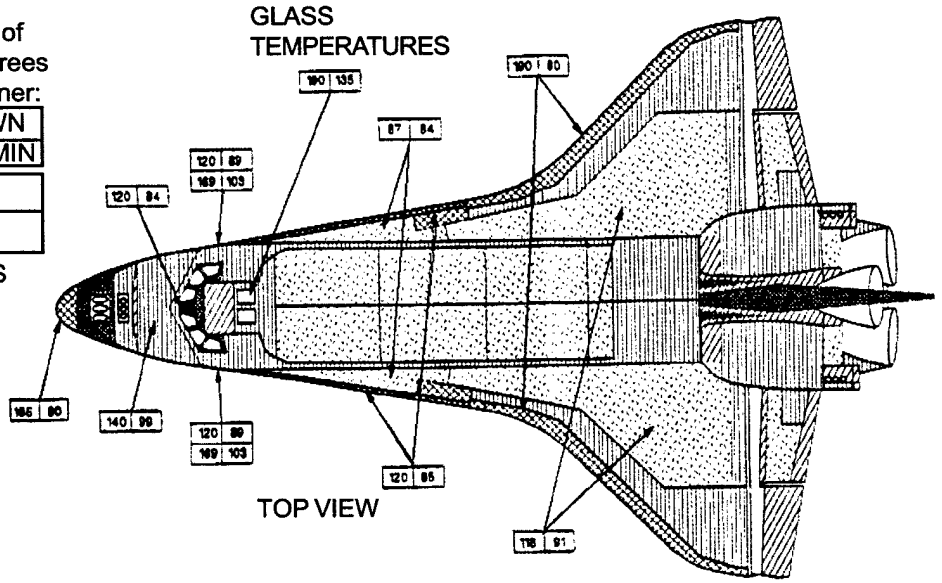
# ORBITER STRUCTURE AND SURFACE TEMPERATURES-Continued
# OV 103 DISCOVERY, OV 104 ATLANTIS, AND OV 105 ENDEAVOUR

- RCC- REINFORCED CARBON-CARBON
- HRSI- HIGH TEMPERTURE REUSABLE SURFACE INSULATION
- LRSI- LOW TEMPERATURE REUSABLE SURFACE INSULATION
- FRSI- FELT REUSABLE SURFACE INSULATION (NOMEX FELT)
- METAL OR GLASS
- AFRSI- ADVANCED FLEXIBLE REUSABLE SURFACE INSULATION (QUILTED)

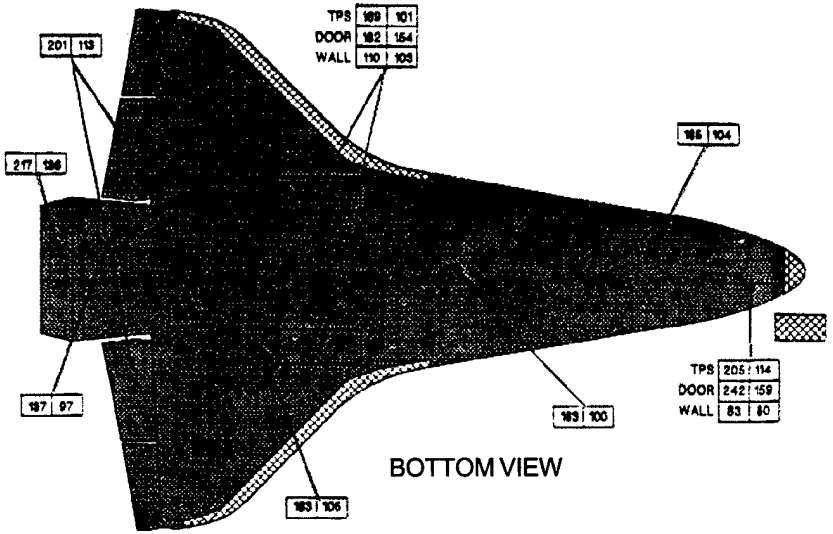
NOTE:
- Post touchdown temperatures of the orbiter are indicated in degrees fahrenheit in the following manner:

| COMPONENT MEASURED | TOUCHDOWN +4 MIN | TOUCHDOWN +30 MIN |
|---|---|---|
| THERMAL PROTECTION SYSTEM (TPS) - | | |
| STRUCTURE - | | |

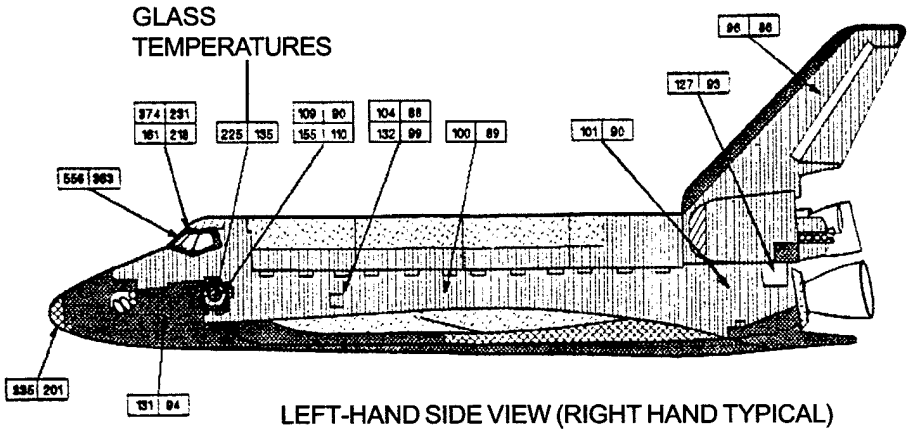
- Single-level boxes indicate TPS temperature only.




TOP VIEW




BOTTOM VIEW




LEFT-HAND SIDE VIEW (RIGHT HAND TYPICAL)

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## Appendix B

## MISHAP RESPONSE CHECKLIST FOR ADVANCED AEROSPACE MATERIALS/COMPOSITES

This appendix is a checklist taken from a USAF, Advanced Composites Program Office report: *Mishap Response Checklist for Advanced Aerospace Materials/Composites*, by J.M. Olson. McClellan Air Force Base, California, 1993.

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## COMPOSITE MISHAP RAPID-RESPONSE CHECKLIST

1. Conduct an initial survey
2. Establish site control
3. Evacuate from smoke plume/Alter flight operations/restrict downwind assembly
4. Extinguish fire and cool to 300°F/ ONLY firefighters w/SCBA until fire safe
5. No helicopters or low-flying aircraft - 500 feet AGL and 1000 feet horizontally
6. Cordon off mishap site w/single entry/exit and establish peripheral area
7. Advise populace on actions
8. Enter mishap site and coordinate with EOD
9. Identify specific aircraft hazards and requirements
10. Advise on-scene-commander of findings/recommendations
11. Avoid disturbance of fibers/particulates by site-traffic/clean footwear
12. Remove contaminants (w/HEPA vacuum or brushes) when exiting site
13. Establish clean sites/areas/rooms
14. No eating, drinking, or smoking is permitted and wash thoroughly before eat/drink/smoke
15. Remove clothing and shower in cool water before going off-duty
16. Remove contaminated clothing (if possible) from victims/personnel before medical help
17. Advise medical personnel of ill/exposure effects and symptoms
18. Properly dispose of clothing and launder clothing properly

### Containment

19. Temporarily secure particulates/fibers/ash with AFFF or water mist
20. Consult aircraft authority/investigators - Apply fixant solution
21. Wrap parts in plastic film or sheet and secure with tape
22. Apply preservation tape to non-fire/crash damaged parts/material and label
23. Use soil tackifiers if necessary
24. Clean improved surfaces, collect effluent, avoid sweeping
25. Flush or clean fixant application equipment
26. Pad sharp projections with foam

### Cleanup and Disposal

27. Dispose materials w/in local, state, federal, and international guidelines and regulations
28. Properly dispose of hazardous waste and demilitarize materials if necessary
29. Properly clean open terrain mishap areas
30. Properly clean aircraft if necessary
31. Properly clean affected structures and equipment if necessary
32. Monitor affected personnel, equipment, and mishap site

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## Appendix C

## RESPONSE TO AIRCRAFT MISHAPS INVOLVING COMPOSITE MATERIALS (INTERIM GUIDANCE): CHECKLIST

This appendix is a checklist taken from Consultative Letter AL-OE-BR-CL-1998-0108 of the USAF Institute for Environment, Safety, and Occupational Health Risk Analysis, Industrial Hygiene Branch: "Industrial Hygiene Branch Field Guide: Response to Aircraft Mishaps Involving Composite Materials (Interim Guidance)." Brooks Air Force Base, Texas, 1998.

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## CHECKLIST FOR RESPONSE TO AIRCRAFT MISHAPS INVOLVING COMPOSITE MATERIALS

1. Have wind direction and speed been recorded?
2. Has an entry control point been established where contaminated protective gear can be removed?
3. Has EOD safed the area for entry by other teams?
4. Have downwind areas been notified to keep windows/doors shut and remain indoors if not evacuated due to fire and smoke plume?
5. Have helicopters been restricted from the area to avoid fiber and dust re-suspension?
6. Have potential composite material locations been identified? (contact Structural Maintenance personnel, the SPO or SPD, or review the weapon-specific technical orders)
7. Have other hazards been identified, such as large quantities of spilled jet fuel or location of radioactive parts, such as depleted uranium?
8. Are HEPA vacuums available if parts, equipment, or protective equipment need decontamination? (HEPA vacuums are the best method to remove residual dusts; possible sources are the Asbestos Removal Team and Structural Maintenance)
9. Is the entry control point controlled for contaminated personnel? Are protective garments removed before passing through?
10. Has an on-site assessment been made of the quantity of exposed composite materials?
11. Are Bioenvironmental Engineering personnel properly outfitted with protective equipment?
12. Are initial site entry teams outfitted with the proper protective equipment? (SCBA, fire-fighting suits)
13. Are recovery site entry teams outfitted with the proper protective equipment? (air-purifying respirator with N100 filters, Tyvek® suit with hood, inner nitrile/outer leather gloves, steel toe work boots [steel shank if boron fibers present], safety goggles).
14. Are entry teams briefed on potential hazards?
15. Are the following sampling equipment and supplies available?
    a. Air sampling pumps
    b. Air flow calibrator
    c. Respirable dust cyclones
    d. Inhalable dust samplers (such as the IOM sampler or modified 37-mm cassettes)
    e. Analytical balance with 1 mg sensitivity (possible locations: PMEL, Fuels Laboratory)
    f. 5-mm polyvinyl chloride (PVC) filters in 37-mm cassettes
    g. 0.8-mm mixed cellulose ester (MCE) filters in 25-mm cassettes with black anti-static cowling
    h. Tygon/rubber tubing
    i. Tripod or mounting stand for area samples
    j. NIOSH Manual of Analytical Methods: Methods 0600, 0500, and 7400
16. Are sampling pumps calibrated, media attached, and pumps placed on the most likely exposed workers?
17. Are area samplers placed 2000 feet upwind in a representative area?

18. Have aircraft parts cooled and a fixant (such as floor wax) been sprayed on exposed, suspected composite material parts? (this may be delayed or ruled inappropriate by aircraft crash investigators based upon their needs and requirements; plastic sheeting may also be used to control spread of fibers and dust)
19. Has a soil tackifier been applied if necessary?
20. Is eating and drinking restricted from the site?
21. Have workers been told to shower at the earliest opportunity to wash off any residual fibers?
22. Has a list of response personnel been collected in the event medical monitoring is needed?
23. Are all areas known to be contaminated with composite fibers adequately cleaned?
24. Have waste disposal procedures for waste composite materials, generated during recovery, been coordinated with Civil Engineering?

# Appendix D

## COMPOSITE MISHAP RAPID-RESPONSE CHECKLIST

This appendix is a checklist taken from a USAF report: *Aircraft Emergency Rescue Information (Fire Protection)*, Technical Order 00-105E-9, Revision 3, 15 January 2001.

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## COMPOSITE MISHAP RAPID-RESPONSE CHECKLIST

1. Initial Response Element
   a. Conduct an initial survey.
   b. Establish site control.
   c. Evacuate from smoke plume/alter flight operations/ restrict downwind assembly.
   d. Extinguish fire and cool to 300 degrees (149°C). Only fire fighters with SCBA in the area until fire safe.
   e. No flying or taxing ground operations – 500 'AGL and 1000' horizontally.
   f. Cordon off site with single entry/exit point.
   g. Advise populace on actions.
   h. Enter site, identify hazards, and avoid disturbance.
   i. Follow entry and exit guidelines.
   j. Temporarily secure small particulates/fibers/ash with water mist.

2. Containment:
   a. Properly secure composite materials.
   b. Use soil tackifiers, if necessary.
   c. Clean improved surfaces; collect effluent. Avoid sweeping.
   d. Flush or clean fixant application equipment.
   e. Pad sharp projections.
   f. Decontaminate vehicle/equipment.

3. Clean-up and Disposal:
   a. Dispose materials within local, state, federal, and international guidelines and regulations.
   b. Properly dispose of hazardous waste/de-militarize materials, if necessary.
   c. Properly clean open terrain mishap areas.
   d. Properly clean aircraft.
   e. Properly clean affected structures/equipment.
   f. Monitor affected personnel, equipment, site.

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# Appendix E

## STANDARD OPERATING GUIDELINES/CHECKLIST FOR FIRE INCIDENTS INVOLVING ADVANCED COMPOSITE MATERIALS

This appendix comprises guidelines and a checklist from *Aircraft Accidents: A Survival Guide for Responders*, by J. R. Anderson. Butte College, Oroville, California, 2000.

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## STANDARD OPERATING GUIDELINES/CHECKLIST

1. Size up the situation. Identify aircraft and/or cargo ASAP.
2. Continue to reassess/update your size up throughout the incident.
3. Establish control at the incident site using an Incident Command System.
4. Assess wind direction and speed
5. Employ appropriate firefighting and rescue tactics based upon the nature of this specific situation.
6. Avoid high-pressure straight streams directed at the burning composites if at all possible. (Minimize breakup and spread suspected composite fiber particles).
7. Try to determine or identify presence of composite materials. Note and advise
8. Dispatch and other responders the spread/direction of heavy smoke, ash, or suspected composite particles.
9. Have Dispatch make contact with FAA as soon as possible. They should ask help from the FAA to obtain:
    a. Aircraft type & owner I.D.
    b. Presence of composites (if known)
    c. Type of cargo (if known)
    d. ETA of personnel from FAA, Military (if applicable) and owning agency/person of involved aircraft.
10. As responding support agencies arrive on scene have them sign the roster at I.C. location. (Establish a Unified Incident Command as soon as possible).
11. Conduct thorough briefings to support agencies on a regular basis, or if the situation changes significantly.
12. Suggest down wind and lateral evacuation of smoke plume based upon your judgment.
13. No aircraft ground or flight operations should be permitted within a minimum 1000 ft. radius and 500 feet above the incident site. These distances may be increased based upon your judgment
14. As soon as possible have all non-firefighting vehicles relocate to a safe area away from the incident.
15. Minimize foot and vehicular traffic within the debris area to prevent spread of composite ash or residue.
16. Isolate the incident site as best as possible
17. Set up a Hot Zone (Exclusion Zone) Based upon your I.D.H.A (Identification and Hazard Assessment)
18. Locate entry/exit control point a <u>minimum</u> of 25 feet from any suspected composite debris
19. Personnel within the fire/crash area must have full protective clothing and respiratory equipment. (This means self-contained breathing apparatus for all rescue personnel during any fire.)
20. Set up appropriate decontamination corridor. (No eating or drinking in the area)
21. Continue to be alert for any indications of burned composites, fibers or ash that may be airborne, scattered loose on the ground or in the proximity of the burned aircraft.
22. Monitor downwind spread of any ash, heavy smoke concentration, or particulate.
23. Assess the extent of property involvement/damage/contamination caused by the fire and/or impact.

24. Preserve evidence that may be of interest to Incident Investigation Teams.
25. Update data from appropriate agencies that may assist you in identifying: Specific aircraft; hazardous cargo; advanced composite materials; or other significant data, that may impact the safety of your personnel and the general public.
26. If this incident is **not an aircraft crash**; establish contact with people from the building or facility involved.
27. Gather as much specific information; (including applicable MSDS sheets, etc.) As soon as possible.
28. Ensure runoff of firefighting agent is monitored and controlled. If debris from burned composites is suspected to be in this runoff, treat runoff as contaminated.

**POST-FIRE CHECKLIST:**

**Additional Guidelines:**

1. You can temporarily contain ash, and loose particles of composites fibers with a fine water spray, foam blanket, or cover the material with sheets of plastic. Acrylic floor wax may be sprayed upon loose debris and particles. The best mixture is 10 parts of water to one part floor wax concentrate.
2. If this incident happened in proximity of other aircraft, vacuum all air intakes with a HEPA type vacuum cleaner.
3. Inspect all external access doors, vents, and hatches for signs of soot, particles or ash. Vacuum as needed with HEPA vacuum
4. Ensure no smoke, ash, or particles have entered the aircraft interior. It is recommended to conduct both a visual and electronic ("sniffer"/LEL check of interior). If contamination is suspected, vacuum the interior thoroughly.
5. Before any exposed aircraft are permitted to fly; recommend electrical checks and engine run-up is performed.
6. If buildings or other structures are exposed:
    a. Thoroughly clean all antenna insulators, exposed transfer bushings, etc.
    b. Inspect air intakes for soot deposits, or other signs of contamination.
    c. Decontaminate these as needed.

**Personnel and equipment:**

1. Decontaminate exposed personnel: HEPA vacuums then wash PPE and turnout clothing.
2. Ensure all involved personnel check themselves for possible puncture wounds, respiratory, eye, or skin irritation.
    a. Exposed personnel should take a cool shower. This minimizes the chances of complications due to exposure to loose fibers, debris, or ash.
3. Contaminated personal protective equipment (PPE) must be placed in airtight sealed container(s).
4. Use HEPA filter type vacuum cleaners to remove loose fibers from fire vehicles, and other equipment.
5. Control decontamination water runoff.

6. After the situation has been controlled, confirm that the appropriate agencies are ready to take over and begin their cleanup and disposal operations.
7. Conduct a "pass on briefing" with the authority assuming control of the site.
8. Terminate your agency involvement after it is no longer needed, and the appropriate Authority Having Jurisdiction has assumed command and control of the incident.

**ADDITIONAL GUIDELINES:**

1. All debris and contaminated materials must be disposed of in accordance with local, state, federal, and international guidelines. Coordinate these efforts with appropriate government agencies, as well as private environmental management officials. The Safety Investigation Board (SIB) and/or Accident Investigation Board (AIB) must advise when it is permitted to release the materials for disposal.
2. All contaminated materials must be in airtight containers and disposed of properly. They must be labeled to say: "Composite Waste. Do Not Incinerate. Do Not Sell For Scrap."
3. Appropriate agencies will ensure any contamination is removed from soil.

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