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Understanding Airplane Turbofan Engine Operation Helps Flight Crews Respond to Malfunctions

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Flight Safety Foundation is an international membership organization dedicated to the continuous improvement of aviation safety. Nonprofit and independent, the Foundation was launched officially in 1947 in response to the aviation industry's need for a neutral clearinghouse to disseminate objective safety information, and for a credible and knowledgeable body that would identify threats to safety, analyze the problems and recommend practical solutions to them. Since its beginning, the Foundation has acted in the public interest to produce positive influence on aviation safety. Today, the Foundation provides leadership to more than 830 member organizations in more than 150 countries.

Understanding Airplane Turbofan Engine Operation Helps Flight Crews Respond to Malfunctions

Maintaining aircraft control, diagnosing correctly the engine malfunction and taking appropriate action are the keys to continued safe flight.

Turbofan Engine Malfunction Recognition and Response Working Group

Many modern airplanes are powered by turbofan engines, which are reliable and can provide years of trouble-free service. Nevertheless, because of the infrequency of turbofan engine malfunctions and the limitations of simulating those malfunctions, some flight crews have been unprepared to diagnose engine malfunctions.

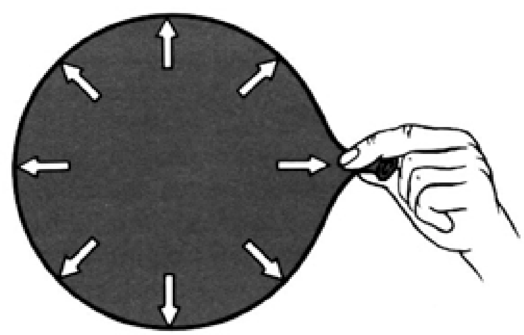
Flight simulators have improved pilot training, but many flight simulators have not been programmed to simulate the actual noise, vibration and aerodynamic forces that specific engine malfunctions cause. In addition, it appears that the greater the sensations, the greater the startle factor, along with greater likelihood that the flight crew will give diagnosis of the problem priority over flying the airplane.

Pilots should understand that some engine malfunctions can feel and sound more severe than anything that they have ever experienced; however, the airplane most likely will remain flyable, and the first priority of the flight crew should be to fly the airplane.

Propulsion

Propulsion is the net force that results from unequal pressures. Gas (air) under pressure in a sealed container exerts equal pressure on all surfaces of the container; therefore, all the forces are balanced and there are no forces to make the container move (Figure 1).

Balanced Forces in a Sealed Container (Balloon)



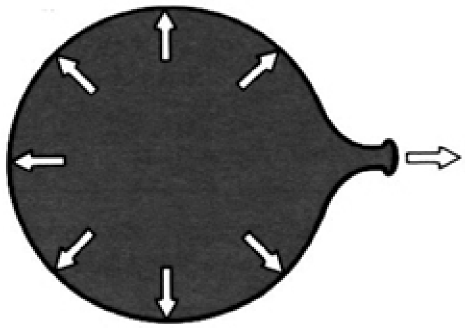
Source: U.S. Federal Aviation Administration

Figure 1

If there is a hole in the container, gas cannot push against that hole; thus, the gas escapes. While the gas is escaping and there is pressure inside the container, the side of the container opposite the hole has pressure against it. Therefore, the net pressures are not balanced and there is a net force available to move the container. This force is called *thrust.*

The simplest example of the propulsion principle is an inflated balloon (container) where the stem is not closed (Figure 2, page 2). The pressure of the air inside the balloon exerts forces everywhere inside the balloon. For every force, there is an opposite force on the other side of the balloon, except on the surface of the balloon opposite the stem. This surface has no opposing force because air is escaping out the stem. This results in a net force that propels the balloon away from the stem. The balloon is propelled by the air pushing on the front of the balloon.

Unbalanced Force Opposite Released Stem Propels Balloon



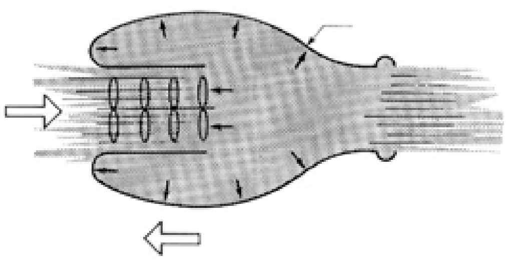
Source: U.S. Federal Aviation Administration

Figure 2

The simplest propulsion engine would be a container of air (gas) under pressure that is open at one end. A diving scuba tank would be such an engine if it fell and the valve was knocked off the top of the tank. The practical problem with such an engine is that, as the air escapes out the open end, the pressure inside the container would drop rapidly. This engine would deliver propulsion for only a limited time.

A turbine engine is a container with a hole in the back end (tail pipe or nozzle) to allow air inside the container to escape and, thus, provide propulsion. Inside the container is turbomachinery to keep the container full of air under constant pressure (Figure 3).

Turbomachinery Maintains Supply of Air Under Constant Pressure



Source: U.S. Federal Aviation Administration

Figure 3

Components of a Turbine Engine

The turbomachinery in the engine uses energy stored chemically as fuel. The basic principle of the airplane turbine engine is identical to other engines that extract energy from chemical fuel. The basic steps for any internal combustion engine are:

- Intake of air (and possibly fuel);
- Compression of the air (and possibly fuel);
- Combustion, where fuel is injected (if it was not drawn in with the intake air) and burned to convert the stored energy; and,
- Expansion and exhaust, where the converted energy is put to use.

In a piston engine, such as the engine in a car or lawn mower, the intake, compression, combustion and exhaust steps occur in the same place (cylinder head) at different times as the piston travels up and down inside the cylinder.

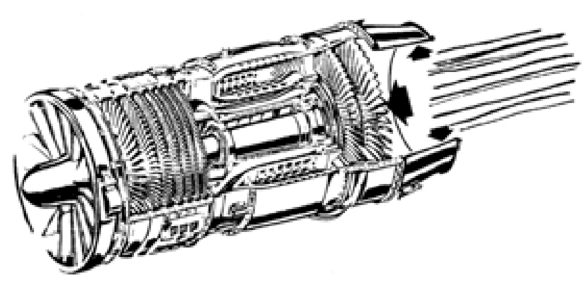
In a turbine engine, however, the four steps occur at the same time but in different places. As a result of this difference, the turbine engine has sections called:

- The inlet section;
- The compressor section;
- The combustion section; and,
- The exhaust section.

Axial-flow Turbine Engine

The turbine engine in an airplane has the sections stacked in a line from front to back (Figure 4). Air enters the front of the engine inlet and passes essentially straight through from front to back. On its way to the back, the air is compressed by the compressor section. Fuel is added and burned in the combustion section, then the air is exhausted through the exit nozzle.

Air Passes Through Inlet, Compressor, Combustion and Exhaust Sections

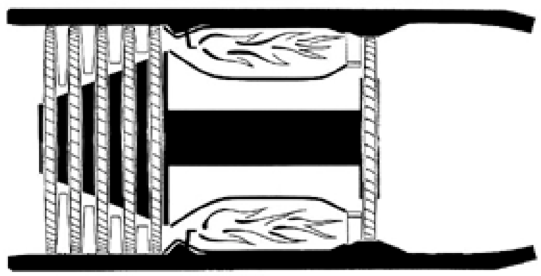


Source: U.S. Federal Aviation Administration

Figure 4

The compressor must be driven by something in order to function. Between the compressor section and the exhaust section, there is a turbine that uses some of the energy in the discharging air to drive the compressor. A long shaft connects the turbine to the compressor (Figure 5).

Basic Layout of Jet Propulsion System



Source: U.S. Federal Aviation Administration

Figure 5

The flight crew and passengers rarely see a complete engine. What is seen is a large elliptically shaped pod hanging from the wing or attached to the fuselage toward the back of the airplane. This pod structure is called the nacelle or cowling. The engine is inside this nacelle.

The first nacelle component that incoming air encounters on its way through a turbine engine is the inlet cowl. The inlet cowl directs the incoming air evenly across the inlet of the engine. The shape of the interior of the inlet cowl is designed carefully to guide this air.

The compressor of a turbine engine has quite a job to do. The compressor must take in an enormous volume of air and compress the air to 1/10th or 1/15th of the volume it had outside the engine. This volume of air must be supplied continuously, not in pulses or periodic bursts.

The compression is accomplished by a rotating disk containing many airfoils, called blades, set at an angle to the disk rim (Figure 6). Each blade resembles a miniature propeller blade, and the angle at which it is set on the disk rim is called the angle-of-attack. This angle-of-attack is similar to the pitch of a propeller blade or an airplane wing in flight. As the disk is forced by the turbine to rotate, each blade accelerates the air, thus pumping the air behind it. The effect is similar to a household window fan.

The air is accelerated rearward and also forced to travel circumferentially in the direction of the rotating disk. Any tendency for the air to go in circles is counterproductive, so this tendency is corrected by another row of airfoils behind the rotating disk. This row is stationary and its airfoils are at an opposing angle.

What has just been described is a single stage of compression. Each stage consists of a rotating disk with many blades on the

Compressor Rotor Disk

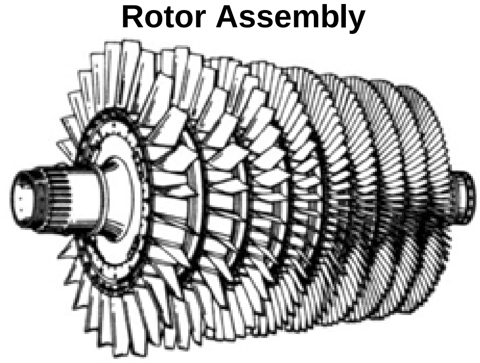
Source: U.S. Federal Aviation Administration

Figure 6

rim, called a rotor stage, and, behind it, another row of airfoils that is not rotating, called a stator. Air on the backside of this rotor/stator pair is accelerated rearward, and any tendency for the air to travel circumferentially is corrected.

A single stage of compression can achieve about a 1.5:1 or a 2.5:1 decrease in the air's volume. Compression increases the energy that can be extracted from the air during combustion and exhaust (which provides the thrust). To achieve the 10:1 to 15:1 total compression required to develop adequate power, the engine is built with many stages of compressors stacked in a line (Figure 7). Depending upon the engine design, there may be as many as 10 to 15 stages in the compressor assembly.

Nine Stages of a Compressor Rotor Assembly



Source: U.S. Federal Aviation Administration

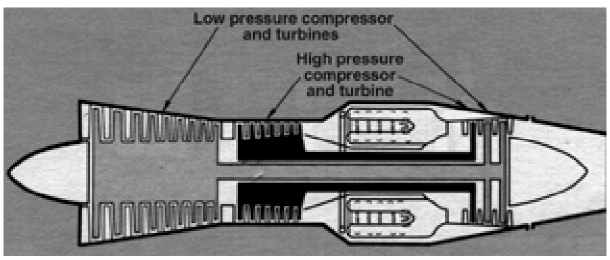
Figure 7

As the air is compressed, the air velocity, temperature and pressure increase. Air does not behave the same at elevated temperatures, pressures and velocities. Therefore, the speed that the compressor rotors must have at the back of the compressor is different than the speed it must have at the front of the compressor. With only a few compressor stages, this difference could be ignored; but, with 10 compressor stages to 15 compressor stages, it would not be efficient to have all the stages rotate at the same speed.

The most common solution to this problem is to break the compressor in two. This way, the front four or five stages can rotate at one speed, while the rear six stages or seven stages can rotate at a different (higher) speed. To accomplish this, two separate turbines and two separate shafts are required.

Most of today's turbine engines are dual-rotor engines; they contain two distinct sets of rotating components (Figure 8). The rear compressor, or high-pressure compressor, is connected by a hollow shaft to a high-pressure turbine. The high-pressure compressor and high-pressure turbine assembly is called the high rotor, high spool or N_2 rotor.

Layout of Dual-rotor Turbine Engine



Source: U.S. Federal Aviation Administration

Figure 8

The front compressor, or low-pressure compressor, is in front of the high-pressure compressor. The turbine that drives the low-pressure compressor is behind the turbine that drives the high-pressure compressor. The low-pressure compressor is connected to the low-pressure turbine by a shaft that goes through the hollow shaft of the high rotor. The low-pressure rotor also is called the N_1 rotor.

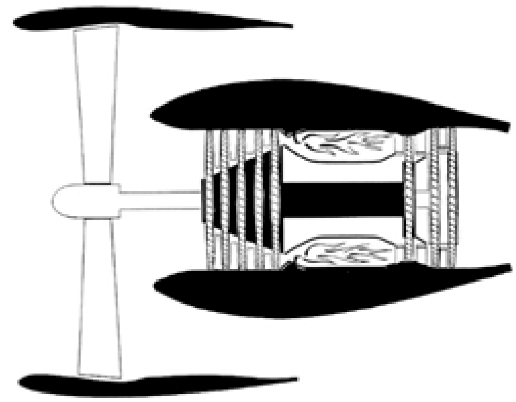
The N_1 rotor and the N_2 rotor are not connected mechanically. There is no gearing between them. As the air flows through the engine, each rotor is free to operate at its own efficient speed. These speeds are precise and are carefully calculated by the engineers who designed the engine. The speed in rpm (revolutions per minute) of each rotor often is displayed by gauges or readouts labeled "N1 RPM" and "N2 RPM." The rotors have specific redline limits.

In some engines, the N_1 rotor and N_2 rotor rotate in opposite directions. Some engines have three rotors instead of two.

The Turbofan Engine

A turbofan engine is a turbine engine in which the first-stage compressor rotor is larger in diameter than the rest of the engine (Figure 9). This larger stage is called the fan. The air

Turbofan Engine



Source: U.S. Federal Aviation Administration

Figure 9

that passes through the fan near its inner diameter also passes through the remaining compressor stages in the core of the engine and is further compressed and processed through the engine cycle. The air that passes through the outer diameter of the fan rotor does not pass through the core of the engine, but instead passes along the outside of the engine. This air is called bypass air, and the ratio of bypass air to core air is called the bypass ratio.

The air accelerated by the fan contributes significantly to the thrust produced by the engine, particularly at low forward speeds and low altitudes. In large engines, such as the engines that power the Boeing 747, B-757, B-767, Airbus A300 and A310, as much as three-quarters of the thrust produced by the engine is developed by the fan.

The fan is not like a propeller. On a propeller, each blade acts like an airplane wing, developing lift as it rotates. The lift on a propeller blade pulls the airplane forward.

In a turbofan engine, thrust is developed by the fan rotor system, which includes the static structure (fan exit guide vanes) around it. The fan system acts like the open balloon in the earlier example and, thus, pushes the engine, and the airplane along with it, through the air.

What the fan and the propeller do have in common is that the core engine drives them both.

Lesson Summary

So far we have learned that:

- Propulsion is created by an imbalance of forces;

- A pressure vessel with an open end delivers propulsion because of the imbalance of forces;

- A propulsion engine is a pressure vessel with an open end in the back;
- An airplane propulsion engine provides a constant supply of air for the pressure vessel;
- An airplane turbine engine operates with the same four basic steps as a lawn mower engine or automobile engine;
- An airplane turbine engine has sections that perform each of the four basic steps of intake, compression, combustion and exhaust;
- Compression is accomplished by successive stages of rotor/stator pairs;
- The compressor stages usually are split into low-pressure and high-pressure compressor sections;
- The low-pressure section is referred to as N_1 and the high-pressure section is referred to as N_2; and,
- A fan is the first stage of compression; the fan rotor and its mating stator are larger in diameter than the rest of the engine.

Engine Systems

From an engineer's point of view, the turbofan engine is a finely tuned piece of mechanical equipment. For the engine to provide adequate power to the airplane at a weight that the airplane can accommodate, the engine must operate at the limit of technical feasibility. At the same time, the engine must provide reliable, safe and economical operation.

Within the engine, there are systems that keep everything functioning properly. The systems associated with the operation of the engine include the following:

- Accessory-drive gearbox;
- Fuel system;
- Lubrication system;
- Ignition system;
- Bleed system;
- Start system; and,
- Anti-ice system.

In addition, there are airplane systems that are powered by the engine or driven by the engine. These systems include the following:

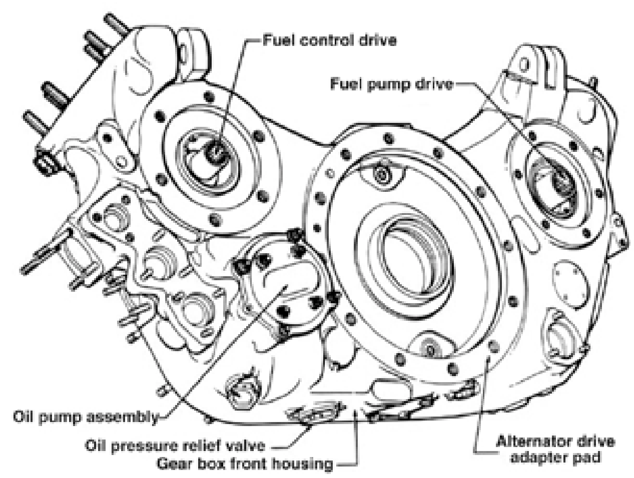
- Electrical system;
- Pneumatic system;
- Hydraulic system; and,
- Air conditioning system.

These systems are not associated with continued function of the engine and have not caused engine malfunctions. The airplane systems may provide cues for engine malfunctions.

Accessory-drive Gearbox

The accessory-drive gearbox typically is attached to the outside cases of the engine at or near the bottom (Figure 10). The accessory-drive gearbox is driven by a shaft that extends into the engine and is geared to one of the compressor rotors. It usually is driven by the high-pressure compressor.

Typical Accessory-drive Gearbox



Source: U.S. Federal Aviation Administration

Figure 10

The gearbox has attachment pads for accessories that must be driven mechanically. These accessories include airplane systems, such as generators for electrical power and the hydraulic pump for airplane hydraulic systems. Also attached to the gearbox are the engine starter and the fuel pump/fuel control.

Fuel System

The fuel system associated with the propulsion system consists of the following:

- A fuel pump;
- A fuel control;
- Fuel manifolds;
- Fuel nozzles;

- A fuel filter;
- Heat exchangers;
- Drains; and,
- A pressurizing and dump valve.

All components, except the fuel nozzles, are external to the engine.

The fuel system supplies pressurized fuel from the main tanks. The fuel is pressurized by electrically driven boost pumps in the tanks and then flows through the spar valve or low-pressure (LP) shut-off valve to the engine LP fuel pump inlet.

The fuel pump is mounted on the gearbox. Most engine fuel pumps have two stages; some engines have two separate pumps. An LP stage increases fuel pressure so that fuel can be used for servos. The fuel is filtered to remove debris from the airplane tanks. Following the LP stage, there is an HP (high-pressure) stage that increases fuel pressure above the combustor pressure. The HP pump always provides more fuel to the fuel control than the engine requires, and the fuel control meters the required amount to the engine and bypasses the rest back to the pump inlet.

The fuel delivered from the pump generally is used to cool the engine oil and integral-drive-generator (IDG) oil on the way to the fuel control. Some fuel systems also incorporate fuel heaters (heat exchangers) to prevent ice crystals from accumulating in the fuel control during low-temperature operation and valves to bypass the fuel heaters, depending on ambient temperatures.

The fuel control is installed on the accessory gearbox, directly to the fuel pump, or, if there is an electronic control, to the engine case. The purpose of the fuel control is to provide the required amount of fuel to the fuel nozzles at the requested time. The rate at which fuel is supplied to the nozzles determines the acceleration or deceleration of the engine.

The flight crew sets the power requirements by moving a thrust lever. When the flight crew moves the thrust lever, they are "telling the control" what power is required. The fuel control senses what the engine is doing and automatically meters fuel to the fuel nozzles within the engine at the required rate to achieve the power requested by the flight crew. A fuel flow meter measures the fuel flow sent to the engines by the control.

In older engines, the fuel control is hydromechanical; the fuel control operates directly from pressure and mechanical speed physically input into the control unit.

In newer engines, control of the fuel metering is done electronically by a computer called the electronic engine control (EEC) or full authority digital engine control (FADEC). The electronic controls have the capability of more precisely metering the fuel and sensing more engine operating parameters to adjust fuel metering. This results in greater fuel economy and more reliable service.

The fuel nozzles are in the combustion section near the compressor. The fuel nozzles provide a precisely defined spray pattern of fuel mist into the combustor for rapid and complete combustion. The fuel nozzle spray pattern is similar to that of a shower head.

The fuel system also includes drains to safely dispose of fuel in the manifolds when the engine is shut down and, in some engines, to conduct leaked fuel overboard.

Lubrication System

An airplane turbine engine requires lubrication for the rotors to turn easily without generating excessive heat. Each rotor system has, as a minimum, a rear bearing and a front bearing to support the rotor. Thus, the N_1 rotor has two bearings and the N_2 rotor has two bearings, for a total of four main bearings. Some engines have intermediate bearings and/or special bearings; however, the number of bearings in a given engine usually is of little direct interest to a basic understanding of the engine.

The lubrication system of a turbine engine includes:

- An oil pump;
- An oil-storage tank;
- A delivery system to the bearing compartments (oil lines);
- Lubricating oil jets within the bearing compartments;
- Seals to keep oil in and air out of the compartments;
- A scavenge system to remove oil from the bearing compartment after the oil has done its job. After the oil is scavenged, it is cooled by heat exchangers and filtered;
- Oil quantity, oil pressure and oil temperature gauges and oil filter bypass indications on the flight deck for monitoring of the oil system;
- Oil filters;
- Heat exchangers. Often, one heat exchanger serves as both a fuel heater and an oil cooler;
- Chip detectors, usually magnetic, to collect bearing compartment particles as an indication of bearing compartment distress. Chip detectors may trigger a flight

deck indication or be examined during line maintenance; and,

- Drains to safely dispose of leaked oil.

Ignition System

The ignition system is relatively straightforward. Its purpose is to provide the spark within the combustion section of the engine so that when fuel is delivered to the fuel nozzles, the atomized fuel mist will ignite and the combustion process will begin.

All four steps of the cycle in a turbine engine are continuous; once the fuel is ignited, the combustion process normally continues until the fuel flow is discontinued during engine shutdown. This is unlike the operation of a piston engine, which requires an ignition spark each time the combustion step occurs in the piston chamber.

Turbine engines can be operated with “continuous ignition;” when this setting is selected, the ignitor will produce a spark every few seconds. This is for those operations or flight phases where, if the combustion process were to stop for any reason, the loss of power could affect safety immediately. With continuous ignition, combustion will restart automatically, often without the pilot even noticing that there was an interruption in power.

Some engines, instead of having continuous ignition, monitor the combustion process and turn the igniters on as required, thus avoiding the need for continuous ignition.

The ignition system includes:

- Igniter boxes that transform low-voltage alternating current (AC) into high-voltage direct current (DC);

- Cables to connect the igniter boxes to the igniter plugs; and,

- Ignitor plugs.

For redundancy, the ignition system has two igniter boxes and two igniter plugs. Only one igniter is required to ignite the fuel in the combustor. Some airplanes allow the pilot to select which igniter is to be used; others use the engine control to make the selection.

Bleed System

Stability bleeds. The compressors are designed to operate most efficiently at cruise. Without help, the compressors may operate poorly or not at all during starting, at very low power or during rapid transient power changes. To reduce the workload on the compressor section during these conditions, engines are equipped with bleed systems to discharge large volumes of air from the compressor section before the air is fully compressed. The bleed system usually consists of:

- Bleed valves;

- Solenoids or actuators to open and close the bleed valves;

- A control device to signal when the valves open and close; and,

- Lines to connect the control device to the actuators.

In older engines, a control device measures the pressure across one of the engine compressors, compares it to the inlet pressure and directs high-pressure air to an air-piston-driven actuator at the bleed valve to close the valve. In newer engines, the electronic fuel control causes the bleed valves to open and to close.

Generally, all the compressor bleed valves are open during engine start. Some of the valves close after start, and some remain open. Those that remain open, close during engine acceleration to full power for takeoff; these valves remain closed for the duration of the flight.

If, during in-flight operation, the fuel control senses instability in the compressors, the control may open some of the bleed valves. This most often will be unnoticed by the flight crew, except for an advisory message on the flight deck display in some airplane models.

Cooling/clearance-control bleeds. Air also is extracted from the compressor section or from the fan section to cool engine components and accessories in the nacelle. In some engines, air extracted from the compressor is ducted and is directed onto the engine cases to control the clearance between the rotor blade tips and the case wall. Cooling the case shrinks the case closer to the blade tips, improving compression efficiency.

Service bleeds. The engines are the primary source of pressurized air for cabin pressurization. In some airplanes, engine bleed air can be used as an auxiliary power source for backup hydraulic power air motors. Air is taken from the high-pressure compressor before any fuel is burned, so that the air is as clean as the outside air. The air is cooled and filtered before it is delivered to the cabin or used for auxiliary power.

Start System

The engine requires an external source of power to start the compressor rotating so that it can compress enough air to get energy from the fuel. If fuel were ignited in the combustor of a non-rotating engine, the fuel would puddle and burn without producing any significant rearward airflow.

A pneumatic starter mounted on the accessory gearbox is powered by air originating from an auxiliary power unit (APU) or from a ground power cart. A start valve controls the input selection. The starter drives the accessory gearbox, which drives the high-compressor rotor via the same drive shaft normally used to deliver power to the gearbox.

Fuel flow during starting is scheduled carefully to allow for the compressor's poor efficiency at very low rpm, and bleeds are used to unload the compressor until it can reach a self-sustaining speed. After the engine reaches the self-sustaining speed, the starter de-clutches from the accessory gearbox. This is important, because starters can be damaged by extended, high-speed operation. The engine then accelerates to idle thrust without further assistance from the starter.

The starter also can be used to assist an in-flight restart. At higher airspeeds, the engine windmill rpm may be sufficient to allow engine starting without use of the pneumatic starter. The specific airplane flight manual (AFM) should be consulted regarding the conditions in which to perform an in-flight restart.

Anti-ice System

An airplane turbine engine requires protection against the formation of ice in the inlet and requires some method to remove ice if it does form. The engine is equipped with a system that takes some compressor air, via a bleed, and ducts it to the engine inlet or to any other place where anti-ice protection is required. Because the compressor bleed air is hot, it prevents the formation of ice and/or removes already-formed ice.

Although the flight crew can turn anti-ice on or off, there is generally no capability to control the amount of anti-ice delivered; for example, "high," "medium" or "low." Such control is not necessary.

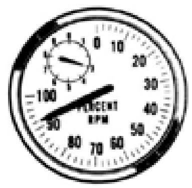
Engine Instrumentation on the Flight Deck

Airplanes in service today have devices that provide feedback to the flight crew about the engine. In older airplanes, these devices were gauges on the panel. In newer airplanes, electronic screens produce computer-generated displays that resemble the gauges. Whether gauges or electronic displays are used, the information provided to the flight crew is the same.

Engine Pressure Ratio (EPR)

EPR is a measure of thrust provided by the engine. EPR indicators show the ratio of the pressure of the air as it comes out of the turbine to the pressure of the air as it enters the compressor. EPR is a certified thrust-setting parameter. Some engine manufacturers recommend that engine power management be performed by reference to EPR.

A low EPR reading may be caused by engine rollback, flameout or internal damage, such as an LP turbine failure. Rapid EPR fluctuations may be caused by engine operational instability, such as surge, or rapidly changing external conditions, such as inclement weather or bird ingestion. Unexpectedly high EPR may indicate a fuel control malfunction, or malfunction or clogging of the inlet air pressure probes.



Rotor Speed

A multiple-rotor turbine engine provides a rotor-speed indication for each rotor. The N_1 gauge provides the rotor speed of the low-pressure rotor, and the N_2 (or N_3 for a three-rotor engine) gauge provides the rotor speed of the high-pressure rotor. N_1 is a certified thrust-setting parameter.

The units of rotor speed are rpm, but rotor speed is indicated as a non-dimensional ratio — engine rotor speed as compared to some nominal 100 percent speed representing a high-power condition (not necessarily the maximum permissible speed). Engine operating manuals specify a maximum operational limit rpm or redline rpm that generally is greater than 100 percent.

Low N_1 may indicate engine rollback, flameout or severe damage, such as LP turbine failure. Rapid N_1 fluctuations may be caused by engine operational instability, such as surge. Higher rotor speeds will be required at high altitudes to achieve takeoff-rated thrust. Unexpectedly high N_1 may indicate a fuel control malfunction.

N_2 is used for limit monitoring and condition monitoring. On older engines, N_2 also is used to monitor the progress of engine starting and to select the appropriate time to begin fuel flow to the engine.

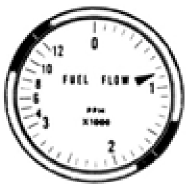
Exhaust Gas Temperature (EGT)

EGT is a measure of the temperature of the gas exiting the rear of the engine. EGT is measured at some location in the turbine section. Often, many sensors monitor EGT. The indicator on the flight deck displays the average of all the sensors.

High EGT can be an indication of degraded engine performance. Deteriorated engines especially are likely to have high EGT during takeoff.

EGT also is used to monitor engine health and mechanical integrity. Excessive EGT is a key indicator of engine stall, difficulty in engine starting, a major bleed air leak and any other situation (including severe engine damage) in which the turbine is not extracting enough work from the air as it moves aft.

There is an operational limit for EGT, because excessive EGT results in turbine damage. Operational limits for EGT often are classified as time-at-temperature.



Fuel Flow Indicator

The fuel flow indicator shows the fuel flow in pounds (or kilograms) per hour as supplied to the fuel nozzles. Fuel flow is of fundamental interest for monitoring in-flight fuel consumption, for checking engine performance and for in-flight cruise control.

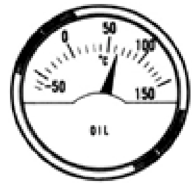
High fuel flow may indicate a significant leak between the fuel control and fuel nozzles, particularly if rotor speeds or EPR appear normal or low.

Oil Pressure Indicator

The oil pressure indicator shows the pressure of the oil as it comes out of the oil pump. In some cases, the oil-pressure indicating system considers the bearing compartment background pressure, called breather pressure, so that the gauge reading reflects the actual pressure of the oil as it is delivered to the bearing compartments. False indications of a problem are as frequent as genuine problems, so cross-checking with other oil system indications is advisable.

Low oil pressure may result from pump failure, a leak allowing the oil system to run dry, a bearing or gearbox failure or an indication-system failure. High oil pressure may be observed during extremely low-temperature operations, when oil viscosity is at a maximum.

Generally, if oil pressure decreases below a given level, a warning light is illuminated or a message is provided.



Oil Temperature Indicator

The oil-temperature indicator shows the oil temperature at some location in the lubrication circuit; the location differs among engine models.

Elevated oil temperature indicates some unwanted source of heat in the system, such as from a bearing failure, sump fire or unintended leakage of high-temperature air into the scavenge system. High oil temperature also may result from a malfunction of the engine oil cooler or a malfunction of the valves scheduling fluid flow through the cooler.

Oil Quantity Indicator

The oil quantity indicator shows the amount of oil in the tank sump. This can be expected to vary with power settings, because the amount of oil in the sump is a function of rotor speed.

A steady decrease in oil quantity may indicate an oil leak. There is likely to be some usable oil in the tank even after the oil quantity gauge reads zero, but the oil supply will be near exhaustion and a low-pressure indication soon will be seen. A large increase in indicated oil quantity may be caused by fuel leaking into the oil system and should be investigated before the next flight. Flight crews should be especially vigilant to check other oil system indications before taking in-flight action solely on the basis of low oil quantity.

Oil Filter Bypass Indication

If the oil filter becomes clogged with debris (either from contamination by foreign material or debris from a bearing failure), the pressure drop across the filter will increase to the point where the oil bypasses the filter. This is announced to the pilot via an oil filter impending bypass indication. This indication may disappear if thrust is reduced (because oil flow through the filter and pressure drop across the filter are reduced).

Fuel Filter Impending Bypass

If the fuel filter at the engine fuel inlet becomes clogged, an impending bypass indication will appear until the filter actually goes into bypass.

Fuel Heat Indication

The fuel heat indicator registers when the fuel heat is on. Fuel heat indicators are not required for engines in which fuel heating is passively combined with oil cooling and no valves or controls are involved.

Engine Starter Indication

During assisted starting, the starter air valve will indicate "open" until starter disconnect. The position of the start switch shows the starter status (running or disconnected). If the starter does not disconnect after the engine reaches idle, or if it disconnects but the starter air valve remains open, the starter will fail when the engine is at high power, potentially damaging other systems. More recent engine installations also may have advisory messages or status messages associated with engine starting.

Vibration Indication

A vibration gauge indicates the amount of vibration measured on the engine LP rotor and/or HP rotor. Vibration is displayed in non-dimensional units and is used for condition monitoring, identification of the affected engine after foreign object ingestion and detection of fan unbalance because of icing. The level of vibration changes with engine speed.

Powerplant Ice Protection Indication

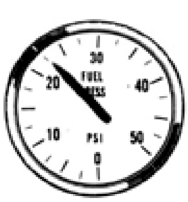
If anti-icing is selected, an indication is provided (such as wing anti-ice or nacelle anti-ice).

Thrust Reverser Indication

Typically, indications show whether the thrust reversers are deployed or in transit. Fault indications and messages also are shown. The indications are installation-specific, and further details may be obtained from the AFM or operations manual.

Fire Warning Indicators

Each engine has a dedicated fire warning indication, which may cover multiple fire zones and may address lesser degrees of high undercowl temperature (using messages such as "engine overheat").



Fuel-inlet Pressure Indicator

The fuel-inlet pressure indicator measures the pressure at the inlet to the engine-driven fuel pump.

Air Temperature Indicator

The air temperature indicator provides the temperature of the air outside the airplane. This temperature may be recorded from specific locations; therefore, the actual value may mean different things, depending upon the particular airplane. This temperature typically is used to help select EPR in those engines in which thrust is set by EPR.

In addition to the above indications, recently designed airplanes have a variety of caution, advisory and status messages that may be displayed in the event of engine malfunction or abnormal operation. The AFM or operations manual provides further information.

Engine Malfunctions

The following information on turbofan engine malfunctions and their consequences does not supersede or replace the specific instructions that are provided in the AFM and appropriate checklists.

Compressor Surge

In modern turbofan engines, compressor surge is rare. If a compressor surge (sometimes called a compressor stall) occurs at high power on takeoff, the flight crew will hear a very loud bang, which will be accompanied by yaw and vibration. The bang likely will be louder than any engine noise or other sound the crew previously experienced in service.

Compressor surge has been mistaken for blown tires and bombs. The flight crew may be startled by the bang and reject a takeoff above V_1. High-speed rejected takeoffs have resulted in injuries and fatalities.

The flight crew's first response should be to maintain control of the airplane and, in particular, continue the takeoff if the event occurs after V_1.

A surge is the result of instability of the engine's operating cycle. Compressor surge may be caused by engine deterioration or failure, or it may be the result of ingestion of birds or ice. The cycle susceptible to instability is compression.

In a turbine engine, compression is accomplished aerodynamically as the air passes through the stages of the compressor, rather than by confinement, as in a piston engine. The air flowing over the compressor airfoils can stall. When a stall occurs, the passage of air through the compressor becomes unstable and the compressor can no longer compress the incoming air. The high-pressure air behind the stall escapes forward through the compressor and out the inlet.

This escape is rapid and often audible as a loud bang similar to an explosion. Engine surge can be accompanied by visible flames from the inlet and from the tail pipe. Instruments may show high EGT and EPR or rotor speed changes; but the event is over so quickly that the instruments often do not have time to respond.

After the air from within the engine escapes, the reason (reasons) for the instability may self-correct and the compression process may re-establish itself. A single surge and recovery will occur quite rapidly, usually within a fraction of a second. Depending on the reason for the cause of the compressor instability, an engine might experience:

- A single self-recovering surge;
- Multiple surges prior to self-recovery;
- Multiple surges requiring pilot action to recover; or,
- A non-recoverable surge.

Flight crews must follow the appropriate checklists and emergency procedures detailed in the AFM. In general, however, during a single self-recovering surge, the cockpit engine indications may fluctuate slightly and briefly. The flight crew may not notice the fluctuation. (Some of the more recent engines may have fuel-flow logic that helps the engine self-recover from a surge without crew intervention. The stall may go completely unnoticed, or it may be annunciated to the crew — for information only — via engine indication and crew-alerting system [EICAS] messages.) Alternatively, the engine may surge two times or three times before full self-recovery. When this happens, there is likely to be cockpit engine instrumentation shifts of sufficient magnitude and duration to be noticed by the flight crew. If the engine does not recover automatically from the surge, it may surge continually until the pilot takes action to stop the process. The desired pilot action is to retard the thrust lever until the engine recovers. The flight crew should then slowly advance the thrust lever.

Occasionally, an engine surges only once and does not self-recover. The actual cause for the compressor surge is often complex and may or may not result from severe engine damage. Rarely does a single compressor surge cause severe engine damage, but sustained surging eventually will overheat the turbine, because too much fuel is being provided for the volume of air that is reaching the combustor. Compressor blades also may be damaged and fail as a result of repeated violent surges; this rapidly will result in an engine that cannot operate at any power setting.

Single self-recoverable surge. The flight crew hears a very loud bang or double bang. The instruments will fluctuate quickly, but, unless someone was looking at the engine gauge at the time of the surge, the fluctuation might not be noticed.

For example, during the surge event, EPR can drop from takeoff (T/O) to 1.05 in 0.2 seconds. EPR can then vary from 1.1 to 1.05 at 0.2-second intervals two or three times. N_1 can drop 16 percent in the first 0.2 seconds, then another 15 percent in the next 0.3 seconds. After recovery, EPR and N_1 should return to pre-surge values along the normal acceleration schedule for the engine.

Multiple surge followed by self-recovery. Depending on the cause and conditions, the engine may surge multiple times, with each bang being separated by a couple of seconds. Since each bang usually represents a surge event as described above, the flight crew may detect the "single surge" described above for two seconds, then the engine will return to 98 percent of the pre-surge power for a few seconds. This cycle may repeat two times or three times. During the surge and recovery process, there likely will be some increase in EGT.

For example, EPR may fluctuate between 1.6 and 1.3, EGT may increase five degrees Celsius (C) per second, N_1 may fluctuate between 103 percent and 95 percent, and fuel flow may drop 2 percent with no change in thrust lever position. After 10 seconds, the engine gauges should return to pre-surge values.

Surge recoverable after flight crew action. When surges occur but do not stop, flight crew action is required to stabilize the engine. Fluctuations and bangs will continue until the flight crew retards the thrust lever to idle. The engine parameters then should decrease to match thrust lever position. After the engine reaches idle, it may be re-accelerated back to power. If, upon advancing to high power, the engine surges again, the engine should be operated at idle or at some intermediate power, or shut down, according to the checklists applicable for the airplane. If the flight crew takes no action to stabilize the engine under these circumstances, the engine will continue to surge and may experience progressive secondary damage to the point where it fails completely.

Non-recoverable surge. When a compressor surge is not recoverable, there will be a single bang and the engine will decelerate to zero power as if the fuel flow had been discontinued. This type of compressor surge can accompany a severe-engine-damage malfunction or occur without any engine damage.

EPR can decrease at a rate of .34 per second, and EGT can increase at a rate of 15 degrees C per second, continuing for eight seconds (peaking) after the thrust lever is pulled back to idle. N_1 and N_2 should decrease at a rate consistent with shutting off the fuel, with fuel flow dropping to 25 percent of its pre-surge value in two seconds, tapering to 10 percent over the next six seconds.

Flameout

A flameout occurs when the combustion process has stopped. A flameout will be accompanied by decreases in EGT, engine core speed and EPR. When engine speed drops below idle, there may be other symptoms, such as low-oil-pressure warnings and electrical generators dropping off line — many flameouts from low initial power settings first are noticed when the generators drop off line and may be initially mistaken for electrical problems. The flameout may result from fuel starvation/exhaustion, severe inclement weather, a volcanic ash encounter, a control system malfunction or unstable engine operation (such as a compressor stall). Multiple engine flameouts may result in a variety of flight deck symptoms as engine inputs are lost from electrical, pneumatic and hydraulic systems. These situations have resulted in pilots troubleshooting the airplane systems without recognizing and fixing the root cause — no engine power. Some airplanes have dedicated EICAS/electronic centralized aircraft monitor (ECAM) messages to alert the flight crew to an engine rolling back below idle speed in flight; generally, an “ENG FAIL” or “ENG THRUST” message.

A flameout at takeoff power is unusual — only about 10 percent of flameouts occur at takeoff power. Flameouts occur most frequently at intermediate power settings or low power settings during cruise and descent. During these flight regimes, it is likely that the autopilot is in use. The autopilot will compensate for the asymmetric thrust up to its limits and may then disconnect. Autopilot disconnect must be followed by prompt, appropriate control inputs by the flight crew if the airplane is to maintain a normal attitude. If no external visual references are available, such as when flying over the ocean at night or in instrument meteorological conditions (IMC), the likelihood of an upset increases. This condition of low-power engine loss with the autopilot on has caused several aircraft upsets, some of which were not recoverable. Flight control displacement may be the only obvious indication. Vigilance is required to detect these engine failures and to maintain a safe flight attitude while the situation is still recoverable.

After the fuel supply has been restored to the engine, the engine may be restarted according to the applicable AFM or aircraft operating manual (AOM). Satisfactory engine restart should be confirmed by reference to all primary parameters — using only N_1, for example, has led to confusion during some in-flight restarts. In some flight conditions, N_1 may be very similar for a windmilling engine and for an engine running at flight idle.

Fire

An engine fire almost always involves a fire outside the engine but within the nacelle. A fire in the vicinity of the engine should be annunciated to the flight crew. It is unlikely that the flight crew will see, hear or immediately smell an engine fire. Sometimes, flight crews are advised of a fire by the control tower.

It is important to know that, given a fire in the nacelle, there is adequate time to fly the airplane before attending to the fire. It has been shown that, even in incidents of fire indication immediately after takeoff, there is adequate time to continue climb to a safe altitude before attending to the engine. There may be damage to the nacelle, but the first priority of the flight crew should be to ensure that the airplane continues in safe flight.

Flight crews should regard any fire warning as a fire, even if the indication goes away when the thrust lever is retarded to idle. The indication might be the result of pneumatic leaks of hot air into the nacelle. The fire indication also could be from a fire that is small or sheltered from the detector so that the fire is not apparent at low power. Fire indications also may result from faulty detection systems. Some fire detectors allow identification of a false indication (testing the fire loops), which may avoid the need for an in-flight engine shutdown (IFSD). There have been times when the control tower mistakenly has reported the flames associated with a compressor surge as an engine fire.

In the event of a fire-warning annunciation, the flight crew must refer to the checklists and procedures specific to the airplane being flown. In general, after the decision is made that a fire exists and the aircraft is stabilized, engine shutdown should be accomplished immediately by shutting off fuel to the engine, both at the engine fuel control shutoff and the wing/pylon spar valve. All bleed air, electrical power and hydraulic power from the affected engine must be disconnected or must be isolated from the airplane systems to prevent any fire from spreading. This is accomplished by one common engine “fire handle.” This controls the fire by greatly reducing the fuel available for combustion, by reducing the availability of pressurized air to any sump fire, by temporarily denying air to the fire through the discharge of fire extinguishant and by removing sources of re-ignition, such as live electrical wiring and hot casings. Some of these control measures may be less effective if the fire is the result of severe damage — the fire may take slightly longer to be extinguished in these circumstances. In the event of a shutdown after an in-flight engine fire, there should be no attempt to restart the engine unless it is critical for continued safe flight, because the fire is likely to re-ignite once the engine is restarted.

Tail Pipe Fires

One of the most alarming events for passengers, flight attendants, ground personnel and even air traffic control (ATC) to witness is a tail pipe fire. Fuel may puddle in the turbine casings, exhaust during start-up or shutdown and then ignite. This can result in a highly visible jet of flame out the back of the engine. Passengers have initiated emergency evacuations, leading to serious injuries, after observing tail pipe fires.

There may be no indication of an anomaly to the flight crew until the cabin crew or control tower draws attention to the problem. They are likely to describe it as an engine fire, but a tail pipe fire will not result in a fire warning on the flight deck.

When notified of an engine fire without any indications on the flight deck, the flight crew should accomplish the tail pipe fire procedure, which will include motoring the engine to help extinguish the flames.

Since the fire is burning within the turbine casing and exhaust nozzle, pulling the fire handle to discharge extinguishant to the space between casings and cowls will be ineffective. Pulling the fire handle may also make it impossible to dry-motor the engine (i.e., rotate the engine without introducing fuel or ignition), which is the quickest way of extinguishing most tail pipe fires.

Hot Starts

During engine start, the compressor is very inefficient. If the engine experiences more than the usual difficulty accelerating (because of such problems as early starter cut-out, fuel mis-scheduling or strong tail winds), the engine may spend a considerable time at very low rpm (sub-idle). Normal engine cooling flows will not be effective during sub-idle operation, and turbine temperatures may appear relatively high. This is known as a hot start (or, if the engine completely stops accelerating toward idle, a hung start). The AFM indicates acceptable time/temperature limits for EGT during a hot start. FADEC-controlled engines may incorporate auto-start logic to detect and manage a hot start.

Bird Ingestion/Foreign Object Damage (FOD)

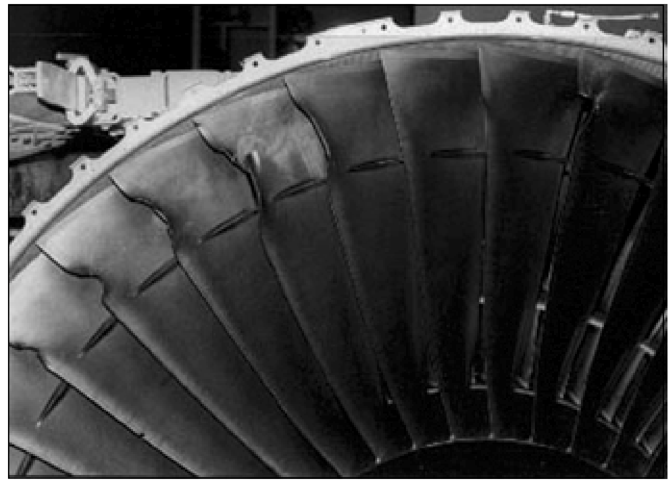
Airplane engines ingest birds most often in the vicinity of airports, either during takeoff or during landing. Encounters with birds occur during both daytime flights and nighttime flights.

Most bird encounters do not affect the safe outcome of a flight. In more than half of the bird ingestions into engines, the flight crew is not even aware that the ingestion took place.

When an ingestion involves a large bird, the flight crew may notice a thud, bang or vibration. If the bird enters the engine core, there may be a smell of burned flesh carried to the flight deck or passenger cabin by the bleed air.

Bird strikes can damage an engine; the photo on this page shows fan blades bent by the ingestion of a bird. The engine continued to produce thrust with this level of damage. FOD from other sources, such as tire fragments, runway debris or animals, also may occur, with similar results.

Bird ingestion also can result in an engine surge. The engine may surge once and recover; it may surge continuously until the flight crew takes action; or it may surge once and not recover, resulting in the loss of power from that engine. Bird ingestion can result in the fracture of one or more fan blades, in which case, the engine likely will surge once and not recover.



Fan blades bent by ingestion of a bird. Photo: U.S. Federal Aviation Administration

Even when a bird ingestion results in an engine surge, the first priority of the flight crew is to fly the airplane. After the airplane is in stable flight at a safe altitude, the appropriate procedures in the AFM can be accomplished.

In rare cases, multiple engines have ingested medium-sized birds or large birds. In the event of suspected multiple-engine damage, taking action to stabilize the engines becomes a much higher priority than if only one engine is involved — but it is essential to control the airplane first.

Severe Engine Damage

Severe engine damage is difficult to define. From the viewpoint of the flight crew, severe engine damage is mechanical damage that looks "bad and ugly." To the manufacturers of the engine and the airplane, severe engine damage may be as obvious as large holes in the engine cases and nacelle, or as subtle as the failure of the engine to respond to thrust lever movement.

It is important for flight crews to know that severe engine damage may be accompanied by a fire warning (from leaked hot air) or an engine surge because the compressor stages that hold back the pressure may not be intact or be functional because of the engine damage.

In this case, the symptoms of severe engine damage will be the same as a surge without recovery. There will be a loud noise. EPR will decrease quickly; N_1, N_2 and fuel flow will decrease. EGT may increase momentarily. There will be a loss of power. It is not important initially to distinguish between a non-recoverable surge with or without severe engine damage, or between a fire and a fire warning with severe engine damage. The priority of the flight crew remains to fly the airplane. After the airplane is stabilized, the flight crew can diagnose the situation.

Engine Seizure

Engine seizure describes a situation in which the engine rotors stop turning in flight, perhaps suddenly. The static parts and rotating parts lock up against each other, bringing the rotor to a halt. This is likely to occur only at low-rotor rpm after an engine shutdown, and almost never occurs in a large engine — the fan has too much inertia, and the rotor is being pushed around too forcefully by ram air to be stopped by the static structure. The HP rotor is more likely to seize after an in-flight shutdown if the nature of the engine malfunction is mechanical damage within the HP system. If the LP rotor seizes, there will be some perceptible drag for which the flight crew must compensate; however, if the HP rotor seizes, there will be negligible effect upon airplane handling.

Seizure is caused by severe engine damage, to the point at which most of the vanes and blades of the compressor and turbine are destroyed. This is not an instantaneous process — the inertia in the turning rotor is greater than the energy needed to break interlocking rotating components and static components.

After the airplane has been landed and the rotor is no longer being driven by ram air, seizure frequently occurs.

Symptoms of engine seizure in flight may include vibration, zero rotor speed, mild airplane yaw and unusual noises (in the event of fan seizure). There may be increased fuel flow in the remaining engine(s) because of aircraft automatic compensations; no special action is required other than that which is appropriate to the severe engine-damage-type failure.

Engine Separation

Engine separation is rare. Separation will be accompanied by loss of all primary parameters and secondary parameters for the affected engine, noises and airplane yaw (especially at high power settings). Separation is most likely to occur during takeoff/climb-out or the landing roll. Airplane handling may be affected. It is important to use the fire handle to close the spar valve and prevent a massive overboard fuel leak; refer to the AFM or operations manual for specific procedures.

Fuel System Problems

Leaks. Major leaks in the fuel system are a concern to the flight crew because they may result in engine fire or, eventually, in fuel exhaustion. A very large leak can cause engine flameout.

Engine instruments will indicate a leak only if it is downstream of the fuel flow meter. A leak between the tanks and the fuel flow meter can be recognized only by comparing fuel usage between engines, by comparing actual usage to planned usage or by visual inspection for fuel flowing out of the pylon or cowlings. Eventually, the leak may result in tank imbalance.

In the event of a major leak, the crew should consider whether the leak must be isolated to prevent fuel exhaustion.

The likelihood of fire resulting from a major leak is greater at low altitude or when the airplane is stationary; even if no fire is observed in flight, the crew should request that emergency services be available upon landing.

Inability to shut down the engine. If the engine-fuel shut-off valve malfunctions, it may not be possible to shut down the engine by the normal procedure; the engine may continue to operate after the fuel switch is moved to the cutoff position. Closing the spar valve by pulling the fire handle will ensure that the engine shuts down as soon as it has used the fuel in the line from the spar valve to the fuel pump inlet. This may take a couple of minutes.

Fuel filter clogging. Fuel filter clogging can result from the failure of one of the fuel-tank boost pumps (the pump generates debris that is swept downstream to the fuel filter), from severe contamination of the fuel tanks during maintenance (scraps of rag, sealant, etc., that are swept downstream to the fuel filter) or from gross contamination of the fuel. Fuel filter clogging usually will be observed at high power settings, when the fuel flow through the filter (and the pressure drop across the filter) is greatest. If multiple fuel-filter-bypass indications are observed, the fuel may be heavily contaminated with water, rust, algae, etc. After the filters bypass and the contaminant goes into the engine fuel system, the engine fuel control may no longer operate as intended. There is potential for multiple-engine flameout. The AFM or AOM provides the required guidance.

Oil System Problems

The engine oil system has a relatively large number of indicated parameters required by regulations (pressure, temperature, quantity, filter clogging). Many sensors are subject to false indications, especially on earlier engine models. Multiple abnormal system indications confirm a genuine failure; a single abnormal indication may or may not be a valid indication of failure.

There is considerable variation between failure progressions in the oil system, so the symptoms given below may vary from case to case.

Oil system problems may occur in any flight phase and generally progress gradually. They eventually may lead to severe engine damage if the engine is not shut down.

Leaks. Leaks will cause a reduction in oil quantity, down to zero (though there still will be some usable oil in the system at this point). Once the oil is exhausted completely, oil pressure will decrease to zero, followed by the low-oil-pressure light. Maintenance error has caused leaks on multiple engines; therefore, the crew should monitor oil quantity on all engines.

Rapid change in the oil quantity indication after thrust lever movement may not indicate a leak — the change may be caused by oil flow fluctuations as more oil flows into the sumps.

Bearing failures. Bearing failures will be accompanied by an increase in oil temperature and vibration will be indicated. Audible noises and filter clog messages may follow; if the failure progresses to severe engine damage, low-oil-quantity indications and low-oil-pressure indications may be observed.

Oil pump failures. Oil pump failure will be accompanied by low-oil-pressure indications and a low-oil-pressure light, or by an oil-filter-clog message.

Contamination. Contamination of the oil system — by carbon deposits, cotton waste, improper fluids, etc. — generally will lead to an oil-filter-clog indication or an impending bypass indication. This indication may disappear if thrust is reduced, because the oil flow and pressure drop across the filter also will decrease.

No Thrust Lever Response

This type of malfunction is more subtle than the other malfunctions previously discussed — so subtle that it can be overlooked.

If an engine slowly loses power — or if, when the thrust lever is moved, the engine does not respond — the airplane will experience asymmetric thrust. This may be concealed by the autopilot's efforts to maintain the required flight condition.

As is the case with flameout, if no external visual references are available, such as when flying over the ocean at night or in IMC, asymmetric thrust may persist for some time without the flight crew recognizing or correcting it. In several cases, this has led to airplane upsets, some of which were not recoverable.

Symptoms may include:

- Multiple system problems such as generators dropping off line or engine low oil pressure;
- Unexplained airplane attitude changes;
- Large unexplained flight control surface deflections (autopilot on) or the need for large flight control inputs without apparent cause (autopilot off); and,
- Significant differences between primary parameters from one engine to the next.

If asymmetric thrust is suspected, the first response must be to make the appropriate trim input or rudder input. Disconnecting the autopilot without first performing the appropriate control input or trim may result in a rapid roll.

Thrust Reverser Malfunctions

Generally, thrust reverser malfunctions are failure conditions in which the reverser system fails to deploy when commanded or fails to stow when commanded. Failure to deploy or to stow during the landing roll will result in significant asymmetric thrust and may require a rapid response by the crew to maintain directional control.

Uncommanded deployments of modern thrust reverser systems have occurred and have led to airworthiness directives requiring additional locking systems. The AFM or AOM provides the required system information.

No Starter Cutout

Generally, this condition exists when the start selector remains in the "start" position or the engine-start valve is "open" when commanded "closed." Because the starter is intended to operate only at low speeds for a few minutes at a time, the starter may fail completely (burst) and cause further engine damage if the starter does not cut out.

Vibration

Vibration is a symptom of a variety of engine conditions, ranging from very benign to serious. The following are some causes of tactile vibration or indicated vibration:

- Fan imbalance at assembly;
- Fan-blade friction or shingling;
- Water accumulation in the fan rotor;
- Blade icing;
- Bird ingestion/FOD;
- Bearing failure;
- Blade distortion or failure; and,
- Excessive fan rotor system tip clearances.

It is not easy to identify the cause of vibration without other indications. Although the vibration from some failures may feel very severe on the flight deck, it will not damage the airplane. There is no need to take action based on a vibration indication alone.

Engine vibration may be caused by fan imbalance (ice buildup, fan blade material loss due to ingested material or fan blade distortion due to FOD) or by an internal engine failure. Reference to other engine parameters will help to establish whether a failure has occurred.

Vibration felt on the flight deck may not be indicated on instruments. For some engine failures, severe vibration may be experienced on the flight deck during an engine failure or after the engine has been shut down, making instruments difficult to read. Such a vibration is caused by the unbalanced fan windmilling close to the airframe's natural frequency, which may amplify the vibration. Changing airspeed and/or altitude will change the fan windmill speed, and an airplane speed may be found where there will be much less vibration. There is no risk of airplane structural failure because of vibratory engine loads.

Table 1 shows that many failures have similar symptoms and that it may not be practicable to diagnose the engine problem from flight deck instrumentation. Nevertheless, it is not necessary to understand exactly what is wrong with the engine — selecting the "wrong" checklist may cause some further damage to the engine, but, provided action is taken with the correct engine and airplane control is the first priority, flight can continue safely.♦

[FSF editorial note: To ensure wider distribution in the interest of aviation safety, this report has been adapted with editing for clarity and style from *Airplane Turbofan Engine Malfunction Recognition and Response*, which is part of a training aid developed by a working group sponsored by the U.S. Federal Aviation Administration (FAA) and the Air Transport Association (ATA). The training aid was developed as a follow-on to a report in November 1998 by a working group chaired by the U.S.-based Aerospace Industries Association and the European Association of Aerospace Industries. The report, *Propulsion System Malfunction Plus Inappropriate Crew Response (PSM+ICR)*, appeared in *Flight Safety Digest* Volume 18 (November–December 1999). The FAA/ATA training aid includes a 22-minute video titled *Turbofan Engine Malfunction Recognition and Response*. FAA is distributing the training aid on a CD-ROM. For more information, contact: FAA Engine and Propeller Directorate, ANE-110, 12 New England Executive Park, Burlington, MA 01803 U.S.A.; telephone: +1 781-238-7110.]

Table 1
Turbofan Engine Failures/Malfunctions and Symptoms

	Engine separation	Severe damage	Surge	Bird ingestion/ FOD	Seizure	Flameout	Fuel control problems	Fire	Tail pipe fires	Hot start	Icing	Reverser inadvertent deploy	Fuel leak
Bang	▲	●	●	▲	▲	□	□	□	□	□	▲	□	□
Fire Warning	▲	▲	□	▲	□	□	□	●	□	□	□	□	□
Visible flame	▲	▲	▲	▲	□	□	□	▲	●	▲	□	□	□
Vibration		●	▲	●	▲	□	□	□	□	□	●	●	□
Yaw	▲	▲	▲	▲	▲	▲	▲	□	□	□	□	●	□
High EGT	□	●	●	▲	▲	□	●	□	▲	●	▲	□	□
N_1 change	●	●	▲	▲	●	●	●	□	□	□	□	□	●
N_2 change	●	●	▲	▲	●	●	●	□	□	□	□	□	●
Fuel flow change	●	▲	▲	□	▲	●	▲	▲	□	□	□	□	●
Oil indication change	●	▲	▲	□	▲	●	□	▲	□	□	□	□	□
Visible cowling damage	●	●	□	□	□	□	□	▲	□	□	□	●	□
Smoke/odor in cabin bleed air	□	▲	□	▲	▲	□	□	□	□	□	□	□	□
EPR change	●	●	●	▲	●	●	●	□	□	□	□	□	□

● = Symptom very likely ▲ = Symptom possible □ = Symptom is unlikely
FOD = Foreign object damage EGT = Exhaust gas temperature EPR = Engine pressure ratio

Source: U.S. Federal Aviation Administration

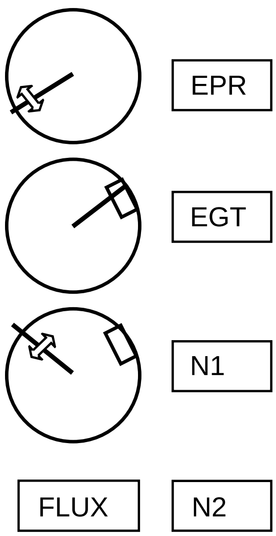
Appendix
Summary of Turbofan Engine Malfunctions

Engine Stall/Surge

Event description: Momentary reversal of the compressor airflow, causing high-pressure air to escape from the engine inlet.

Symptoms: High power: loud bang and yaw (may be repetitive); flames from inlet and tail pipe; vibration; high exhaust gas temperature/turbine gas temperature (EGT/TGT); parameter fluctuation. Low power: Quiet bang/pop or rumble.

Corrective action: After stabilizing airplane flight path, observe engine instruments for anomalies. Stall/surge may be self-correcting, may require the engine to be throttled back, or may require engine shutdown if the engine can be positively identified and the stall will not clear.



Possible Messages

ENG STALL

EGT OVERLIMIT

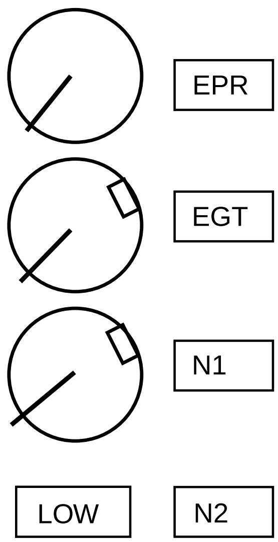
ENG FAIL

Flameout

Event description: A condition in which the combustor no longer is burning fuel.

Symptoms: Single engine: Core speed, EGT and engine pressure ratio (EPR) decrease; electrical generator drops off line; low oil pressure warning as core speed decreases below idle. Multiple engines: As above, but also hydraulic, pneumatic and electrical system problems.

Corrective action: After stabilizing airplane flight path, verify fuel supply to engine. Re-start engine according to airplane flight manual (AFM).



Possible Messages

ENG FAIL

OIL LOW PR

GEN OFF

BLD OFF

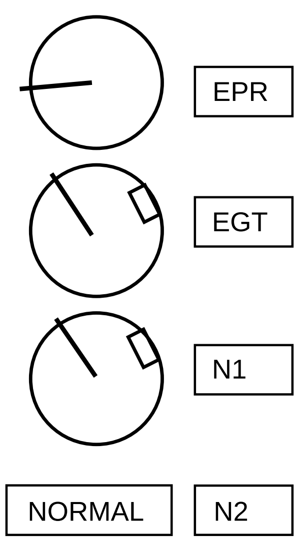
ALL ENG FLAMEOUT

Fire

Event description: A fuel, oil or hydraulic fluid fire between the engine casing and the cowlings (or occasionally a metal fire). It could result from severe damage. Hot air leaks also can give a fire warning.

Symptoms: Fire warning; flame or smoke may be observed.

Corrective action: After stabilizing airplane flight path, shut down the engine and discharge extinguishant. Avoid restarting the engine.



Possible Messages

ENG FIRE

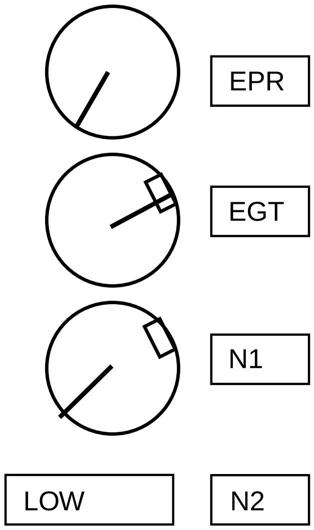
PARAMETERS MAY LOOK NORMAL

Tail Pipe Fire

Event description: Fuel puddles in the tail pipe and ignites on hot surfaces.

Symptoms: Observed flames and smoke; no fire warning.

Corrective action: Shut off fuel to the engine and dry-motor the engine.



Possible Messages

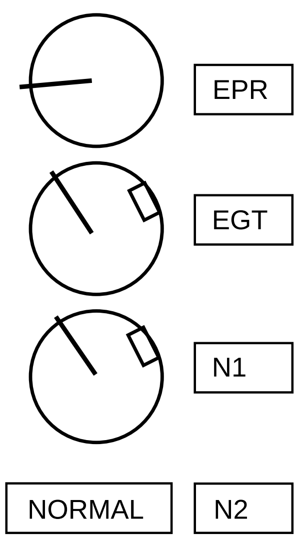
START FAULT

Bird Ingestion

Event description: A bird (or other creature) is sucked into the engine inlet. Note: ingestion of ice slabs, blown tires, etc., will produce similar, but more severe, symptoms.

Symptoms: Thud, bang, vibration; odor in cabin; surge may result from bird ingestion.

Corrective action: After stabilizing airplane flight path, observe engine instruments for anomalies. If the engine surges, throttle back or shut down the engine. If multiple engines are affected, operate engines free of surge/stall to maintain desired flight profile.



Possible Messages

ENG STALL

EGT OVERLIMIT

VIB

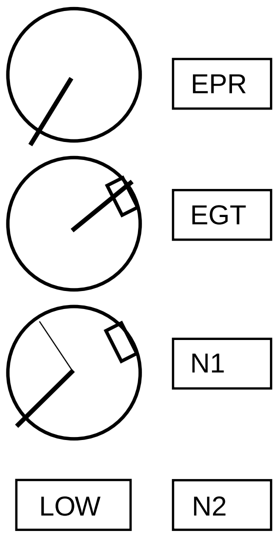
PARAMETERS MAY LOOK NORMAL

Severe Engine Damage

Event description: Engine hardware is damaged to the point where the engine is in no condition to run — such as bearing failure, major fan damage from ingestion of foreign objects, blade or rotor disk failures, etc.

Symptoms: Depending on nature of damage — surge/stall, vibration, fire warning, high EGT, oil system parameters out of limits, rotor speed and EPR decrease, yaw.

Corrective action: After stabilizing airplane flight path, observe engine instruments for anomalies. Shut down engine.



Possible Messages

ENG FAIL

EGT OVERLIMIT

ENG STALL

VIB

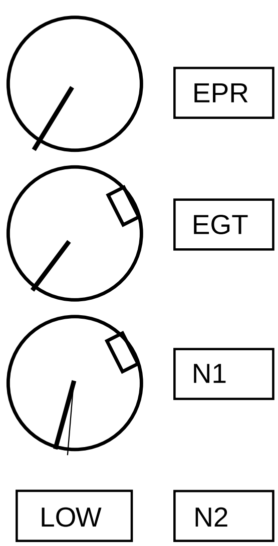
OIL LO PR

Engine Seizure

Event description: The locking of one rotor or more rotors. It only happens after engines are shut down for severe damage.

Symptoms: After shutdown, zero speed on one of the rotors; minor increase in required thrust for flight conditions.

Corrective action: Trim and adjust power for increased drag.



Possible Messages

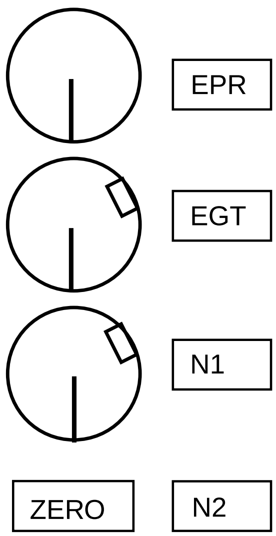
ENG SHUT DOWN

Engine Separation

Event description: The departure of the engine from the airplane because of mount failure or pylon failure.

Symptoms: Loss of all engine parameters; hydraulic, pneumatic and electrical system problems.

Corrective action: After stabilizing airplane flight path, observe engine instruments for anomalies. Turn off fuel to appropriate engine.



Possible Messages

ENG FIRE

HYD OFF

GEN OFF

BLD OFF

Data Show Increase in False Alarms From Cargo-compartment Smoke Detectors in U.S.-registered Aircraft

An FAA report says that, from 1995 through 1999, the ratio of false alarms to events that involved smoke or fire was 200-to-1.

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Data from the U.S. Federal Aviation Administration (FAA) and the U.S. National Transportation Safety Board show increases in the number of false alarms from cargo-compartment smoke detectors in U.S.-registered aircraft and in the ratio of false alarms to real alarms. The data involve aircraft operating under U.S. Federal Aviation Regulations (FARs) Part 121 and Part 135.

The ratio of false cargo-compartment fire-detector alarms to events that involved smoke or fire was 200-to-1 from 1995 through 1999, said an FAA technical note, "Aircraft Cargo Compartment Smoke Detector Alarm Incidents on U.S.-Registered Aircraft, 1974–1999." (A false alarm is defined as "any incident in which a cargo-compartment smoke-alarm light illuminates in the cockpit for any reason other than a cargo-compartment fire.")

The technical note said that, without improvements in fire-detection technology, the number of false cargo-compartment fire-detector alarms should be expected to increase further because of requirements that take effect in March 2001 to install additional cargo-compartment fire detectors in about 3,000 U.S.-registered aircraft.

In the past, FARs have required fire detectors in Class B, Class C and Class E cargo compartments. The new regulation requires fire detectors in Class D cargo compartments — small cargo compartments below the cabin floor, typically inaccessible during flight.

Most airplane flight manuals say that, if a cargo-compartment fire-detector alarm is activated, the crew should respond by shutting off applicable ventilation, discharging a fire-suppression agent and landing at the nearest suitable airport. Diverting a narrow-body airplane to an alternate airport costs about US$30,000; diverting a wide-body airplane costs about $50,000, the technical note said.

"In addition to the direct costs associated with a diversion, there could also be an increased safety risk due to a variety of factors, such as unfamiliar airports, less effective navigational aids, inadequate maintenance facilities, shorter runways, inferior airport rescue and fire fighting (ARFF) capabilities, etc.," the technical note said. "Obviously, diversions due to false cargo-compartment fire alarms are undesirable. In addition … a high ratio of false alarms to actual fire or smoke events can erode confidence in the detection system and possibly delay appropriate action in the event of a real smoke or fire emergency."

Figure 1 (page 23) shows reported incidents of false cargo-compartment fire alarms in U.S.-registered Part 121 and Part 135 aircraft. The report said that there was no explanation for the decrease in the number of reported incidents from 1989 through 1995.

Figure 2 (page 24) shows the number of reported unscheduled landings that resulted from the false cargo-compartment fire alarms. Not every false alarm results in an unscheduled landing, partly because some alarms occur while the aircraft is on the ground or near the end of a flight, when the destination airport is the nearest suitable airport for landing in response to a fire alarm and partly because some fire alarms involve accessible cargo compartments and crewmembers are able to determine that the alarm is false.

Figure 3 (page 24) shows the number of false cargo-compartment fire alarms that were attributed to electrical sources (defined as "any electrical hardware problem discovered with the detection system").

Figure 4 (page 25) shows the number of false cargo-compartment fire alarms and fire alarms that resulted from smoke or fire. The highest number of occurrences involving smoke or fire in any year was two, recorded in 1984 and 1998. The technical note said that, in one of the two events in 1998, the source of the smoke was the smoke detector. (The technical note did not include details of that incident.)

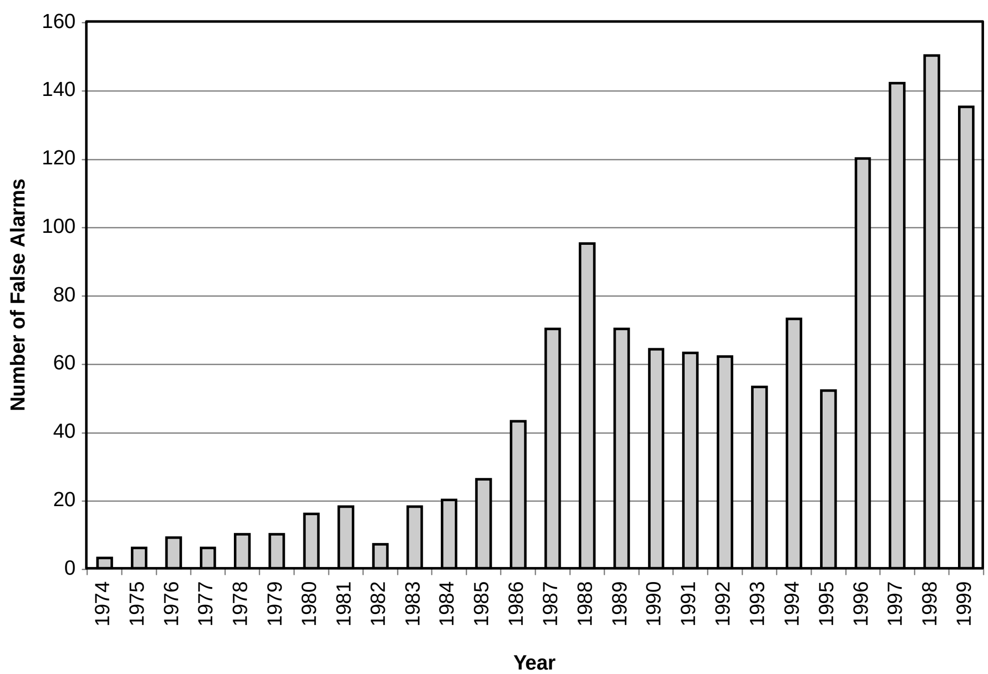
Figure 5 (page 25) shows the number of false alarms for every alarm caused by smoke or fire. The data, in five-year intervals from 1975 through 1999, show an increasing trend in false alarms; the lowest ratio was less than 30-to-1 in 1980–1984, and the highest was 200-to-1 in 1995–1999.

Figure 6 (page 26) shows the number of false alarms in large transport category airplanes compared with smaller regional/commuter airplanes. In recent years, a greater proportion of false alarms has occurred on smaller airplanes. (The transport category comprises all incidents that occurred on Boeing 707/720, Boeing 727, Boeing 737, Boeing 747, Boeing 757, Boeing 767, and Boeing 777 models; Douglas DC-8, DC-9/MD-80/MD-90 and DC-10/MD-11 models; Airbus A300, Airbus A310, Airbus A320/319, Airbus A330 and Airbus A340 models; and Lockheed L-1011 models. The regional/commuter category comprises all other incidents that occurred on fixed-wing aircraft.)

Figure 7 (page 26) shows the number of false alarms that occurred during each phase of flight. Most false alarms occurred during cruise, the phase in which the majority of flight time occurs. Nevertheless, the number of false alarms that occurred during takeoff/climb and descent was nearly as high as the number that occurred during cruise.

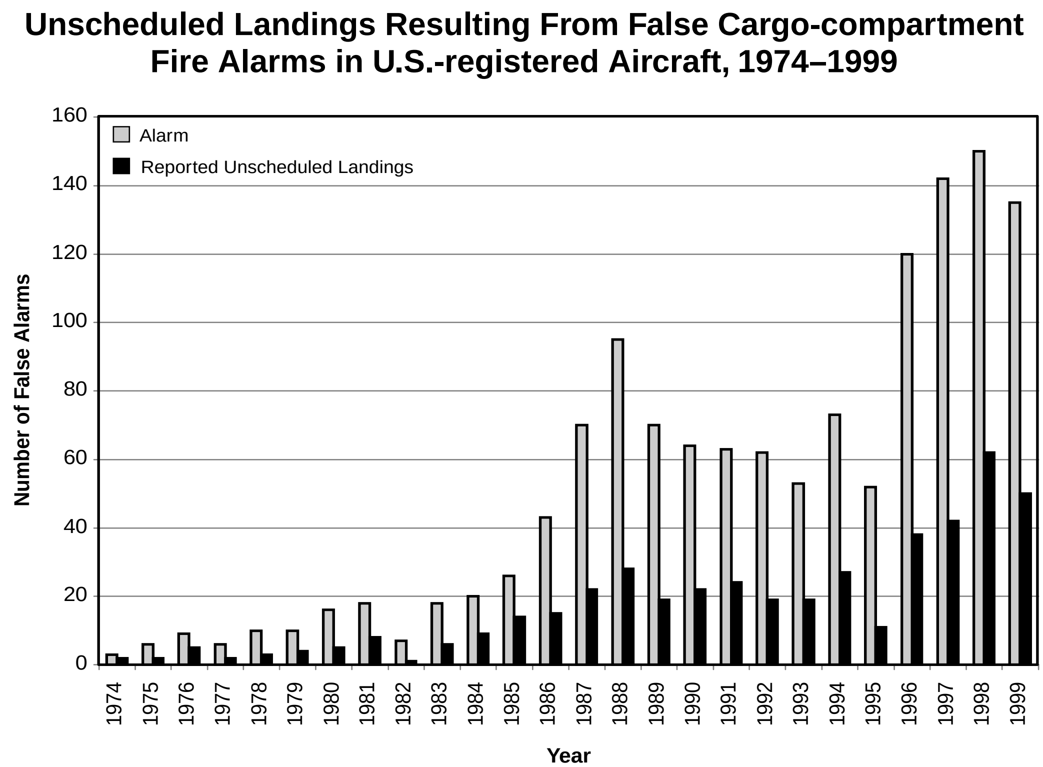
"This result would not normally be expected," the technical note said. "One possible reason … could be the increased vibrations during the high engine power settings used for takeoff and initial climb. Another possible factor is that the temperature-and-pressure environment within cargo compartments changes most rapidly when the airplane is changing altitude during climb and descent. Because the reasons for the false alarms in the vast majority of cases are never determined, the above possibilities are only speculation."♦

False Cargo-compartment Fire Alarms in U.S.-registered Aircraft, 1974–1999



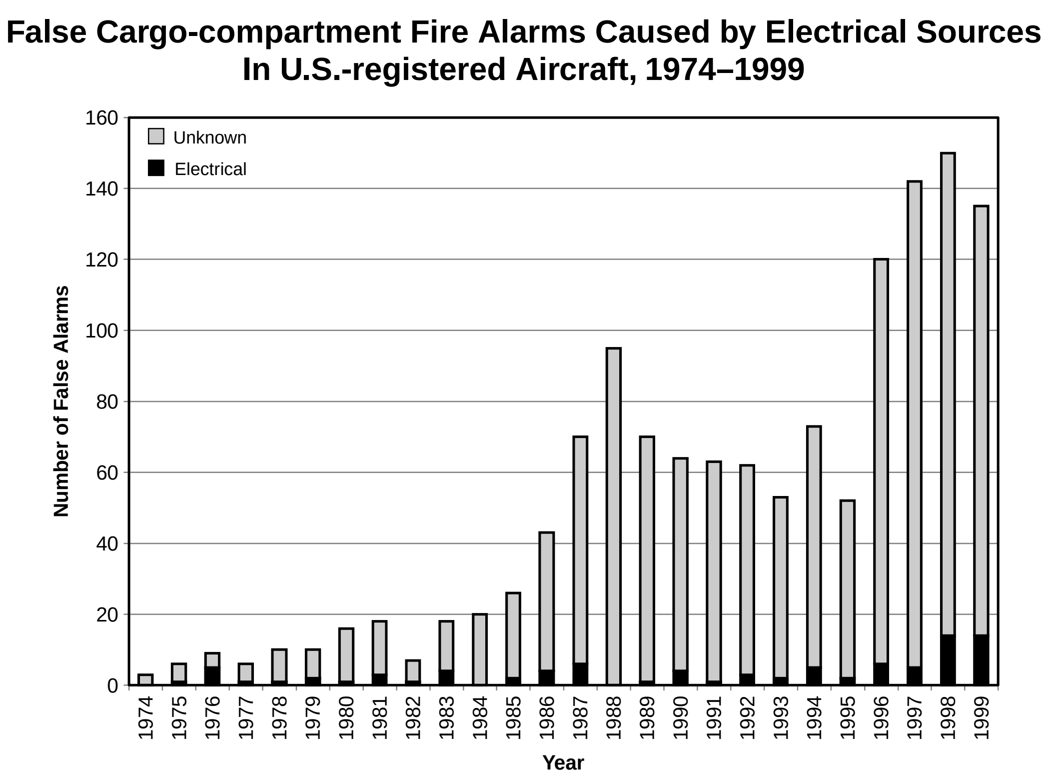
Source: U.S. Federal Aviation Administration

Figure 1



Source: U.S. Federal Aviation Administration

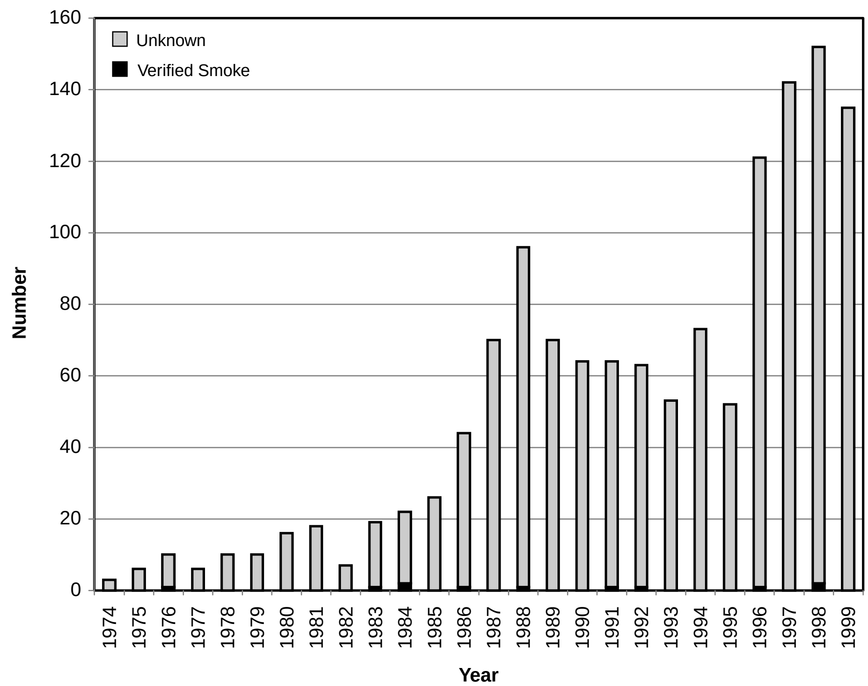
Figure 2



Source: U.S. Federal Aviation Administration

Figure 3

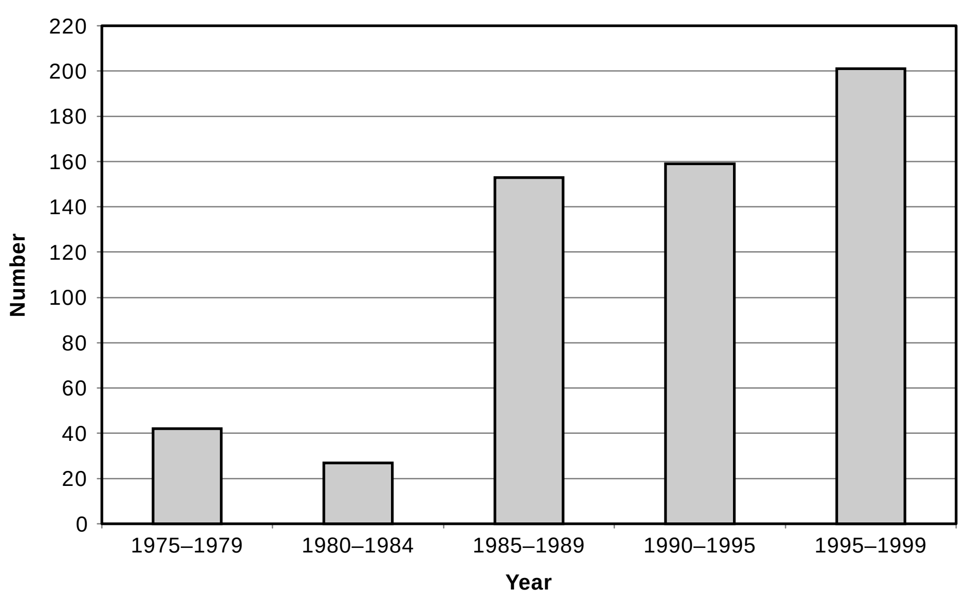
Verified Fire Events and Fire Alarms in Cargo-compartments Of U.S.-registered Aircraft, 1974–1999



Source: U.S. Federal Aviation Administration

Figure 4

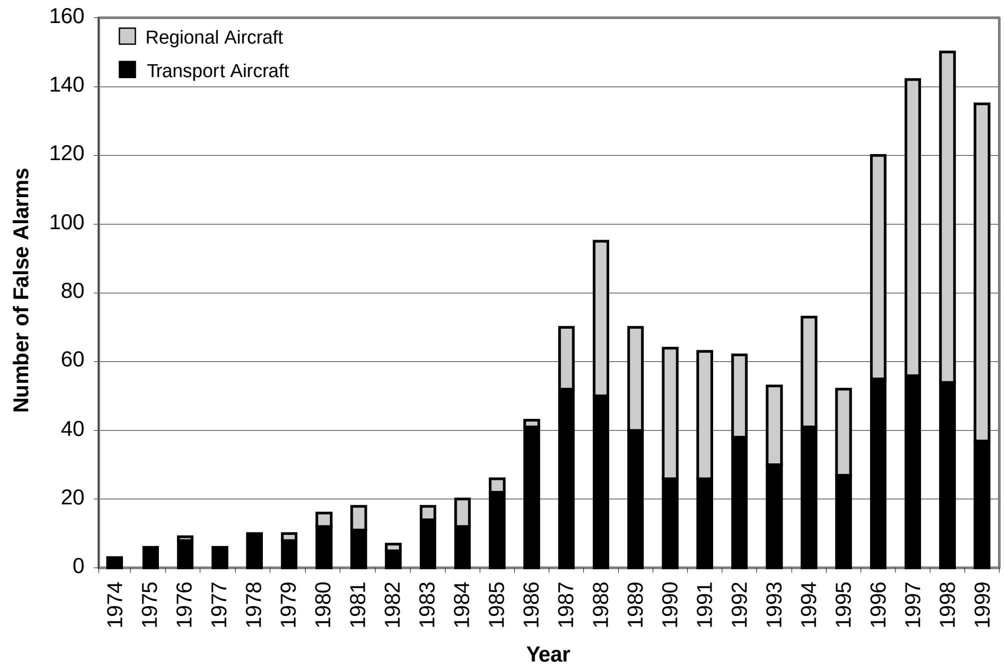
Number of False Cargo-compartment Fire Alarms for Every Alarm Caused by a Verified Smoke Source in U.S.-registered Aircraft, 1975–1999



Source: U.S. Federal Aviation Administration

Figure 5

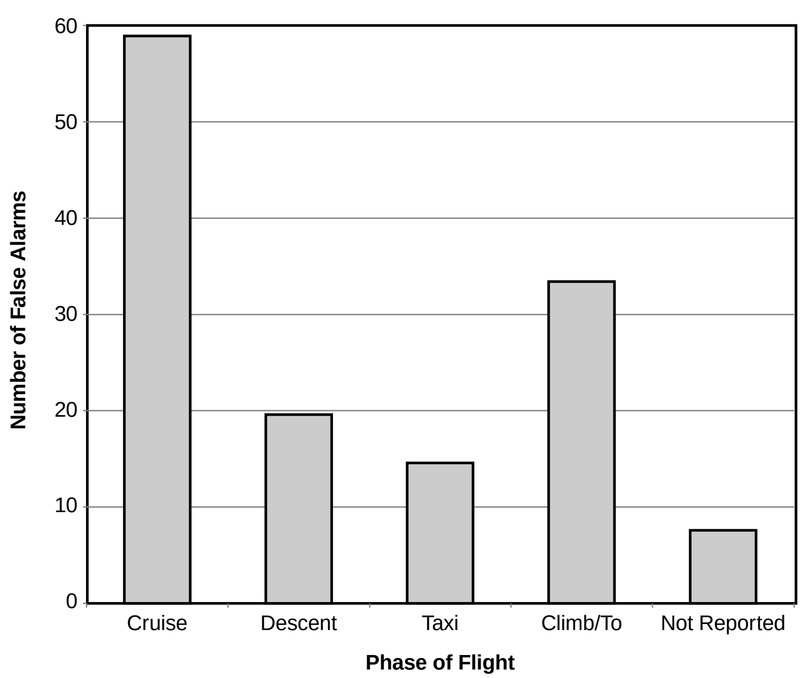
False Cargo-compartment Fire Alarms on U.S.-registered Commuter/Regional Aircraft and Transport Aircraft, 1974–1999



Source: U.S. Federal Aviation Administration

Figure 6

False Fire Alarms in Cargo-compartments of U.S.-registered Aircraft Per Phase of Flight, 1974–1999



Source: U.S. Federal Aviation Administration

Figure 7

FAA Publishes Guidelines for Assessment of Structural Repairs on Some Aging Aircraft

The advisory circular provides guidance for aircraft operators, holders of airplane type certificates and airframe modifiers.

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Advisory Circulars

Damage Tolerance Assessment of Repairs to Pressurized Fuselages. U.S. Federal Aviation Administration (FAA) Advisory Circular (AC) 120-73. Dec. 14, 2000. 10 pp. Available through GPO.*

In 1988, FAA sponsored a conference on aging aircraft that resulted in formation of the Airworthiness Assurance Task Force. The task force represented the interests of aircraft operators and type certificate holders, regulatory authorities and other aviation organizations. The task force identified five major elements for keeping aging aircraft airworthy. This AC addresses one of the five elements, the assessment of damage-tolerance of fuselage structural repairs. The AC provides guidance for operators under U.S. Federal Aviation Regulations Part 91, Part 121, Part 125 and Part 129; airplane type certificate holders; and airframe modifiers. The AC includes information about incorporating FAA-approved repair-assessment guidelines into air carrier maintenance programs or inspection programs.

Damage Tolerance for High Energy Turbine Engine Rotors. U.S. Federal Aviation Administration Advisory Circular (AC) 33.14-1. Jan. 8, 2001. 92 pp. Figures, appendixes. Available through GPO.*

Service experience with turbine engines has shown that anomalies in material and manufacturing may degrade the structural integrity of high-energy rotors. Conventional rotor life management (safe-life method) procedures have been developed "on the assumption of the existence of nominal material variations and manufacturing conditions" and therefore are not explicitly concerned with anomalies, the AC says. The AC describes an acceptable method for demonstrating compliance with U.S. Federal Aviation Regulations Part 33.14, which includes requirements for the design and life management of high-energy rotating components of turbine engines. The AC provides guidelines for damage tolerance of new-design critical titanium-alloy rotor components. The guidelines are not intended to apply retroactively to existing hardware.

Announcement of Availability: FAA Certificated Repair Stations Directory. U.S. Federal Aviation Administration (FAA) Advisory Circular (AC) 140-7K. Nov. 28, 2000. 2 pp. Availability.**

The AC announces the availability of the FAA Certificated Repair Stations Directory. The new edition covers repair stations certificated as of Sept. 12, 2000. Manufacturers' maintenance facilities no longer are included.

Land Acquisition and Relocation Assistance for Airport Improvement Program Assisted Projects. U.S. Federal Aviation Administration Advisory Circular (AC) 150/5100-17, "Change 3." Dec. 1, 2000. 27 pp. Available through GPO.*

U.S. laws require organizations that sponsor U.S. government-assisted airport projects to provide adequate relocation assistance to qualified individuals, businesses and others who are displaced because of airport projects — but preclude assistance to those living illegally in the United States. “Change 3” defines the criteria to be applied to people who are living illegally in the United States and the subsequent documentation required of airport sponsors. The AC includes questionnaires and claim forms for complying with the regulations.

Reports

Access-to-Egress: A Meta-Analysis of the Factors That Control Emergency Evacuation Through the Transport Airplane Type-III Overwing Exit. McLean, Garnet A. U.S. Federal Aviation Administration Office of Aviation Medicine. DOT/FAA/AM-01/2. January 2001. 26 pp. Tables. Available through NTIS.***

Many factors are involved in the emergency evacuation of transport aircraft. Physical factors include aircraft structure and configuration of aircraft interior components, such as aisles and seating arrangements. Information factors include signage and markings, lighting and safety-briefing cards, demonstrations and videos. Trained crewmembers conduct emergency evacuations and provide the passenger-management required for fast, effective evacuations.

Passengers typically have a negative impact on evacuations because of their inexperience with, and limited knowledge of, aircraft emergencies and related procedures. This is particularly evident when evacuations involve passenger egress through Type-III overwing exits because passengers not only must depart through the exits but also must operate them. U.S. Federal Aviation Regulations Part 25.807 defines a Type III exit as “a rectangular opening of not less than 20 inches [51 centimeters] wide by 36 inches [91 centimeters] high, with corner radii not greater than seven inches [18 centimeters] and with a step-up inside the airplane of not more than 20 inches. If the exit is located over the wing, the step-down outside the airplane may not exceed 27 inches [69 centimeters].”

This study included a review of literature to identify information on the factors affecting emergency evacuations. The author compared data, methodologies and analyses from 11 studies on experimental Type-III exit evacuations. The report said that the studies confirmed that human factors effects related to passengers present the greatest challenge to successful evacuations. Deficiencies involving the configuration of aircraft interiors and information factors are expressed through their interactions with human factors effects. Therefore, solutions designed to overcome deficiencies must address both the deficiencies and the interactions.

A Novel Method for the Determination of Sildenafil (Viagra) and Its Metabolite (UK-103,320) in Postmortem Specimens Using LC/MS/MS and LC/MS/MS/MS. Lewis, Russell J.; Johnson, Robert D.; Blank, C. LeRoy. U.S. Federal Aviation Administration (FAA) Office of Aviation Medicine. DOT/FAA/AM-00/20. May 2000. 12 pp. Figures, tables. Available through NTIS.***

During aviation accident investigation, postmortem samples from accident victims are submitted to the FAA Civil Aeromedical Institute (CAMI) for drug analysis. In addition to drug analysis, CAMI is responsible for developing methods to detect the presence of drugs. This paper reports on a rapid and reliable method for identifying and quantifying the presence of sildenafil (Viagra), which is used to treat erectile disfunction, and its metabolite, UK-103,320, in postmortem specimens.

Sildenafil has been relatively safe when used properly. Nevertheless, the drug has known side effects that could create problems for users. One possible side effect is “blue tinge,” the inability to distinguish between blue and green. Another is the drug’s hypotensive effect on individuals being treated for some heart conditions. The report describes one method used in laboratory tests to identify and measure sildenafil and UK-103,320 in blood. The same method was used to detect sildenafil and UK-103,320 in postmortem fluid and tissue specimens from fatal aviation accident victims.

Aviation Competition: Issues Related to the Proposed United Airlines-US Airways Merger. U.S. General Accounting Office (GAO). December 2000. GAO-01-212. 51 pp. Figures, tables, appendixes. Available through GAO.****

GAO, which conducts research for the U.S. Congress, examined factors related to the proposed merger of two of the largest airlines in the United States — United Airlines and US Airways. GAO focused its study on the competitive aspects of the proposed merger. The study analyzed how the proposed merger would alter the U.S. domestic airline industry, the potentially harmful effects and potentially beneficial effects on consumers, and how services would compare within the same market. The report did not review anti-trust matters and other legal aspects of the proposed merger. Appendixes show financial data for some airlines, measures of airline size and markets in which the proposed merger could reduce competition or increase competition.

A Human Error Analysis of Commercial Aviation Accidents Using the Human Factors Analysis and Classification System (HFACS). Wiegmann, D.A.; Shappell, S.A. U.S. Federal Aviation Administration (FAA) Office of Aviation Medicine. DOT/FAA/AM-01/3. February 2001. 13 pp. Figures, tables. Available through NTIS.***

Human error is a factor in a variety of occupational accidents, including accidents in civil aviation and military aviation. Statistics show that the number of aviation accidents attributable, at least in part, to human error have declined at a slower rate over the past 40 years than those attributable solely to mechanical failure. The authors said that interventions aimed at reducing occurrences of human error and the consequences of human error have not been as effective as interventions aimed at reducing mechanical failures. For this to change, more emphasis is needed on the causes of human error in relation to accidents, the authors said.

The prevailing means of investigating human error in aviation accidents is the analysis of accident data and incident data. Accident reporting systems have been designed to identify engineering failures and mechanical failures, and the terms and variables used by those systems to assess human factors typically are poorly defined, the authors said. Before new investigative methods are designed and existing databases are restructured, human error taxonomies and error-analysis systems that take into account the multiple causes of human failure should be developed, they said. One such system is the Human Factors Analysis and Classification System (HFACS). HFACS was developed and tested within the U.S. military as a tool for investigating and analyzing human error causes of aviation accidents (see "Human Factors Analysis and Classification System," *Flight Safety Digest* Volume 20 [February 2001]: 15–28). Based on psychologist James Reason's model of latent and active failures/errors and their interrelationships, HFACS helps to identify underlying causes of human error. HFACS describes human error at four levels of failure: unsafe acts of operators/flight crew, such as decision errors; preconditions for unsafe acts, such as loss of situational awareness; unsafe supervision, such as inadequate training; and organizational influences, such as equipment design.

The purpose of this study was to assess whether HFACS could be applied for error analysis and error classification outside the military and whether the HFACS framework is comprehensive enough to capture data on all underlying human causal factors associated with commercial aviation accidents. The study also was intended to determine whether all users of the system would be able to classify data in the same way and whether HFACS would highlight unknown safety issues.

The authors reviewed all accidents involving U.S. Federal Aviation Regulations Part 121 and Part 135 scheduled air carriers between January 1990 and December 1996, using database records maintained by the U.S. National Transportation Safety Board and FAA. They excluded accidents in which investigations were incomplete and those in which causes were not determined, as well as accidents that were not attributed to the flight crew. In the remaining 119 flight-crew-related accidents, researchers applied all 319 HFACS human causal factors and identified trends over the seven-year period and safety issues in need of intervention research.

Latent Trait Theory Analysis of Changes in Item Response Anchors. Farmer, W.L.; Thompson, R.C.; Heil, S.K.R.; Heil, M.C. U.S. Federal Aviation Administration (FAA) Office of Aviation Medicine. DOT/FAA/AM-01/4. February 2001. 16 pp. Figures, tables, appendix. Available through NTIS.***

The authors compared the structure of surveys administered by FAA in 1993 and 1995 to assess employee attitudes toward specific changes within the organization. Both survey instruments used five-point rating scales; in some instances, rating terms were revised for the second survey. The authors compared rating terms and responses and found that the revision of rating terms on the scale (for example, changing "agree/disagree" responses to "extent of … agreement with" responses) altered measurements and affected the comparisons of responses. The authors said that individuals who design surveys should be conservative in their approach to revising the response terms. This report may be helpful to those who design or administer surveys that may be repeated periodically to measure change, such as surveys of employees and customers.

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Washington, DC 20013 U.S.
Internet: http://www.gao.gov

Books

The International Directory of Civil Aircraft 2001/2002. Frawley, Gerard. Fyshwick, Australia: Aerospace Publications, 2001. 206 pp.

This directory is a reference of civil aircraft in production or development around the world. The directory comprises 384 aircraft entries, each accompanied by a color illustration and detailed description, including information on country of origin, aircraft type, power plant, performance, weights, dimensions, capacity, production and history. The book is current through late December 2000.

Logging Flight Time: and Other Aviation Truths, Near Truths, and More Than a Few Rumors That Could Never Be Traced to Their Sources. Kershner, William K. Ames, Iowa, U.S. Iowa State University Press, 2001. 245 pp.

This book comprises a series of articles about the author's experiences during an aviation career that has spanned more than 50 years. The collection includes new articles and articles that were published previously. The articles examine some of the author's most memorable experiences as a U.S. Navy fighter pilot, a corporate pilot and a flight instructor.♦

Abrupt Yawing Motion Prompts Return to Departure Airport

The Airbus A300 flight crew believed that the motion, which was accompanied by a bang, was the result of an uncommanded rudder input. An investigation found that the airplane had encountered the wake vortex of a Boeing 777.

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The following information provides an awareness of problems through which such occurrences may be prevented in the future. Accident/incident briefs are based on preliminary information from government agencies, aviation organizations, press information and other sources. This information may not be entirely accurate.

Air Carrier

Investigation Reveals No Anomalies in Airplane's Operation

Airbus A300. No damage. No injuries.

The airplane was being hand-flown following an afternoon takeoff from an airport in England for a flight to the United States. As the airplane approached Flight Level 220 (22,000 feet), at 325 knots, there was "an abrupt disturbance, which was perceived by the flight crew to be a disturbance in yaw," and a bang, the incident report said.

The flight crew believed that the yawing motion was the result of an uncommanded rudder input and that the noise was related to the yawing motion.

At the time, the airplane's flaps and slats were retracted, the landing gear was retracted, the autopilot was disengaged, and pitch-trim systems 1 and 2 and yaw-damper systems 1 and 2 were engaged. No other aircraft were reported in the vicinity, and the airplane was clear of clouds.

After the yawing motion, the airplane appeared to fly normally. Nevertheless, the captain decided to return to the departure airport, "rather than commence a trans-Atlantic flight following a suspected uncommanded flight-control input," the report said. The landing was normal.

The investigation of the incident, including analysis of data from the airplane's flight data recorder, showed that the yawing motion was "a small disturbance, but it is probable that the flight crew, being seated in the cockpit, perceived a higher level of lateral acceleration, which they interpreted as uncommanded rudder input," the report said.

The report said, "Extensive engineering investigation did not find any reason for the disturbance to have occurred, and no anomalies in the operation of the aircraft were found during the test flight. Furthermore, there was nothing from the engineering investigation that could explain the loud noise."

Investigators also considered the possibility that the airplane had encountered various meteorological phenomena. The report said, "It is most probable that the reason for any localized turbulence was an encounter with the wake vortex generated by a Boeing 777 aircraft which had passed through the same airspace some four minutes and 18 seconds earlier."

Research has shown that a loud noise can occur when an airplane enters the core of the wake vortex "if the geometry is appropriate," the report said.

First Officer Injured by Lightning Strike

Boeing 757. No damage. One minor injury.

The first officer was flying the airplane on a midday approach to an airport in the Netherlands. Cumulonimbus clouds were in the area, and the captain was providing steering advice to navigate between two storm cells.

"The first officer was seated with his right hand and part of his right arm resting on the cockpit coaming [the raised frame below the windscreen], close to the right forward windscreen," the accident report said. "At about 5,000 feet on the approach, the aircraft was struck by lightning just below the right windscreen.

"The first officer was aware of a loud bang and bright flash and described feeling as if he had been kicked in the chest."

After the incident, the first officer had difficulty using his right arm, and the captain took over flying duties. A medical examination showed that the first officer had a burn wound on his chest "consistent with an electrical discharge," but an inspection of the aircraft showed no evidence of a lightning strike. The first officer resumed flight duties two weeks after the incident but later developed "a medical condition that may be a consequence of the incident," the report said.

Airplane Struck by Deicing Truck

Boeing 767. Minor damage. No injuries.

The airplane was being deiced at an airport in Canada when a deicing truck slid on ice and struck the airplane above the passenger windows aft of the left wing. The collision resulted in a 15-inch (38-centimeter) crease in the fuselage.

The flight was canceled, and the aircraft was removed from service for inspection and subsequent maintenance.

Crew Observes Rudder Oscillation During Final Approach

Boeing 737. No damage. No injuries.

The airplane was being flown at 1,000 feet on final approach to an airport in Australia when the flight crew felt a "kick" in the rudder pedals and a minor yaw oscillation. There were no aircraft ahead of the incident aircraft that would have caused wake turbulence.

The operator's investigation showed that there had been a problem with the rudder power control unit. The unit, which had accumulated 3,064 operating hours since the manufacturer's overhaul two years before the incident, was examined by the component manufacturer.

The incident report said, "No discrepancies that may have led to the anomaly in the operation of the rudder power control unit were found. The internal and external components contained no evidence of excessive wear, damage or over-travel and met the manufacturer's standards for in-service units."

The U.S. National Transportation Safety Board conducted a performance simulation study based on aircraft configuration data at the time of the incident.

"The study concluded that the rudder had oscillated," the incident report said. "The investigation was unable to determine why the rudder … oscillated."

'Smoke' Prompts Emergency Landing

Boeing 747. Minor damage. No injuries.

After takeoff from an airport in England, the flight crew observed what appeared to be smoke below the center console. The cabin crew reported smoke throughout the cabin, and air traffic control told the flight crew that smoke momentarily had been seen from one of the airplane's left engines.

The flight crew declared an emergency and returned to the departure airport for a normal landing. The airport fire and rescue service told the crew that the smoke was coming from the no. 2 engine; the crew shut down the engine and the airplane was returned to the gate, where passengers deplaned normally.

An inspection by maintenance personnel showed evidence that oil from the no. 2 engine had entered the air-conditioning bleed ducts and that the no. 2 engine vane controller (EVC) was defective.

"An EVC trim run was therefore carried out," the incident report said. "During this trim run, the EVC showed indications of failure. In addition, evidence of bird strikes was apparent across the front of the no. 2 engine, and there

[were] also associated signs of slight damage to the fan blades, inlet guide vanes and fan-exit guide vanes."

A borescope inspection showed no damage to the high-pressure compressor. The fan blades and the fan-exit guide vanes were cleaned, and another EVC trim run and high-power run were conducted. This time, results were considered satisfactory.

"Maintenance personnel concluded that the bird debris had affected the airflow-sensing system for the inlet-vane control system, which had affected inlet-vane scheduling, causing a reduction in compressor airflow and [an] associated loss of the correct air pressure balance across one or more of the internal oil/air labyrinth seals," the report said. "This had allowed oil to pass across the seals and to enter the airflow within the compressor stages, where the oil-laden air would have become heated before being passed into the bleed duct for the air conditioning system."

The result was that an oily mist — mistaken for smoke — entered the flight deck and the cabin. The airplane was returned to service the day after the incident, and the engine operated normally.

Air Taxi
Commuter

Engine-fire Warning Light Illuminates During Final Approach

De Havilland DHC-8. Minor damage. No injuries.

Visual meteorological conditions prevailed for the morning flight to an airport in the United States. The airplane was being flown on final approach when the flight crew observed an increasing turbine-inlet-temperature indication on the no. 2 engine. The crew also felt a vibration, and a burning odor was detected in the cabin.

The flight crew declared an emergency and continued the approach and landing. During the rollout, the engine-fire warning indicator illuminated, and the flight crew shut down the no. 2 engine. The crew and passengers deplaned through the forward left-main cabin exit onto the runway.

An inspection showed that the no. 5 (compressor) bearing and its air seal were destroyed, that there was evidence of an oil leak and a fire within the breather case and compressor section and that the breather tube had melted.

The engine was removed for further inspection.

Airplane Strikes Snow-covered Terrain During Landing

Hawker Siddeley HA 125-700. Substantial damage. No injuries.

Night instrument meteorological conditions prevailed for most of the domestic flight in the United States. Nevertheless, the captain said that he and the first officer could see the runway at the destination airport when the airplane was at 2,500 feet and five nautical miles (nine kilometers) away. He said that he flew an instrument landing system approach and landed the airplane on the runway.

An investigation showed that the airplane first contacted the ground 160 feet (49 meters) left of the runway and 3,500 feet (1,068 meters) beyond the threshold. The airplane settled into snow that was two feet to three feet (0.6 meter to 0.9 meter) deep and left tracks in the snow for about 600 feet (183 meters). The airplane's right wing separated; the left wing was substantially damaged.

Pilots Faulted for Beginning Takeoff Without Clearance

Embraer EMB-120ER. No damage. No injuries.

Saab AJS-37 Viggen (two-aircraft military formation). No damage. No injuries.

Day visual meteorological conditions prevailed when the two military aircraft were taxied to Runway 22 at an airport in Sweden. Soon afterward, the EMB-120 flight crew received clearance from a tower controller to taxi to Runway 32, an intersecting runway; while taxiing, the crew received an instrument flight rules clearance.

The pilots of the military aircraft received clearance for takeoff from Runway 22. As the military pilots began their takeoffs from Runway 22, the EMB-120 flight crew began a takeoff on Runway 32. The tower controller observed that the EMB-120 crew had begun a takeoff without clearance and ordered them to discontinue the takeoff.

The EMB-120 crew stopped the airplane about 600 meters (1,969 feet) before the intersection of the two runways.

The EMB-120 crew said that they probably had been monitoring the radio frequency for ground control when the military pilots received their taxi clearance and their takeoff clearance and that they were unaware that the military formation was departing on the intersecting runway.

The company said that the pilots had not properly confirmed that they had been given takeoff clearance. The captain could not remember whether he had asked the first officer to place the condition levers in the takeoff position — action that typically is taken after receiving takeoff clearance.

The report said, "The company has offered a possible explanation in that the [first officer] continued to complete the pre-takeoff checklist prior to receiving takeoff clearance."

The incident report said, "In a well-functioning two-pilot cockpit, mistakes of this nature shall not normally happen. The fact that it did occur points to a breakdown in [crew] resource management."

The report said that factors contributing to the incident were the short taxi distance of 300 meters (984 feet) from the terminal to Runway 32, that takeoff clearances often are issued before pilots have completed their pre-takeoff checklists and "that complacency can arise in pilot routines, as the company only operates on the one route."

The operator revised procedures after the incident to require that flight crews review all clearances before departure.

Corporate Business

Both Engines Stop During ILS Approach

De Havilland DHC-6-300 Twin Otter. Substantial damage. No injuries.

Instrument meteorological conditions prevailed for the mid-afternoon instrument landing system (ILS) approach to an airport in the United States. The pilot said that the airplane was established on the localizer course but had not intercepted the glideslope when the right engine surged and stopped. Then the left engine surged and stopped.

The pilot was given vectors to a nearby airstrip but believed that the airplane could not be flown that far, so he conducted an emergency landing in a field. After touchdown, the right wing struck a tree, and the nose-landing gear struck a mound of dirt and separated from the airplane.

A subsequent inspection showed that the aft-main fuel tank was 33 percent full of fuel to 50 percent full of fuel, and the forward-main fuel tank was 90 percent full of fuel. The accident report said that the integrity of the right-wing fuel tank was compromised, and fuel was leaking from the right wing. The left-wing fuel tank was empty. The cockpit fuel selector for the main tanks was in the "NORMAL" position; in that position, the aft-main tank supplies fuel to the left engine, and the forward-main tank supplies fuel to the right engine.

The pilot said that the airplane had been fueled the day before the accident, then flown to another airport. The airplane was placed in a hangar overnight, then flown nearly three hours before the accident occurred.

Faulty ELT Switch Disrupts Air Traffic Operations

Cessna 425 Conquest. No damage. No injuries.

The pilot was flying the airplane on an early morning final approach to a major airport in Canada when all very-high-frequency avionics equipment failed. For about 30 seconds, the pilot heard a progressively louder signal from the emergency locator transmitter (ELT). Then he used a cellular telephone to call air traffic control (ATC). During the telephone call, he was told to descend to 7,000 feet and to fly a heading of 140 degrees. He lost contact with the controller, made another call using his cellular telephone and told the controller that he would fly a visual flight rules approach to a nearby airport.

He conducted a normal landing. ATC said that the incident resulted in departure delays at the major airport, ground delays for 13 aircraft at satellite airports and the issuance of holding instructions for three airborne aircraft.

A maintenance inspection showed that a switch in the airplane's ELT was faulty and that the faulty switch probably had interfered with the operation of avionics equipment.

Airplane Slides off Runway After Snowfall

Learjet 60. Substantial damage. No injuries.

Visual meteorological conditions prevailed for the morning flight to an airport in the United States. The captain said that, because of a "maintenance discrepancy," they had flown the 43-minute repositioning flight with the airplane's thrust reversers mechanically pinned to the forward thrust position.

The flight crew planned to fly an instrument landing system approach to Runway 18, which was 6,299 feet (1,921 meters) long and had a gradient of minus 0.611 percent. As they approached the airport, the automatic weather observing system reported that the wind was from 030 degrees at nine knots; 90 seconds before touchdown, the wind was from 010 degrees at seven knots.

Snow had fallen the night before the accident, and the airport manager said that airport ground crews had plowed the runway. At 0516 local time, more than three hours before the accident, the runway condition report said that there was thin ice on the runway and that braking action was fair.

The captain said that he was told braking action was fair and that he flew the final approach at "V_{REF} plus a couple of knots, continued the approach and made a normal touchdown approximately 800 [feet] to 1,000 feet [244 meters to 305 meters] down the runway." The captain said that when he applied the brakes about 500 feet (153 meters) to 800 feet after touchdown, he "noticed very little deceleration." He told a company official immediately after the accident that he had used "emergency braking" and said in an accident report to the U.S. National Transportation Safety Board that he had used maximum braking effort. Later, he told accident investigators that he could not remember whether he had used emergency braking.

The captain said that, at about mid-runway, the airplane slid back and forth across the runway. The airplane departed the end of the runway at about 40 knots and traveled forward about 160 feet (49 meters) in snow that was about two feet (0.6 meter) deep. The nose landing gear separated and penetrated the airplane pressure vessel.

A representative of the manufacturer said that, when emergency braking is used, "a very loud, high-pitched sound would be heard in the cockpit as the high-pressure air went into the brake lines."

The cockpit voice recorder (CVR) recorded a high-pitched sound at 0839:44, and the report said, "The CVR documentation suggests that the airplane left the runway at 0840:00."

The manufacturer's airplane flight manual says that when emergency braking is used, anti-skid protection is deactivated. The manual also says that the airplane should be landed on a contaminated runway only when there is no tail wind, the runway gradient is between minus 1 percent and 2.2 percent and the anti-skid system is operational.

Tires Fail During Hard Landing on Fog-covered Runway

Learjet 35A. Substantial damage. No injuries.

Instrument meteorological conditions prevailed for the early morning approach to an airport in the United States.

The pilot said that he told air traffic control that he had the runway in sight.

The accident report said, "[The pilot] followed the VOR [very-high-frequency omnidirectional radio] radial and made an approach. At 800 feet, he lost sight of the runway because of 'light fog.' He performed a missed approach and stayed in the pattern VFR (visual flight rules). He performed a second approach visually and said he was distracted by the fog but did not lose sight of the runway. He said the landing was hard but did not realize he had a problem until the airplane started pulling to the left."

The left-main landing-gear tires failed, and the airplane traveled 4,100 feet (1,250 meters) along the runway before stopping. The pilot said that the two-member crew and three passengers deplaned quickly because of a fuel leak.

Reported visibility at the time of the accident was zero.

Other General Aviation

Deicing Attempt Leaves Ice on Wings

Bellanca 8GCBC Scout. Substantial damage. No injuries.

The float-equipped airplane was being flown on a short midday visual flight rules flight in Canada. The pilot said that he was unable to control the pitch attitude as the airplane descended for its water landing and that the airplane "felt very sluggish," even though full power had been applied, the accident report said.

About 300 feet above the water, the airplane descended rapidly. The right wing struck the water, but the airplane remained upright and the pilot taxied to the dock. The pilot observed "a heavy layer of ice" on the wings, flaps, elevators and floats.

"The pilot had poured water on the wings and flight control surfaces to clear off the layer of accumulated snow before they took off," the report said "The temperature at that time was about minus 5 degrees Celsius [23 degrees Fahrenheit]."

Insufficient Directional Control Cited in Landing Accident

Yakovlev 50. Substantial damage. No injuries.

The pilot planned to fly his newly purchased airplane from Russia to Sweden and France. Visibility was six kilometers (four miles) in haze, and wind was from 130 degrees at eight knots as the pilot prepared for a late-afternoon landing on Runway 19 at an airport in Sweden.

After touching down, the airplane "developed yaw disturbances in connection with the rollout," the accident report said. The pilot attempted to steer the airplane with asymmetrical braking, but the airplane experienced a ground-loop to the left, which broke the right-main landing gear.

The accident report said that the accident was caused by "insufficient heading control in connection with the rollout." The pilot also may have pushed the control stick forward of its neutral position, "thus suspending the locking of the tail wheel," the report said.

Airplane Strikes Terrain After Takeoff With 20-knot Tail Wind

Cessna 172P. Substantial damage. One serious injury.

Visual meteorological conditions prevailed for the afternoon takeoff from an airport in Haiti. The pilot began to taxi toward the west on Runway 27 in preparation for a takeoff on Runway 9. Another aircraft was inbound for landing.

The accident report said, "When the accident aircraft was about mid-runway during the back-taxi, the pilot performed the takeoff to the west with a 20-knot tail wind to vacate the runway surface."

The aircraft owner said that, during the initial climb-out, the pilot began a turn to the south, and the airplane stalled, descended and struck terrain while inverted.

Airplane Strikes Cable During Landing on Farm Field

Piper PA-18-150 Super Cub (modified). Minor damage. No injuries.

Visibility was described as good for the early evening landing at a farm field in England. The pilot intended to tow a glider that had landed in the field and to transport the glider to a gliding club's field.

The glider pilot had told individuals associated with the gliding club that the farm field was suitable for landing and that the farmer had given permission for the airplane pilot to land. He mentioned no obstructions.

The airplane pilot said that he overflew the landing area to check for obstructions. He said that he observed telegraph wires along both sides of a road adjacent to the western end of the field and believed that there was enough distance for the airplane to clear the wires and to be landed safely. The pilot flew the airplane on final approach as he had planned, but when he was about to flare the airplane, he observed a single-strand feeder cable in front of the airplane. The airplane struck the cable, pitched nose-down and banked to the right. The cable broke the airplane's right wing, and the propeller struck the ground, causing the engine to stop and the aircraft to roll inverted.

The report said, "The pilot concluded that, during his assessment of the site, he had not seen the wires, which were difficult to detect, although he thought it might have been possible to see them if he had … searched at a lower height. A more thorough search for obstacles by the glider pilot and use of the radio communications, if available to the pilots, would have provided a method of drawing attention to any obstructions, which might have been a hazard to the tug as it landed."

Rotorcraft

Fuel Exhaustion Cited in Helicopter's Forced Landing

Bell 206L-3 LongRanger. Minor damage. No injuries.

Visual meteorological conditions prevailed for the flight near an oil platform in the Gulf of Mexico. The pilot said in radio transmissions that he had 0.9 hour of fuel remaining and that he was departing from one location at 1125 local time and expected to arrive at the oil platform at 1139. He said that the helicopter would have a "critical fuel" situation, and he asked that the platform's refueling pad be left open. The pilot also said that he had missed a platform "a couple of miles" to the east.

As the pilot turned the helicopter to approach the platform for landing, the engine lost power.

The accident report said, "Subsequently, the pilot declared 'mayday,' deployed the skid-mounted float system and autorotated the helicopter to a successful water landing. Upon landing, the pilot stopped the main-rotor blades perpendicular to the longitudinal axis of the aircraft. The pilot and passenger deployed the life raft, exited the helicopter and were later recovered to the platform with no reported injuries."

About five minutes after the landing, the helicopter rolled inverted and "settled into the water," the report said. The helicopter was recovered, and an examination showed that about 1.2 gallons (4.5 liters) of Jet-A fuel were in the fuel tanks. Tests showed that the fuel-quantity indicator and "low-fuel" warning-system light functioned normally. The operator said that the forced landing was a result of apparent fuel exhaustion.

Helicopter Strikes Hillside After Uncommanded Yaw

Bell 206B JetRanger. Helicopter destroyed. Two minor injuries.

Visual meteorological conditions prevailed at the beginning of a pipeline-survey flight in Wales but deteriorated to visibility of three kilometers to six kilometers (1.9 miles to 3.7 miles) with an overcast cloud base of 1,000 feet to 1,500 feet in the mountains. The pilot said that, as conditions deteriorated ahead of the helicopter and to the right, he turned the helicopter left, toward a steep hillside, to maintain visual contact with the ground.

"During the turn, an unidentified amber caution on the central warning panel illuminated, and an [uncommanded] yaw to the right developed," the accident report said.

The pilot was uncertain which amber caution light had been illuminated, but, when his corrective action on the yaw pedals did not stop the yawing motion, he suspected a tail-rotor failure. He turned the helicopter in the direction of the yaw to attempt to regain directional control, but the helicopter continued to yaw to the right "and in doing so, intermittently entered cloud," the report said. "Ultimately, the helicopter made contact with the ground and broke up."

Subsequent inspection of the helicopter showed that the tail-rotor drive system was functional at the time of impact.

Helicopter Rolls on Side During Forced Landing

Westland Scout AH1. Aircraft destroyed. No injuries.

The pilot departed from an airport in England in weather that was forecast to include "generally good visibility … with conditions expected to deteriorate in occasional rain showers." He established the helicopter in cruise at 1,200 feet, and, about five minutes later, visibility began to deteriorate. Because of a lowering cloud base, the pilot descended to 800 feet, then decided to return to the departure airport.

He conducted a 180-degree turn, but conditions deteriorated further, and the pilot then decided to conduct a forced landing in a field.

The accident report said, "To keep the field in sight, the pilot put the helicopter into a tight right-hand descending spiral and reduced the forward speed. As it approached the ground, still turning to the right and with low forward speed, the pilot applied collective pitch to reduce the rate of descent and left yaw pedal. … [W]ith full left yaw pedal applied, the pilot was unable to stop the yaw, and, as he applied more collective lever for the landing, the over-torque warning sounded."

The helicopter continued to yaw to the right as it descended, and the tail and the rear of the left skid struck the ground. The left skid dug into the ground, causing the helicopter to roll onto its left side and the main rotors to strike the ground. The pilot and his passenger climbed out the right-front door.

The pilot said that he was unable to stop the yaw to the right because the tail rotor had stalled.

The *Army Aircrew Manual* for the Scout says, "If an excessive amount of left pedal is being used during the final stages of any approach, there is a danger of losing yaw control; in this event, the collective lever should be lowered slightly, maintaining the left pedal position, and forward speed increased smoothly using left cyclic cautiously to aid directional control. Should the loss of yaw control be allowed to develop before recovery action is initiated, a high rate of descent will follow and considerable over-torquing will be required to prevent the aircraft striking the ground."

Pilot Blames Encounter With Wasp for Damage to Helicopter

Bolkow BO-105. Minor damage. No injuries.

During a post-maintenance flight at an airport in England, the pilot hovered the helicopter. He observed that the friction of the collective pitch lever was loose and began to move the helicopter clear of the taxiway and away from other aircraft.

The accident report said, "As the helicopter moved forward, a wasp flew into the pilot's face, stinging him on the cheek below his left eye. Instinctively, he moved his left hand from the collective control to swat the wasp. As he did so, the helicopter descended from approximately eight feet (2.4 meters), landing and rotating about the left skid until the right skid made contact with the surface."

The pilot observed that both landing-gear cross tubes had been damaged. The pilot requested help from maintenance personnel, and after an inspection, the helicopter was repositioned to the helipad for a normal shutdown.♦

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