1. **INTRODUCTION.**

Fire can either be the cause of an aircraft accident or result from it. As a cause, it used to be quite rare considering all causes of all aircraft accidents. Modern aircraft design practices separate, as much as possible, flammables from sources of ignition and provide for containment or extinguishment of fires that do occur. In spite of that, the past ten years has seen an increase of in-flight fires some of which resulted in accidents. In some cases, this is due to a better understanding of the in-flight fire process. Other reasons involve aging or overloaded electrical systems and poor choices of insulating material. The inability of the flight crew to identify the source of the fire or (in some cases) do anything about it has also contributed. These will be discussed.

Fires can occur in engines, engine bays, cockpits, cabins, cargo holds, wheel wells, and fuel tanks. They can also occur in electrical circuitry not readily available to the flight crew. If the fire is not contained or extinguished and the aircraft crashes, a post-impact fire invariably results which destroys considerable evidence of the nature and origin of the in-flight fire.

While the in-flight fire may be rare, the post impact fire is not. Once the fuel tanks of the aircraft are ruptured, the resulting fuel mist is almost certain to encounter one or more ignition sources in the form of hot engine parts, sparks or electrical arcs. Even when there was no in-flight fire (or reason to suspect in-flight fire) the post impact fire can destroy a lot of evidence related to the aircraft structure or systems. Thus knowledge of how materials behave in the presence of fire is useful to the investigator even though the fire itself is not suspected as a cause.

This chapter will deal with some basic concepts about fire chemistry, the behavior of aircraft fluids and materials, the difference between in-flight and post impact fires and the characteristics of in-flight explosions.

2. **DEFINITIONS.**

The following terms and definitions will be used throughout this chapter.

A. **FIRE.** This is a collective term for an oxidation reaction producing heat and light. There are several types of fires.

B. **DIFFUSION FLAME OR OPEN FLAME.** A rapid oxidation reaction with the production of heat and light. A gas flame or a candle flame is termed an open flame. So is the burning of residual fuel following the initial “fire ball” during an aircraft impact.

C. **DEFLAGRATION.** Subsonic gaseous combustion resulting in intense heat and light and (possibly) a low level shock wave. Most aircraft impact “fireballs” are technically deflagrations.

D. **DETONATION.** A supersonic combustion process occurring in a confined or open space characterized by a shock wave preceding the flame front.

E. **EXPLOSION.** Detonation within a confined space resulting in rapid buildup of pressure and rupture of the confining vessel. Explosions may be further categorized as either mechanical or chemical. A mechanical explosion involves the rupture of the confining vessel due to a combination of internal overpressure and loss of vessel integrity. A chemical explosion involves a chemical reaction resulting in catastrophic overpressure and subsequent vessel rupture.
F. **FLASH POINT.** This is the lowest temperature at which a material will produce a flammable vapor. It is a measure of the volatility of the material.

G. **AUTO-IGNITION TEMPERATURE.** This is also called Ignition Temperature or Autogenous Ignition Temperature. It is the temperature at which the material will ignite on its own without any outside source of ignition.

H. **FLAMMABILITY LIMITS.** These are generally listed as the upper and lower flammability or explosive limits. These describe the highest and lowest concentrations of a fuel in air by volume percent which will sustain combustion. In other words, a fuel-air mixture below the lower limit is too lean to burn while a mixture above the upper limit is too rich to burn. This is of little consequence in a post impact fire, because all possible combinations of fuel-air mixtures will be present. In considering in-flight fires, though, the upper and lower limits may be useful as they vary with temperature and altitude. Thus, for an in-flight fire to occur, the aircraft must be operating in a temperature/altitude regime where a combustible fuel-air mixture can exist. This, as it turns out, is not as simple as it sounds (see discussion on pages 63-65 and Figure 8-1).

I. **FLASHOVER.** This term is used to describe the situation where an area or its contents is heated to above its auto-ignition temperature, but does not ignite due to a shortage of oxygen. When the area is ventilated (oxygen added) the area and its contents ignite simultaneously, sometimes with explosive force.

3. **FIRE CHEMISTRY.**

   Fire is essentially an oxidation reaction. In order for fire to occur, four conditions must exist:
   1. Combustible material
   2. Oxidizer
   3. Ignition
   4. Enough heat or energy to sustain the reaction.

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**Figure 8-1.**
Combustible Limits Versus Altitude for Various Fuels.

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A. COMBUSTIBLE MATERIAL. The flammable liquids (fuel, hydraulic fluid) used on aircraft do not burn as liquids. Their vapors burn. Thus the fire chemistry involving a liquid is essentially a gaseous reaction and the characteristics of the liquid itself are of little consequence. Since combustion takes place in the vapors above the surface of the liquid (or in a mist formed of the liquid) the key characteristic of a liquid is its tendency to form flammable vapors. (“Vapors” refer to the gaseous form of a substance. “Mists” refer to suspended liquid droplets of a substance.) This is a function of the liquid’s volatility and temperature. A highly volatile liquid such as Avgas produces flammable vapors at a very low temperature. Jet-A, on the other hand, is much less volatile and requires elevated temperatures to produce flammable vapors (see Figure 8-2).

If you think about it, a fuel tank that is nearly empty can be more dangerous than one that is full. The nearly empty tank has more space (called “ullage”) for the formation of flammable vapors. If the tank is full, the small ullage above the fuel level is the only place a fire can occur. This is not news to the aircraft industry. The Boeing B-47 had DC fuel pump motors which produced continuous arcing. Boeing mounted the fuel pumps (motor and all) in sumps at the bottom of the fuel tanks. Since the sumps were always filled with fuel, the pump motors were always covered and there was no hazard.

As a result of the TWA 800 accident, fuel tank inerting systems are under study and installation may be in progress at the time of publication of this book. Full installation is expected by 2012. Fuel tank inerting systems are not new and have been used in several military aircraft. They are heavy and expensive and require a lot of maintenance. Current thinking is a self-contained unit which uses pressurized air from the engines, a heat exchanger, and a set of filters to produce nitrogen-enriched air. This is piped to the fuel tank ullage and replaces the oxygen-enriched air.

Flammable vapors can also be created in the form of a mist. This is basically what happens in a jet engine when fuel is sprayed into the combustion chamber in a fine mist. It is also what happens when a leak or rupture occurs in a hydraulic system. The fluid under a pressure of 3,000 psi. (or more) can spray out in a fine mist and form a flammable vapor. A misting fluid can generally be ignited at a lower temperature than the fluid’s vapor flash point.

Solid materials used on the aircraft may burn, char or melt. Some may burn or melt depending on physical composition. A steel forging, for example, would melt before it burned; but a pile of thin steel shavings would probably burn before it melted. If the material burns, the burning takes place on the surface of the material only.

<table>
<thead>
<tr>
<th>FLUID</th>
<th>FLASH POINT (°F)</th>
<th>IGNITION TEMP. (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aviation Gasoline</td>
<td>-45</td>
<td>825-960</td>
</tr>
<tr>
<td>JP-4</td>
<td>-20 to -30</td>
<td>435-484</td>
</tr>
<tr>
<td>JP-5</td>
<td>147-150</td>
<td>435-484</td>
</tr>
<tr>
<td>JP-8</td>
<td>115</td>
<td>435-484</td>
</tr>
<tr>
<td>Jet A/A1</td>
<td>105-140</td>
<td>435-484</td>
</tr>
<tr>
<td>Kerosene</td>
<td>95-145</td>
<td>440-480</td>
</tr>
<tr>
<td>Engine Oil</td>
<td>437</td>
<td>440-480</td>
</tr>
<tr>
<td>Hydraulic Fluid</td>
<td>195</td>
<td>437</td>
</tr>
<tr>
<td>(Petroleum-Based)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hydraulic Fluid</td>
<td>320</td>
<td>945</td>
</tr>
<tr>
<td>(Synthetic)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
In the process of charring or burning, some cabin materials may produce a thick black smoke which impedes both breathing and vision and, therefore, escape. Others, in the process of burning or charring, may decompose into other elements or compounds. An organic material (wool, for example) will usually decompose into a compound containing hydrogen cyanide. A material containing a carbon molecule is almost certain to produce carbon monoxide as a byproduct of combustion. Products of decomposition may have different flash points than the original material and may contribute to flashover.

During the investigation of fires involving solids, it is well to remember that almost any substance found on an airplane will react, somehow, to heat. The nature of the reaction and the temperature at which the reaction occurs is a function of the material itself.

B. OXIDIZER. Since air is 20% oxygen, ordinary air is sufficient to support most fires. If a fire occurs in flight and the fire is exposed to the slipstream, oxygen is added and the fire will burn faster and hotter.

Although the percentage of oxygen in air is constant at any altitude, the partial pressure is not. This is reduced as atmospheric pressure is reduced and may be thought of as a reduction in the quantity of oxygen available. At some point, depending on the volatility of the fuel and the temperature, the quantity of oxygen available becomes insufficient to support the oxidation reaction. This may be thought of as a problem in fuel-oxygen mixture or, more properly, upper and lower flammability limits. In theory, an exactly correct mixture of fuel vapor and oxygen would be called a stoichiometric mixture and it would result in a complete and perfect reaction of the fuel and oxygen molecules. There would be no byproducts in the form of smoke. Surrounding this perfect mixture is a range of flammability defined by the upper and lower flammability limits. Above the upper limit, the mixture is too rich to burn. Below the lower limit, it is too lean. Jet-A, for example, cannot form a flammable mixture at certain altitudes and temperatures (See Figure 8-1) because the available oxygen will always form a mixture with the Jet-A vapor that is too lean. Thus if the fuel, flight altitude and temperature are known, the investigator can make a determination whether an in-flight fire was theoretically possible. This does not apply, of course, to fuel that is misted in the combustion chamber (or cylinders) and supported by compressed air (oxygen) through the air intake. That's why the engines keep running even at high altitude. This theory also does not apply to fires originating within the pressurized compartment or an oxygen-rich area; or if the fire starts inside the plane and is then exposed to the slipstream where additional oxygen can be continuously added.

As it turns out, there are a few other holes in this theory. We always assumed that the temperatures on the flammability limits chart referred to outside air temperature (OAT). In July of 1996, a B-747 exploded after takeoff from New York and crashed off the coast of Long Island. For convenience, we call this the TWA Flight 800 accident. Since the accident occurred around 13,000 feet, according to Figure 8-1 it couldn’t have been the fuel. At that altitude and temperature it wouldn’t form a flammable vapor. The investigators discovered that the center wing tank (CWT) had very little fuel in it and the tank was directly above the air conditioning packs which had been running on the ground for quite some time. The combination of heat from the packs and the small amount of fuel in the tank created a situation where the vapors formed were well within the flammability limits. Thus the important consideration is the actual temperature of the fuel, not the OAT.

Another factor not taken into account in Figure 8-1 is ignition dwell time. This is the time flammable vapors must be in contact with an ignition source before fire results. This is a function of absolute pressure and varies greatly with altitude.

C. IGNITION. In order for a fire to ignite, the ignition source must first raise the temperature of the combustible vapors (or material) in its immediate vicinity to the ignition temperature of the material. Sparks from the aluminum alloys, for example, are generally incapable of igniting turbine fuel vapors; they are not hot enough.
Likewise, it is pointless to hypothesize a bleed air duct leak as an ignition source if the temperature of the bleed air is not above the ignition temperature of the fuel. Back to the TWA 800 accident, the question of ignition consumed a lot of investigation time and the source was never proven with absolute certainty. It could have been static electricity, which almost never leaves any evidence. After months of investigation, the NTSB concluded that the ignition source was an electrical short circuit outside of the CWT that allowed excessive voltage to enter it through electrical wiring associated with the fuel quantity indication system. Evidence of the electrical short was never found, which isn’t surprising. All of the wreckage went into the ocean in three large wreckage areas. All of the wreckage recovered was reconstructed three-dimensionally, a process which took over a year (see Chapter 9). If the evidence exists, it is probably still on the bottom of the ocean.

**D. HEAT OR ENERGY TO SUSTAIN THE REACTION.** If the ignition process provides this energy, the fire will be self-sustaining. If not, the fire will go out when the source of ignition is removed. Most synthetic hydraulic fluids (“Skydrol” and Mil–83282) exhibit this characteristic. They will burn, but only in the presence of continuous ignition; assuming, of course, that the fluid has not been heated to above its auto-ignition temperature. Petroleum based hydraulic fluids will continue to burn after the ignition source is removed.

Once properly ignited (and in the presence of sufficient heat or energy) the fire will continue until one of four events occur:

1. The combustible material is consumed or removed. An example would be an engine fire wherein the fuel is shut off at the firewall or tank. The fire burns the fuel remaining in the lines — and then goes out.

2. The oxidizing agent concentration is lowered to below that necessary to support combustion. This can occur in a closed area such as a cargo hold or a passenger cabin. A fire starts and consumes enough of the oxygen so that the remaining mixture is too fuel-rich to burn. At this point, the fire goes out. This led to the early design philosophy on the need for fire extinguishing systems in aircraft cargo holds. The thinking was that any fire would rapidly consume the available oxygen and extinguish itself. Unfortunately, this does not hold true for very large cargo holds or very intense fires that burn through the aircraft skin and obtain additional oxygen from the slipstream. It also doesn’t work if the cargo itself contains oxidizers. A case in point is the Valujet accident in Florida in 1996. Included in the cargo were chemical oxygen generators which were used on another type of aircraft. When ignited, they chemically produced oxygen for the passenger emergency oxygen masks. When one of these ignited in the cargo hold of the Valujet, everything needed for an intense fire was present. This accident led to the requirement for fire warning and extinguishing systems in all cargo holds. At this writing, that requirement is not yet completely accomplished.

What can also occur in a cargo hold is that the fire, while it is consuming oxygen, raises the temperature of the surrounding materials to above their auto-ignition temperature. Auto-ignition does not occur until the cabin or cargo hold is opened or burned through and oxygen is added. Now we have a violent situation called, “Flashover” which is the instant ignition of all materials which have been heated above their auto-ignition temperatures.

3. The combustible material is cooled to below its ignition temperature. This seldom occurs by itself. Once heated, the material stays heated until it is consumed. This is one of the basic methods of fire fighting — lower the temperature of the material by cooling it with an extinguishent.

4. The fire is chemically inhibited. The fire extinguishing chemical Halon works by chemically terminating the reaction between the fuel and oxygen. For environmental reasons, Halon is no longer being manufactured although existing Halon extinguishers are still in use. A replacement chemical is being developed.
4. LEVEL OF BURNING REACTION.

There are several different types or levels of burning. These should be understood as the terms tend to be used interchangeably. The term, “explosion” for example, may mean something entirely different to a witness than it does to a fire specialist. These terms are defined earlier in this chapter.

A. DIFFUSION FLAME OR OPEN FLAME. This is the lowest level of burning reaction and is analogous to a candle flame.

B. DEFLAGRATION. Most “fireballs” seen immediately after an aircraft impacts are deflagrations.

C. DETONATION. This is the third level of burning reaction and differs from an explosion only in that it is unconfined.

D. EXPLOSION. This is a form of detonation occurring in a confined space and may be either mechanical or chemical. The extensive damage is due largely to overpressure and a supersonic shock wave.

5. CHARACTERISTICS OF AIRCRAFT FLUIDS AND MATERIALS.

A. FLUIDS. Characteristics of common aircraft fluids are listed in Figure 8-2. The flash point is the lowest temperature at which the fluid will produce a flammable vapor. The auto-ignition temperature is the temperature at which the fluid vapors will ignite (assuming sufficient oxygen) without any outside source of ignition. Fluid flash point ranges are listed in Figure 8-2. Flammability limits of common aircraft fuels are shown in Figure 8-1.

B. AIRCRAFT MATERIALS. The melting points of metals and materials commonly used in aircraft are shown in Figure 8-3. The behavior characteristics of some aircraft materials and some useful temperature ranges are plotted in Figure 8-4.

C. COMPOSITE MATERIALS. Technically, any non-homogenous material could be called a composite material. The principal composites currently used in aircraft construction are fiberglass or carbon fiber. These may be used alone, in combination with each other, or sandwiched around a metallic or non-metallic core.

When exposed to fire, fiberglass will melt at around 1,200°F. The reaction of a carbon fiber composite depends on the resin in which the fibers are imbedded. The fibers, being pure carbon, aren’t going to decompose any further. The resin will melt which liberates the fibers or reduces their structural integrity. The temperature at which the resin melts varies with the resin; a characteristic frequently considered proprietary among manufacturers. Most resins will “burn out” at 1,100°F or below.

D. ALUMINUM ALLOYS. Most aircraft metal structure is about 95% pure aluminum alloyed with copper or zinc and small amounts of other elements. The behavior of the structure in a fire depends on the alloying elements, the configuration (heavy forged or cast structure vs. thin paneling), the temperature and time of exposure, and the amount of stress on the structure.

Initial heating. The principal result of exposure to heat is loss of strength. This is a function of time and can occur rapidly at a high temperature or slowly at a low temperature. If some assumptions about time of exposure can be made, then it is possible to test the hardness of the alloy and calculate the temperature as a function of loss of hardness over that specified for the alloy.

Eutectic melting. This is the lowest melting temperature of any of the alloying metals. At this temperature, an interesting phenomena called the “broom straw Effect” occurs if the aluminum part is highly stressed. In this case, the failed area will show delamination along grain boundaries and would resemble the fibers one would see in a “green stick” fracture. This is considered highly indicative of in-flight fire, the assumption being that the heating occurred in flight and the stress occurred at impact. This can also occur if the part is under high stress as it is normally used in the aircraft and then heated. Thus a “broom straw” fracture is not a 100% guarantee of in-flight fire. The eutectic melting temperature of aluminum alloys is approximately 890°F.
Figure 8-3. Melting Points of Aircraft Materials.