FLIGHT SAFETY FOUNDATION

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Boeing 747 In-flight Breakup Traced to Fuel-tank Explosion

Investigators concluded that a flammable mixture of fuel and air in the center-wing fuel tank likely was ignited by voltage from an external short circuit that was conducted into the tank by electrical wiring associated with the fuel quantity indication system.

FSF Editorial Staff

About 2031 local time July 17, 1996, a Boeing 747-131 operated as Flight 800 by Trans World Airlines (TWA) struck the Atlantic Ocean near East Moriches, New York, U.S. The 230 occupants were killed. En route from New York, New York, to Paris, France, the airplane had been climbing through about 13,760 feet when an explosion occurred, followed by a structural breakup of the airplane.

The U.S. National Transportation Safety Board (NTSB) said, in its final report, that "the probable cause of the TWA Flight 800 accident was an explosion of the center-wing fuel tank (CWT), resulting from ignition of the flammable fuel/air mixture in the tank. The source of ignition energy for the explosion could not be determined with certainty, but, of the sources evaluated by the investigation, the most likely [source] was a short circuit outside of the CWT that allowed excessive voltage to enter [the tank] through electrical wiring associated with the fuel quantity indication system.

"Contributing factors to the accident were the design-and-certification concept that fuel tank explosions could be prevented solely by precluding all ignition sources and the design and certification of the Boeing 747 with heat sources located beneath the CWT with no means to reduce the heat transferred into the CWT or to render the fuel vapor in the tank nonflammable."

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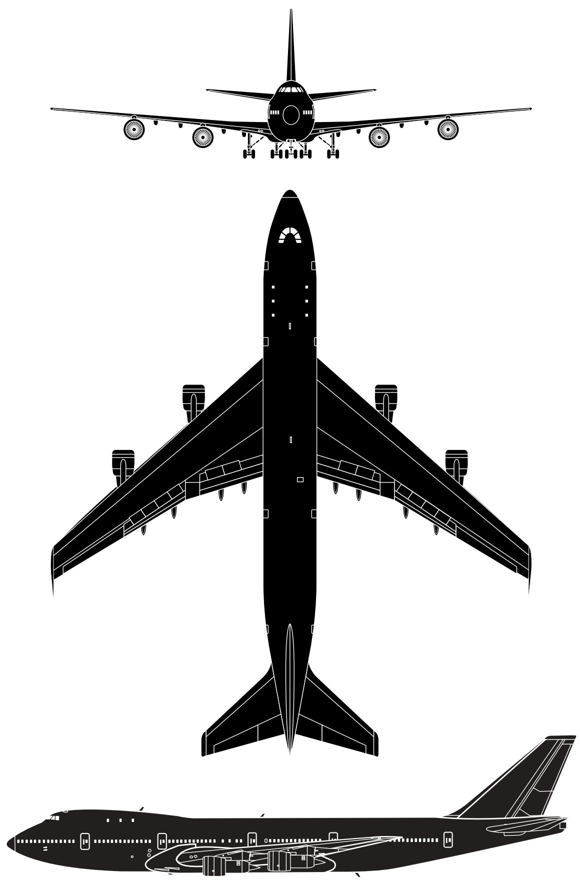
On the day of the accident, the airplane was flown from Athens, Greece, to John F. Kennedy International Airport (JFK).

"A scheduled flight crew change occurred at JFK," the report said. "The accident airplane was refueled at JFK and remained at [the gate] with the auxiliary power unit (APU) and two of its three air-conditioning packs operating (for about 2.5 hours) until it departed as TWA Flight 800."

Purchased new by TWA in 1971, the airplane had accumulated 93,303 hours of operation and 16,869 flight cycles (takeoff-and-landing sequences).

The crew of TWA Flight 800 included four flight crewmembers and 14 flight attendants.

The captain, 58, was hired by TWA in May 1965. He served as a first officer of Convair 880s and as a first officer and a captain of B-707s and Lockheed 1011s. He earned a B-747 type rating in February 1990 and began training to upgrade as a B-747 captain in May 1996. He completed a proficiency check on June 19, 1996. At the time of the accident, the captain had accumulated approximately 18,800 flight hours, including 5,490 flight hours in B-747s. He occupied the left-front seat and was the pilot flying (PF) during the accident flight.



Boeing 747-100

The B-747-100 first flew in 1968, and deliveries began in 1969. The airplane accommodates three flight crewmembers and up to 500 passengers.

Each of the four Pratt & Whitney JT9D-series engines produces from 43,500 pounds to 47,000 pounds (19,732 kilograms to 21,319 kilograms) thrust, depending on engine version installed. Maximum fuel capacity is 47,210 gallons (178,690 liters).

Maximum takeoff weight is 710,000 pounds (322,056 kilograms). Maximum landing weight is 564,000 pounds (255,830 kilograms). Range at long-range cruise power with 374 passengers and fuel reserves is 5,028 nautical miles (9,312 kilometers).♦

Source: *Jane's All the World's Aircraft*

A captain/check airman occupied the right-front seat and was the pilot not flying (PNF). The PNF, 57, was hired by TWA in April 1964. He served as a first officer in Convair 880s and as a flight crewmember in B-707s, B-727s and L-1011s. He earned a B-747 type rating in December 1974 and qualified as a B-747 check airman in May 1993. At the time of the accident, he had accumulated approximately 17,000 flight hours, including 4,700 flight hours in B-747s.

A flight engineer trainee occupied the flight engineer's station. The flight engineer trainee, 24, was hired by TWA on June 22, 1996. He held a flight engineer certificate and had accumulated approximately 2,520 flight hours, including approximately 30 flight hours as a B-747 flight engineer trainee.

A flight engineer/check airman occupied the flight deck jump seat. The flight engineer/check airman, 62, was hired by TWA in February 1966. He served as a flight engineer and as a first officer in Lockheed Constellations before he earned a B-747 type rating in 1986. He served as a B-747 first officer and captain until reaching the mandatory pilot-retirement age of 60 in July 1993, whereupon he elected to continue flying as a B-747 flight engineer. He had accumulated approximately 3,047 flight hours as a flight engineer, including 2,397 flight hours as a B-747 flight engineer.

TWA Flight 800 was scheduled to depart from JFK at 1900 but was delayed by a disabled vehicle blocking the airplane's exit from the gate and by a "passenger/baggage mismatch."

"Although a passenger's bag had been pulled because [gate agents] suspected it was unattended, they subsequently confirmed that 'the passenger was on board the whole time,'" said the report.

The airplane was pushed back from the gate at 2002 and took off from Runway 22R at 2019. Visual meteorological conditions prevailed in the area.

The flight crew received several heading assignments and altitude assignments from air traffic control (ATC). [A partial transcript of the cockpit voice recorder (CVR) recording begins on page 11.] At 2023, a Boston Air Route Traffic Control Center controller told the flight crew to fly directly to BETTY intersection. At 2025, the controller told the flight crew to climb to Flight Level 190 (19,000 feet) and to maintain FL 190.

At 2026, the controller amended the clearance and told the crew to maintain 13,000 feet. The controller told the crew that there was traffic, a Beech 1900, at their one o'clock position and seven miles (13 kilometers) ahead, southbound at 14,000 feet. The PNF told the controller that they did not have the traffic in sight.

At 2029, the captain said, "Look at that crazy fuel flow indicator there on [the] number four [engine]." He then said, "Somewhere in here, I better trim this thing [in (or) up]."

The PNF said, “Huh?”

The captain said, “Some place in here, I better find out where this thing’s trimmed.”

At 2030, the controller told the crew to climb to 15,000 feet and to maintain 15,000 feet.

The PNF read back the clearance to the controller, and the captain told the flight engineer to set climb thrust.

The captain then said, “Ollie.”

The flight engineer said, “Huh?”

The captain said, “Climb thrust.”

The flight engineer said, “Power’s set.”

The report said, “The CVR recording of the next 30 seconds from the cockpit area microphone (CAM) includes the following sounds:

- “A sound similar to a mechanical movement in the cockpit (at 2030:42);
- “An unintelligible word (at 2031:03); and,
- “Sounds similar to recording tape damage noise (at 2031:05).”

(The report said that the sounds similar to recording tape damage noise were caused by water damage to the tape head.)

At 2031:12, the CVR stopped recording, the flight data recorder (FDR) stopped recording, and the last return from the airplane’s transponder was recorded by air traffic control (ATC). Several pilots then told ATC that they had observed an explosion.

“Many witnesses in the vicinity of the accident at the time it occurred stated that they saw and/or heard explosions, accompanied by a large fireball over the ocean, and [that they] observed debris, some of which was burning, falling into the water,” the report said. “About one-third of these witnesses reported that they observed a streak of light, resembling a flare, moving upward in the sky to the point where a large fireball appeared. Several witnesses reported seeing this fireball split into two fireballs as it descended toward the water.

“Pieces of the airplane wreckage were discovered floating on and beneath the surface of the Atlantic Ocean about eight miles [15 kilometers] south of East Moriches … . The main wreckage was found on the ocean floor.”

The report said that the widespread distribution of the airplane wreckage and the witness reports indicated that an in-flight structural breakup had occurred.

“On the basis of this initial information, investigators considered several possible causes for TWA Flight 800’s in-flight structural breakup: a structural failure and decompression; detonation of a high-energy explosive device, such as a bomb exploding inside the airplane or a missile warhead exploding upon impact with the airplane; and a fuel/air explosion in the [CWT],” said the report.

Investigators found no signs of preexisting conditions that might have caused a structural failure and decompression.

“The examination revealed that the structure did have minimal preexisting corrosion damage, none of which would have led to or affected the breakup of the airplane,” the report said. “Small fatigue cracks were found in some parts of the airplane, including in the lower chord of the front spar and in the shear ties for the floor beams and stiffeners at the front spar; however, none of these cracks had coalesced into a propagating crack that could have led to the in-flight breakup.”

The possibility that the breakup resulted from in-flight separation of the forward cargo door was examined. All eight latching cams on the bottom of the door and some pieces of the door were found attached to the pins on the lower door sill; no signs were found of preimpact failure of the upper door hinge.

“This evidence indicates that the door was closed and locked at impact,” said the report.

The report said that speculation that the breakup might have been caused by a bomb or missile was generated by the following factors: heightened safety concerns and security concerns because the 1996 Olympics were being held in the United States; TWA Flight 800 was an international flight; the sudden and catastrophic nature of the in-flight breakup; and reports by several witnesses of a “streak of light” and then a “fireball.”

The U.S. Federal Bureau of Investigation (FBI) found trace amounts of explosives on a piece of canvas-like material and on two pieces of floor panel.

“However, none of the damage characteristics typically associated with a high-energy explosion of a bomb or missile warhead … were found on any portion of the recovered airplane structure, including the pieces on which the trace amounts of explosives were found,” the report said. “Only about 5 percent of the airplane’s fuselage was not recovered, and none of the areas of missing fuselage were large enough to have encompassed all of the damage that would have been caused by the detonation of a bomb or missile.”

The report said that no signs of a high-energy explosion were found on interior components or on the occupants’ remains. The bodies of 99 occupants were recovered by surface vessels during the first 24 hours after the accident. Remains of the other occupants were recovered by divers and by trawling operations.

The report said, "A medical forensic investigation analysis report … concluded the following:

- "Exhaustive analysis of all available medical data on the victims of TWA Flight 800 by an experienced team of forensic pathologists, biomechanicists and criminal investigators failed to find any evidence that any victim was directly exposed to a bomb blast or missile warhead detonation. This finding makes it highly unlikely that a localized explosion occurred within the passenger cabin of TWA Flight 800;

- "All injuries found in the victims were consistent with severe in-flight breakup and subsequent water impact;

- "Injury and burn patterns to the victims as well as some body locations suggest that there was a severe breakup of the passenger cabin early in the crash sequence; [and,]

- "Fire propagated in the [cabin section above the CWT] after most occupants [of this section] had been ejected. The small number of passengers with burn injuries exhibited only superficial burns consistent with exposure to a flash-flame front."

Trace amounts of explosives had been spilled by a dog handler while placing training aids aboard the accident airplane during an explosives-detection training exercise conducted by the U.S. Federal Aviation Administration (FAA) on June 10, 1996.

FAA said, however, that residues of explosives in the accident airplane would have dissipated completely after two days of immersion in sea water.

"Very few pieces of airplane wreckage were recovered during the first two days after the accident, and those pieces that were recovered were found floating on the ocean's surface," the report said. "Therefore, it is very likely that the pieces on which the explosive residues were found were immersed in ocean water for considerably more than two days before they were recovered."

The report said that the trace amounts of explosive residue possibly were not present before the airplane struck the water but were deposited during recovery operations.

"The military personnel, ships and ground vehicles used during the recovery operations had come into frequent previous contact with explosives," the report said. "Trace amounts of these substances could have been transferred from the surfaces of the ships or ground vehicles, or from clothing and boots of military personnel, onto wreckage pieces during recovery operations or through subsequent contact with the pieces in the airplane hangar where the airplane wreckage was later assembled and laid out.

"Despite being unable to determine the exact source of the trace amounts of explosive residue found on the wreckage, the lack of any corroborating evidence associated with a high-energy explosion indicates that these trace amounts did not result from the detonation of a high-energy explosive device on TWA Flight 800."

Based on these findings, the report said that the in-flight breakup was not initiated by a bomb or a missile strike.

Metallurgical examination showed that the breakup began with an *overpressure event* (in which pressure builds quickly to a level sufficient to compromise structural integrity) in the CWT.

Figure 1 (page 5) shows a cross-section of the B-747-100 wing center section. The CWT comprises four compartments (bays) between the rear spar and spanwise beam 3. (The compartment between spanwise beam 3 and the front spar is a dry bay.) Spanwise beam 1, the midspar and spanwise beam 2 have several cutouts and vent holes through which air and fuel move between the CWT bays.

The CWT was full of fuel when the airplane departed from Athens. The CWT contained approximately 300 pounds (136 kilograms) of fuel when the airplane arrived in New York; no fuel was added to the tank before departure.

The report said that, at the time of the accident, the fuel vapor in the *ullage* (the space in the CWT not occupied by liquid fuel) was flammable.

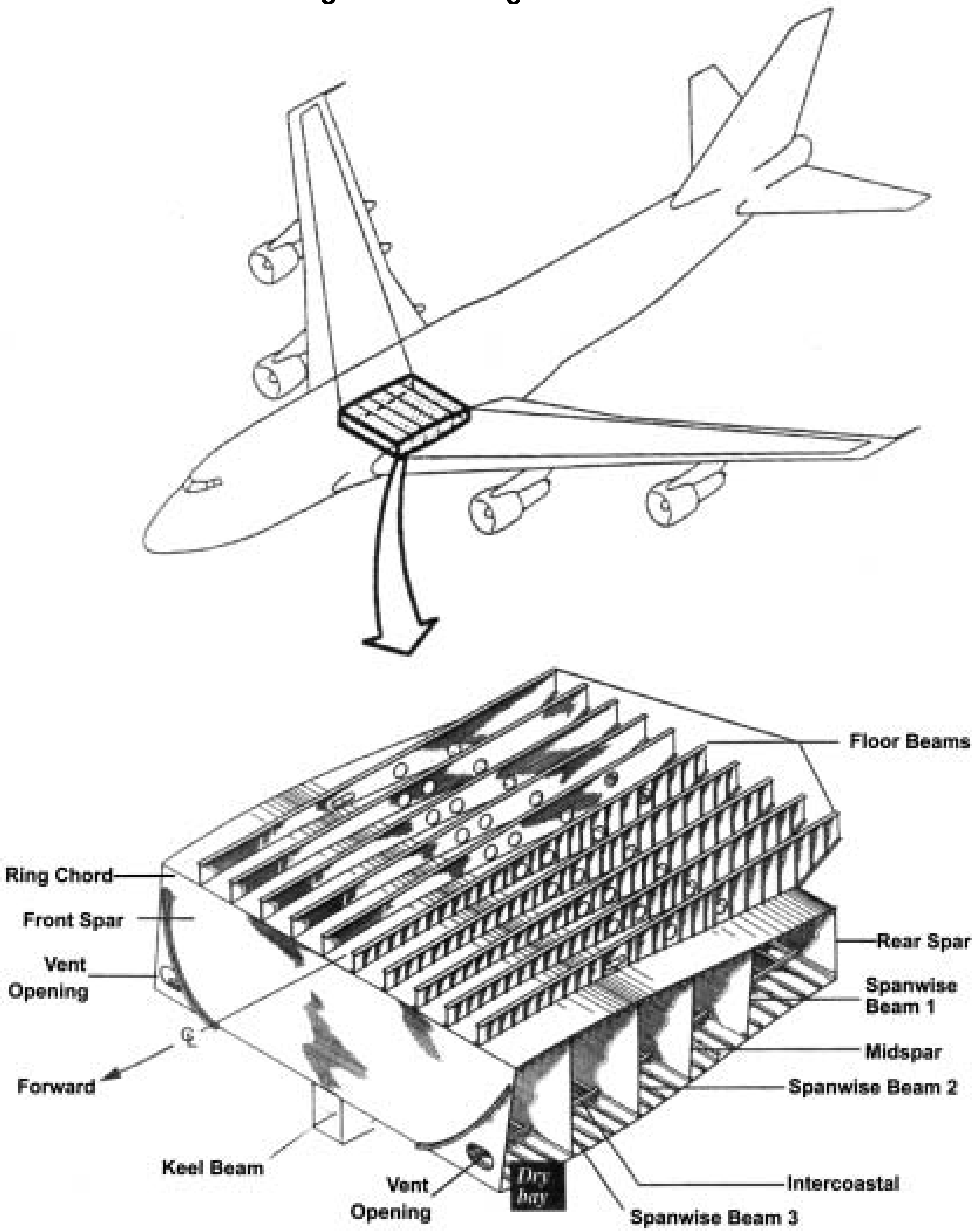
"Fuel vapor temperatures within the CWT at the time of the accident ranged from 101 [degrees Fahrenheit (F)] to 127 F [38 degrees Celsius (C) to 53 C]," the report said. "Jet A fuel vapors under conditions simulating the pressure, altitude and fuel mass loading of TWA Flight 800 are flammable at these temperatures and at [temperatures] as low as 96.4 F [35.8 C]."

The report said that CWT explosions were known to have been involved in two previous accidents:

- On Nov. 27, 1989, an Avianca B-727 was departing from Bogota, Colombia, when a small bomb, which had been placed under a passenger seat above the CWT, exploded. The airplane was destroyed, and all 107 occupants were killed. The Colombian government, in its final report, said that the bomb explosion had punctured the CWT and ignited the fuel/air mixture in the ullage; and,

- On May 11, 1990, a Philippine Airlines B-737-300 was being pushed back from the gate at Manila, Philippines, when the fuel/air mixture in the CWT exploded. Of the 120 occupants, eight were killed and 30 were seriously injured. The ignition source was not found, but NTSB cited the possibility that, because of previously damaged fuel-quantity-indication-system (FQIS) wiring and a

Boeing 747-100 Wing Center Section



Source: U.S. National Transportation Safety Board

Figure 1

malfunctioning float switch, an electrical arc or overheating of the float switch led to ignition of vapor in the CWT.

The report said that the Avianca accident and the Philippine Airlines accident showed that "a CWT explosion involving Jet A fuel can break apart the fuel tank and lead to the destruction of an airplane."

The report said, "Analysis of the results of computer modeling of combustion in a full-scale CWT under conditions simulating those of TWA Flight 800 indicated that a localized ignition of the flammable vapor could have generated pressure levels that … would cause the damages observed in the wreckage of the accident airplane's CWT."

Of the 736 witness documents obtained during the investigation by NTSB and the FBI, 258 documents said that a streak of light (or a flare-like object, or fireworks) was observed before the fireball appeared. The report said that the streak of light likely was burning fuel released by the airplane during the breakup and that the fireball was the burning wreckage falling toward the ocean.

The report said that the nose of the airplane separated about three seconds to five seconds after the CWT explosion occurred. The remainder of the airplane pitched up, rolled left, ascended to about 15,000 feet or 16,000 feet, then rolled into a descending turn to the right.

"It is likely that, after the nose portion separated from the aft fuselage, a fuel-fed fire within the breached CWT (or any other fire that might have existed, such as from fuel that might have been leaking at the wing roots) would have been visible to witnesses from some distance and was the streak of light reported by many of the witnesses," said the report.

As the aft portion of the airplane descended, outboard sections of the wings likely separated, and fires fed by fuel from the outboard main wing tanks created the fireball observed by witnesses.

"This fireball probably began to develop about 34 seconds after the CWT explosion," said the report.

Investigators examined several possible sources of ignition of the fuel/air mixture in the CWT, including: a lightning strike; meteorite strike; missile fragment; autoignition or hot-surface ignition resulting from heat produced by sources outside the CWT; fire entering the CWT from another fuel tank; uncontained engine failure or a turbine burst in the air-conditioning packs beneath the CWT; malfunctioning CWT jettison/override pumps; malfunctioning CWT scavenge pump; static electricity; and FQIS wiring.

The report said that a lightning strike or a meteorite strike was very unlikely.

"No witnesses reported that lightning struck the accident airplane or that lightning was in the area," the report said. "Further, recorded meteorological data indicated no atmospheric disturbances in the area."

A meteorite specialist calculated that a meteorite could be expected to strike an aircraft once every 59,000 years to 77,000 years.

"Further, none of the holes in the CWT or fuselage structure exhibited characteristics of high-velocity penetration through the exterior … that would be expected from a meteorite strike," said the report.

Investigators found no signs of a direct missile strike but examined whether a missile might have exploded near the airplane. The report said that a shoulder-launched missile will self-detonate, releasing about 1,000 fragments, about 15 seconds after launch if no target has been struck. The detonation would have had to occur within 40 feet (12 meters) of the airplane for a fragment to have had sufficient velocity to penetrate the CWT.

The report said that if such a detonation had occurred, many fragments would have struck the airplane, and the fragment strikes would have created impact marks.

"No such impact marks were found on the accident airplane's wreckage," said the report.

Autoignition (from heating of the fuel/air mixture) or hot-surface ignition (from contact between the fuel/air mixture and a hot surface) was unlikely, the report said. No signs were found of possible causes of autoignition or hot-surface ignition, such as a fire outside the CWT, an engine bleed air leak near the CWT or multiple engine malfunctions that could have resulted in excessively hot bleed air entering the air-conditioning packs.

Flames from a fire in another fuel tank would have had to travel through the fuel-vent system to a wing-tip surge tank before continuing to travel to the CWT. The report said that, at 13,800 feet, the fuel/air mixture in the vent system near the surge tanks would have been too cool to sustain a flame. Also, the surge tanks are protected by fire-extinguishing systems. The surge-tank fire-extinguishing systems in the accident airplane had not discharged.

Investigators found no signs of an uncontained engine failure or a turbine burst in the air-conditioning packs.

The CVR recorded nothing to indicate that the two CWT jettison/override pumps were used during the accident flight. The report said that because the CWT was nearly empty, there was no reason for the flight crew to have used the pumps.

Examination of one pump showed no signs of any malfunction or overheating. Signs were found of contact between the impeller and impeller housing in the other pump. The report said, however, that tests conducted during the investigation of the Philippine Airlines B-737 accident showed that such contact would not result in ignition of flammable vapor.

The scavenge-pump motor and impeller were not recovered. The scavenge-pump control switch was found in the OFF position.

"Even if the pump had been on and a flame had developed inside the pump's motor housing, it is still unlikely that the flame could have entered the tank," said the report.

U.S. Federal Aviation Regulations (FARs) Part 25, the certification standards for transport category airplanes, require that major components of powerplant installations be electrically bonded (i.e., connected) to other parts of the airplane.

"Boeing design practices permit parts that are less than three inches [7.6 centimeters] long in any direction (including some types of clamps and connectors installed in fuel tanks) to be electrically unbonded, presumably because such parts are not believed to have enough capacitance to retain hazardous levels of static electricity under experienced operating conditions," said the report.

Tests showed that Teflon-cushioned wire clamps in B-747 CWTs and inboard-main fuel tanks are particularly susceptible to electrostatic charging from fuel striking the clamps. The highest voltage attained in tests using fuel similar to that in the accident airplane was 650 volts, which could produce a discharge energy of about 0.0095 millijoules (mJ).

"Even assuming that the clamp could attain a voltage of 1,150 volts (which was produced in tests using fuel of a higher conductivity than the fuel in the CWT on TWA Flight 800), the highest discharge energy that voltage could produce was estimated to be about 0.030 mJ, which is still well below the 0.25 mJ [minimum ignition energy] for Jet A fuel vapor," said the report.

Although these findings showed that the ignition of the fuel/air mixture by static electricity likely was not a factor in the TWA Flight 800 accident, the report said that discharges of static electricity have resulted in airplane fuel-tank explosions.

"Tests conducted by Boeing after two fuel-tank explosions in 1970 found that a single unbonded clamp could store up to five mJ of energy during the increased fuel-flow rates associated with ground refueling," the report said. "Further, according to the FAA's *Aircraft Lightning Protection Handbook*, unbonded clamps could present an ignition hazard in the event of a lightning strike."

Boeing specifications require that the FQIS wiring — which was the only wiring inside the accident airplane's CWT — be limited in voltage so that it cannot discharge energy of more than 0.02 mJ.

"Therefore," the report said, "for the FQIS to have played a role in igniting the flammable fuel/air [mixture] in the CWT, the following two events would have had to have occurred:

- "(1) A transfer of higher-than-intended voltage onto FQIS wiring from a power source outside of the fuel tank; and,
- "(2) The release of energy from that FQIS wiring into the inside of the tank in a way that could ignite the fuel/air [mixture] in the tank."

Investigators examined whether the transfer of higher-than-intended voltage onto FQIS wiring might have been caused by electromagnetic interference from outside the airplane or inside the airplane, or by a short circuit.

Studies showed that if all the radio-frequency (RF) transmitters that could have affected the airplane were emitting the highest possible electromagnetic signal levels, the maximum available energy inside the airplane would have been less than 0.1 mJ, and any energy that coupled to aircraft wiring would have been several orders of magnitude less than 0.1 mJ.

"[Electromagnetic interference] from RF sources external to TWA Flight 800 did not produce enough energy to ignite the fuel/air [mixture] in the CWT," said the report.

Studies showed that the strongest electromagnetic energy from onboard personal electronic devices that could have been coupled to FQIS wiring was about one-tenth the minimum energy required to induce a spark from the FQIS.

Investigators also examined whether a transient current spike from higher-voltage aircraft systems could have been induced into co-routed FQIS wiring.

"Early in the investigation, Boeing was able to induce transient voltages in excess of 1,000 volts (estimated to be capable of producing 0.6 mJ of energy in FQIS wiring)," the report said. "However, these tests did not accurately represent the voltage sources that would exist in an actual airplane."

Testing conducted with actual airplane systems showed that the maximum energy released by FQIS wiring inside the fuel tank was 0.125 mJ.

"This is significantly less than the 0.5 [mJ] to 500 mJ that would have been needed to ignite the Jet A fuel/air [mixture] in TWA Flight 800's CWT and only half of the generally accepted [minimum ignition energy] level for Jet A fuel (0.25 mJ)," said the report.

The report defined a short circuit as an unintended current path between conductors.

"Short circuits can occur either directly, if the protective insulation covering between internal conductors in each wire is compromised and there is direct contact between the conductors, or through a 'bridge' created by contaminants, such as metal shavings or fluid," said the report.

When a short circuit occurs in wires carrying relatively high current, excess voltage from the short circuit can be transferred to wires carrying lower voltage.

"The investigation found that Boeing design specifications permit FQIS wiring to be bundled with, or routed next to, higher-voltage airplane system wires, some carrying as much as 350 volts," the report said.

The report said that examination of airplanes ranging in age from new to 26 years old showed that some of the wiring was degraded (i.e., cracked, chafed, mechanically damaged or contaminated).

"Much of the insulation on the wiring recovered from the accident airplane was cracked or otherwise damaged, often exposing the inner conductor," the report said. "When powered, such damaged wires would be vulnerable to short-circuiting."

Although some damage to the wiring probably occurred during the accident and recovery operations, some damage likely existed before the accident.

"Given what was found during the inspections of other airplanes, it is also likely that metal shavings and other contaminants were interspersed with the wiring system on the accident airplane before the accident," said the report.

No signs of electrical arcing were found in the components connected to the FQIS (the fuel-quantity indicator, fuel-totalizer gauge, airborne integrated data system, volumetric-shutoff unit and left-wing refueling station).

"The interior of each of these components contained numerous complex wiring and circuit assemblies that could have obscured evidence of a short circuit," the report said. "Further, it is also possible that a short circuit at lower power or through moisture could occur without leaving evidence of arcing. Therefore, there were several possible locations at which a short circuit of higher-voltage wiring could have affected the CWT FQIS wires in the accident airplane."

The report said that the following were signs that anomalous electrical events occurred before the CWT explosion:

- The captain commented about a "crazy fuel flow indicator" about 2.5 minutes before the CVR lost power;

- Two "dropouts" of background power harmonics were recorded less than one second before the CVR lost power; [and,]

- Although CWT fuel quantity was recorded as 300 pounds during refueling before departure, the CWT fuel-quantity indicator showed 640 pounds (290 kilograms) after the accident.

"Testing showed that applying power to a wire leading to the fuel-quantity gauge can cause the digital display to change by several hundred pounds in less time than is required to trip the circuit breaker," the report said.

Based on these findings, the report said that the most likely source of ignition of the fuel/air [mixture] in the CWT was a short circuit that produced excess voltage that was transferred to the FQIS wiring.

The investigation did not determine how the excess voltage was released inside the CWT. The report said, however, that silver-sulfide deposits found on the FQIS probes, compensators and wiring might have facilitated the release of ignition energy inside the CWT. Silver-sulfide deposits are semiconductive; the deposits are formed over time by exposure of silver-coated copper parts to jet fuel and fuel vapors, which contain sulfur.

The report said that FAA's fuel-tank design and certification philosophy, which focuses on elimination of ignition sources and accepts that a flammable fuel/air mixture exists in fuel tanks, is flawed and that "operating transport category airplanes with flammable fuel/air mixtures in fuel tanks presents an avoidable risk of an explosion."

Heat generated by air-conditioning packs located below the CWTs in B-747s and several other transport airplanes can cause internal tank temperature to increase.

"Heat from the pack bay can transfer to the CWT through the bottom of the tank and cause temperatures to rise above the lower flammability limit [i.e., the lowest temperature that will provide a sufficient concentration of fuel vapor to propagate a flame]," said the report.

During the investigation of the TWA Flight 800 accident, FAA inspected five "aging" transport category airplanes and found deteriorated wiring, brittle wiring, contaminated wiring, corroded connector pins and improper wire installation and repairs. FAA also found wire bundles that were difficult to inspect.

"The FAA concluded that current maintenance practices do not adequately address wiring components, wire-inspection criteria are too general, unacceptable conditions are not described in sufficient detail, repair instructions and data are difficult to extract from [manuals], wire-replacement criteria may not be adequate, and current incident/maintenance reporting procedures do not allow for easy identification of failures," said the report.

To identify solutions to wiring problems and to address other non-structural issues related to aging transport airplanes, FAA developed the Aging Transport Non-Structural Systems Plan and established the Aging Transport Systems Rulemaking Advisory Committee.

During the accident investigation, NTSB made the following recommendations to FAA:

- "Require the development and implementation of design [changes] or operational changes that will preclude the operation of transport category airplanes with explosive fuel/air mixtures in the fuel tanks:

– "(a) Significant consideration should be given to the development of airplane design modifications, such as nitrogen-inerting systems and the addition of insulation between heat-generating equipment and fuel tanks. Appropriate modifications should apply to newly certificated airplanes and, where feasible, to existing airplanes. (A-96-174);

– "(b) Pending implementation of design modifications, require modifications in operational procedures to reduce the potential for explosive fuel/air mixtures in the fuel tanks of transport category aircraft. In the 747, consideration should be given to refueling the [CWT] before flight whenever possible from cooler ground fuel tanks, proper monitoring and management of the CWT fuel temperature, and maintaining an appropriate minimum fuel quantity in the CWT. (A-96-175);

- "Require that the 747 Flight Handbooks of TWA and other operators of 747s and other aircraft in which fuel-tank temperature cannot be determined by flight crews be immediately revised to reflect the increases in [CWT] fuel temperatures found by flight tests, including operational procedures to reduce the potential for exceeding CWT temperature limits. (A-96-176);

- "Require modification of the [CWT] of 747 airplanes and the fuel tanks of other airplanes that are located near heat sources to incorporate temperature probes and cockpit fuel-tank temperature displays to permit determination of fuel-tank temperatures. (A-97-177);

- "Develop and implement procedures, including a checklist of safety-related items, for the handling and placement of explosive training aids by K-9 [dog] explosives-detection teams to prevent contamination of aircraft and airport facilities and to ensure an effective K-9 explosives-detection program. (A-97-11);

- "Issue, as soon as possible, an airworthiness directive to require a detailed inspection of [FQIS] wiring in Boeing 747-100, -200 and -300 series airplane fuel tanks for damage, and the replacement or the repair of any wires found to be damaged. Wires on Honeywell Series 1-3 probes and compensators should be removed for examination. (A-98-34);

- "Issue an airworthiness directive to require the earliest possible replacement of the Honeywell Corporation Series 1-3 terminal blocks used on Boeing 747 fuel probes with terminal blocks that do not have knurled surfaces or sharp edges that may damage [FQIS] wiring. (A-98-35);

- "Conduct a survey of [FQIS] probes and wires in Boeing 747s equipped with systems other than Honeywell Series 1-3 probes and compensators in other model airplanes that are used in [FARs] Part 121 service to determine whether potential fuel tank ignition sources exist that are similar to those found in the 747. The survey should include removing wires from fuel probes and examining the wires for damage. Repair or replacement procedures for any damaged wires that are found should be developed. (A-98-36);

- "Require research into copper-sulfide deposits on [FQIS] parts in fuel tanks to determine the levels of deposits that may be hazardous, how to inspect and clean the deposits, and when to replace the components. (A-98-37);

- "Require in Boeing 747 airplanes, and in other airplanes with [FQIS] wire installations that are co-routed with wires that may be powered, the physical separation and electrical shielding of FQIS wires to the maximum extent possible (A-98-38); [and,]

- "Require, in all applicable transport airplane fuel tanks, surge-protection systems to prevent electrical power surges from entering fuel tanks through [FQIS] wires. (A-98-39)."

In response to NTSB recommendations A-96-174 and A-96-175, FAA said that it was evaluating methods to reduce the flammability of fuel/air mixtures in aircraft fuel tanks. The methods included directed ventilation and on-board/ground-based nitrogen-inerting systems. The TWA Flight 800 accident report said that FAA should expedite its research initiatives and rule-making initiatives, and evaluate a broader range of inerting technologies.

"For example, the FAA should research the effectiveness of inerting gases other than nitrogen and various methods of gas storage, delivery and availability," said the report.

FAA also determined that the use of ground sources for conditioned air, rather than the airplane's air-conditioning packs, reduces generation of flammable vapors in CWTs more effectively than adding cooler fuel to CWTs before flight. FAA said that it would encourage all U.S. air carriers to apply a Boeing service letter, issued May 5, 2000, which recommends that operators use ground-conditioned air when available and practical, and that operators consider opening pack-bay doors to increase ventilation.

In response to A-96-176, FAA in May 2000 said that TWA no longer operated B-747s and that Boeing had determined that none of the flight/operations manuals used by operators provide CWT temperature information for flight crews.

FAA told NTSB that flight deck displays of fuel temperature, as recommended in A-96-177, were not practical and would not be required when using fuel-tank-directed ventilation and fuel-inerting systems.

"The FAA stated that, although certain military airplanes incorporate fuel-temperature indications with cockpit temperature displays for each tank, those displays are not used to determine fuel-tank flammability; instead, they are used to monitor fuel-tank temperatures during extended ground operation to ensure that the fuel temperatures in the main fuel tanks (wing tanks) do not rise to a range that would cause degraded fuel-pump performance or pump cavitation when the engines are operating at high thrust levels."

FAA responded to A-97-11 by increasing the training of dog handlers, procuring equipment that reduces contamination by explosives and developing a national database to record explosives-detection training in aircraft.

In response to A-98-34 and A-98-35, FAA issued airworthiness directives (AD 98-08-02 R1 and AD 98-20-40) requiring compliance with Boeing service bulletins (SB 747-28-2205 R1 and SB 747-28-A2208) on replacement of FQIS components, shielding/separation of FQIS wiring and fuel-tank-inspection procedures.

In response to A-98-36, FAA established an industry team to check FQIS probes and wiring in transport category airplanes, and proposed on Oct. 26, 1999, a review of fuel-tank designs "to ensure that failures could not create ignition sources within the fuel tanks."

FAA responded to A-98-37 by establishing a fuel tank system copper-sulfide research program.

"In [a] May 17, 2000, letter, the FAA stated that it was continuing to make progress in understanding copper-sulfur and silver-sulfur deposits and the potential hazards that they may cause," the report said.

The report said that the electrical-wiring shielding-and-separation requirements in AD 98-20-40, issued by FAA in response to NTSB recommendations A-98-38 and A-98-39, might not be adequate.

"Information from several investigations indicated that Boeing's minimum separation standard of 0.25 inch [0.6 centimeter] might be insufficient," the report said. "For example, [during the] investigation of a Jan. 9, 1998, wiring fire on board a United Airlines 767, investigators found insulation melted away from wires located more than one inch [2.5 centimeters] from the location of the electrical arc."

The report said that FAA withdrew a proposal to require installation of electrical transient suppression devices (TSDs).

"The FAA stated that … TSD technology was not fully developed for application to in-service airplanes and that wire separation and shielding could provide the required level of protection," said the report.

Based on the findings of its completed investigation, NTSB on Sept. 19, 2000, made the following recommendations to FAA:

- "Examine manufacturers' design practices with regard to bonding of components inside fuel tanks and require changes in those practices, as necessary to eliminate potential ignition hazards. (A-00-105);
- "Review the design specifications for aircraft wiring systems of all U.S.-certified aircraft and (1) identify which systems are critical to safety and (2) require revisions, as necessary, to ensure that adequate separation is provided for the wiring related to those critical systems. (A-00-106);
- "Require the development and implementation of corrective actions to eliminate the ignition risk posed by silver-sulfide deposits on [FQIS] components inside fuel tanks. (A-00-107); [and,]
- "Regardless of the scope of the Aging Transport Systems Rulemaking Advisory Committee's eventual recommendations, address (through rulemaking or other means) all of the issues identified in the Aging Transport Non-Structural Systems Plan, including:
  - "The need for improved training of maintenance personnel to ensure adequate recognition and repair of potentially unsafe wiring conditions;
  - "The need for improved documentation and reporting of potentially unsafe electrical wiring conditions; and,
  - "The need to incorporate the use of new technology, such as arc-fault circuit breakers and automated wire-test equipment;

  "To determine whether adequate progress is being made in these areas, [NTSB] believes that, within 90 days, [FAA] should brief [NTSB] on the status of its efforts to address all of the issues identified in the Aging Transport Non-Structural Systems Plan. (A-00-108)."

[Based in part on these recommendations, FAA on May 7, 2001, issued a special federal aviation regulation (SFAR) affecting 6,971 transport category airplanes with 30 or more seats manufactured by Airbus, Aerospatiale (ATR), Boeing, British Aerospace, Bombardier, de Havilland, Dornier, Embraer, Fokker, Lockheed, Saab and Shorts.

FAA, in news release APA 16-01, said that the SFAR requires the following for existing airplanes:

- "Manufacturers must conduct a one-time design review of the fuel-tank system for each transport airplane model in the current fleet to ensure that failures could not create ignition sources within the fuel tank;

- "Manufacturers must then design specific programs for the maintenance and inspection of the tanks to ensure the continued safety of fuel-tank systems; [and,]

- "Based on the information provided by the manufacturers under the SFAR, operators must then develop and implement FAA-approved fuel-tank maintenance-and-inspection programs for their airplanes."

FAA said that the SFAR requires the following for new airplane types:

- "Manufacturers must further minimize the existence of ignition sources in fuel tanks. Future transport category airplanes will be designed to better address potential failures in the fuel-tank system that could result in an ignition source;

- "Manufacturers must develop maintenance and inspection programs to ensure fuel-tank safety; [and,]

- "Some airplane types are designed with heat sources adjacent to the fuel tank, which can heat the fuel and increase the formation of flammable vapors in the tank. The [SFAR] requires manufacturers to reduce the time fuel tanks operate with flammable vapors in the tank by designing fuel tank systems with a means to minimize the development of flammable vapors in the fuel tank or a means to prevent catastrophic damage in the unlikely event ignition occurs."

The SFAR becomes effective June 6, 2001. FAA said that manufacturers have 18 months from that date to conduct the required safety reviews and develop the required maintenance-and-inspection programs. Operators have 36 months to incorporate FAA-approved maintenance-and-inspection programs.]♦

[This article, except where specifically noted, is based on the U.S. National Transportation Safety Board *Aircraft Accident Report: In-flight Breakup Over the Atlantic Ocean, Trans World Airlines Flight 800, Boeing 747-131, N93119, Near East Moriches, New York, July 17, 1996*. The 425-page report contains diagrams, maps, tables, photographs and appendixes.]

Appendix
Cockpit Voice Recorder Transcript, Trans World Airlines Flight 800, July 17, 1996

[FSF editorial note: The following transcript begins when the flight crew is instructed by air traffic control to climb to, and maintain, Flight Level 190 (19,000 feet). The transcript is as it appears in the U.S. National Transportation Safety Board (NTSB) report, except for minor column rearrangement and minor editing for consistency and style. All times are local.]

RDO	=	Radio transmission from accident aircraft
CAM	=	Cockpit area microphone sound or source
-1	=	Voice identified as captain (left seat)
-2	=	Voice identified as first officer (right seat)
-3	=	Voice identified as second officer
-4	=	Voice identified as instructor flight engineer
-?	=	Voice unidentified
FIC	=	Trans World Airlines (TWA) flight information controller
CTR	=	Boston Air Route Traffic Control Center controller (center)
*	=	Unintelligible word
( )	=	Questionable text
(( ))	=	NTSB editorial insertion

Time	Source	Content
2025:41	**CTR**	roger sir climb and maintain flight level one niner zero and expedite through fifteen.
2025:47.1	**RDO-2**	TWA's eight hundred heavy climb and maintain one niner zero and expedite through one five thousand.
2025:53	**CAM-1**	climb to one nine zero expedite through one five thousand.
2025:57	**CAM-3**	pressurization checks.
2025:59	**CAM-3**	(takeoff) thrust go on cross feed?
2026:02	**CAM-?**	ah.
2026:04	**CAM-1**	yeah.
2026:07	**CAM-3**	I'll leave that on for just a little bit.
2026:12	**CAM-3**	is that right?
2026:13	**CAM-4**	yes.
2026:24	**CTR**	TWA eight hundred amend the altitude maintain ah one three thousand thirteen thousand only for now.
2026:29	**CAM-1**	thirteen thousand.

2026:30.3	**RDO-2**	TWA's eight hundred heavy okay stop climb at one three thousand.
2026:35	**CAM-1**	stop climb at one three thousand.
2026:51	**CAM-1**	*.
2026:59	**CAM-2**	twelve for thirteen.
2027:35	**CAM**	((sound of click)).
2027:47	**CAM**	((sound of altitude alert tone)).
2028:13	**CTR**	TWA eight hundred you have traffic at one o'clock and ah seven miles south bound a thousand foot above you he's ah Beech nineteen hundred.
2028:20.6	**RDO-2**	TWA's ah eight hundred heavy ah no contact.
2028:22.5	**RDO-3**	FIC TWA eight hundred.
2028:25	**FIC**	TWA eight hundred.
2028:25.7	**RDO-3**	Eight hundred with an off report ah plane number one seven one one nine we're out at zero zero zero two, and we're off at zero zero one nine, fuel one seven nine decimal zero, estimating Charles de Gaulle at zero six two eight.
2028:42	**FIC**	TWA eight eight hundred got it all.
2028:44.8	**RDO-3**	Thank you.
2029:15	**CAM-1**	look at that crazy fuel flow indicator there on number four.
2029:23	**CAM-1**	see that.
2029:35	**CAM-1**	some where in here I better trim this thing (in/up).
2029:39	**CAM-2**	huh?
2029:39	**CAM-1**	some place in here I better find out where this thing's trimmed.
2030:15	**CTR**	TWA eight hundred climb and maintain one five thousand.
2030:18	**CAM-1**	climb thrust.
2030:19.2	**RDO-2**	TWA's eight hundred heavy climb and maintain one five thousand leaving one three thousand.
2030:24	**CAM-1**	Ollie.
2030:24	**CAM-3**	huh.
2030:25	**CAM-1**	climb thrust.
2030:28	**CAM-1**	climb to one five thousand.
2030:35	**CAM-3**	power's set.
2030:42	**CAM**	((sound similar to a mechanical movement in cockpit))
2031:03	**CAM**	*.
2031:05	**CAM**	((sounds similar to recording tape damage noise)).
2031:12		End of Recording.

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