KOÇ UNIVERSITY


# MECH 428: INTRODUCTION TO AEROSPACE ENGINEERING

## Investigation of TWA Flight 800 Boeing 747 Crash

**Team Members:**

| | |
|---|---|
| Sinan Noyan | 69190 |
| Batuhan Yalçın | 64274 |
| Beratcan Altuntaş | 63904 |
| Mehmet Can İlker | 64389 |
| Emre Güzelaydın | 64734 |
| Buğra Tavukçuoğlu | 64148 |

**INSTRUCTOR**

Arif Karabeyoğlu

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# Executive Summary


## Flight Information

On July 17th, 1996, Trans World Airlines Flight 800 suffered a catastrophic accident. The flight was initially scheduled to go Charles de Gaulle, Paris from John F. Kennedy International Airport. The airplane which was a Boeing 747-131 underwent mid-air break-up approximately 15 minutes after lift-off. The repercussions were heavy with 230 people losing their lives.

## Root and Direct Causes

Given the magnitude of the accident, many theories were investigated as it pertains to the causes of the catastrophe including conspiracy theories. None were found plausible and were disregarded on the grounds that there wasn't sufficient evidence. Meteorological events as well as engine failures, malfunctioning pumps, significant pre-existing damage to integral components of the plane were also deemed irrelevant and untrue. The most probable root cause appeared to be a short circuiting in one of the systems close to the Central Wing Fuel Tank. The specific system that experienced the short circuiting, however, could not be identified. The short circuiting led to a high voltage release into the Fuel Quantity Indication System in the Central Wing Fuel Tank and the excess energy caused an explosion and an overpressure event within the CWT which was the direct cause of in-flight break-up. As for the contributing causes, the temperature of the fuel-air mixture was higher than it was supposed to be since the airplane was run for two hours before take-off and the fuel-air mixture was less in quantity than usual which created more vaporization space for Kerosene. Silver Sulfide Deposits on the FQIS were also deemed important in causing ignition due to electrical arcing.

## Corrective Measures

To preclude any similar explosions due to short circuiting, the Safety Board pushed for better insulation of the wires that are close to the CWT. More research on silver sulfide deposits was called to understand the threshold at which they considerably contribute to ignition and replace the parts. The necessity of inspection of existing Boeing 747's and their fuel tanks were also recognized. Nitrogen inerting systems to prevent explosions and less sharp terminal blocks were also advised together with cooler ground fuel tanks to mitigate fuel temperature.

# 1) Introduction

On 17th of July 1996, TWA flight 800 was scheduled to take off from John F. Kennedy International Airport (JFK) in New York and land on to Charles DE Gaulle (CDG) International Airport, in Paris. Sadly, TWA 800 crashed in the Atlantic Ocean near East Moriches in New York. The plane departed in 20:14, and the last radar return was in 20:31:12, meaning that the issue occurred relatively briefly after takeoff. The aircraft was shattered and unfortunately 230 passengers on board were dead. Before the accident, the plane had 93,303 hours of flying operation which is towards the end of the spectrum. In this report TWA Flight 800, a Boeing 747-131 is investigated from the standpoints of aircraft information, system analysis in terms of designs and statistical reliability, specific accident characteristics and sequence. Also, similar accidents involving the same components have been discussed to identify system vulnerabilities and suggest corrective actions.

## 1.1) Aircraft Information

The airplane N93119, with a series number of 100, of the models 747-131, was manufactured by the global aviation giants Boeing. The plane was able to carry more than 400 passengers with cargo. The airplane had four turbofan engines and one APU-driven generator. It also consisted of seven fuel tanks with a fueling station and a cross-feed engine system. In general, designs of 747-100 consisted of 16 fuel pumps with four fuel boost pumps in the wings. The aircraft had 68.5 m in length and 19.2 m in height with a 59.4 m wingspan. On the day of the accident, the airplane's weight was 356,888 kg.

## 1.2) General Measurement of 747-100 Airplane

Maximum take-off weight = 334 tons

Cruising Mach Number = 0.84

The maximum range of flight = 9.800 km

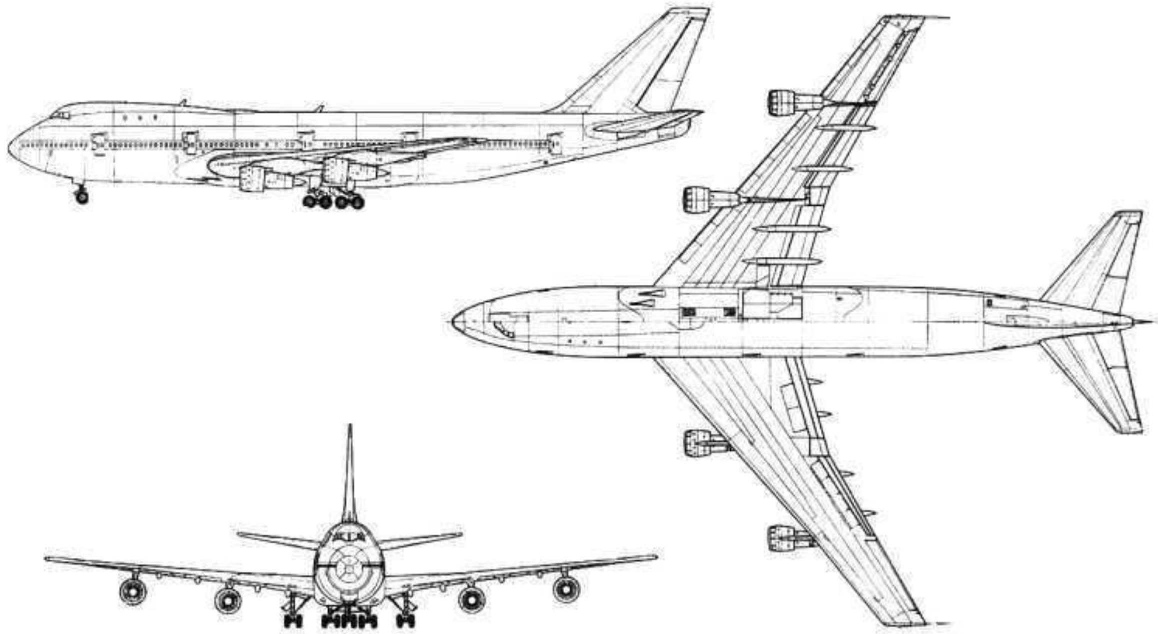

Figure 1 : General Look of Boeing 747-100 Airplane [13]

## 1.3) Engine Models

### 1.3.1) PW JT9D-7A

The engine is made with titanium and nickel alloys for fuel efficiency and reliability. The engine consists of 1 fan, 3 low-pressure compressors, 11 high-pressure compressors, 2 high-pressure turbines, and 4 low-pressure turbines.

### 1.3.2) GE CF6-45A2

The engine consists of 1 low-pressure,16 high-pressure fans, and 5 high-pressure and high-pressure turbines with 9.925 maximum horsepower.

### 1.3.3) RR RB211-524 B2

The RB221 series were established in the 1990s by Rolls-Royce company. RR RB211-524 B2 engines have a 3-shaft architecture which provides multiple benefits. Such as the structure is stiffer and shorter, and engine has fewer stages. These features enable the rotors to run at the optimum speed. [12]

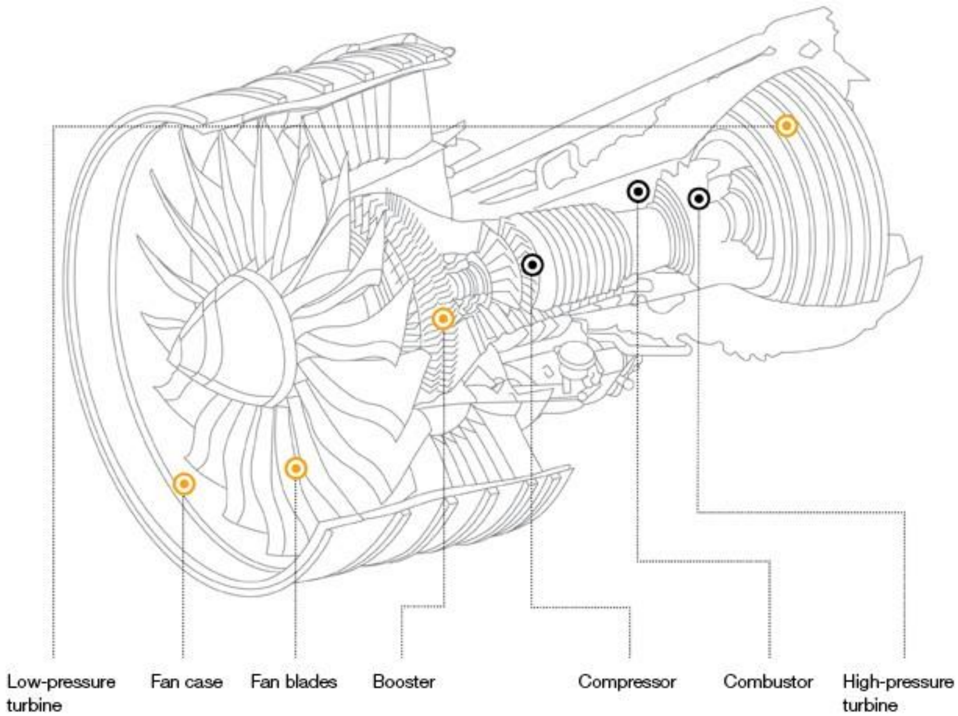


Figure 2 : Engine Scheme of Boeing 747-100 [14]

## 1.4) Accident Details

It has been stated in the introduction paragraph that TWA Flight 800 took off from JFK Airport in New York to CDG International Airport in Paris. At 20:17:18, the air traffic control records from the CVR showed that the aircraft got in heavy turbulence and started to feel the effects of turbulent air. However, later investigations that will be extensively discussed did not associate the accident with any turbulence or malpractice regarding the pilots preferred flight conditions. Nevertheless, it is meaningful to mention that ATC recommended and informed the pilots of TWA flight 800 that the wind was out of 240° at 8 knots and cleared flight 800 for take-off on runway 22R [9]. The airplane reached 13,000 feet at 20:27:54. Later, with the instruction of the air traffic control, the pilots increased the engine power then the aircraft reached approximately 15,000 feet 20:30:18. The last radar message was taken at 20:31:12 when the plane was at 13,760 feet, already in decline. The pieces of the wreckage were discovered 8 miles south of East Moriches, New York. The main wreckage was found between 40° 37' 42" and 40° 40' 12" north latitude and 72° 40' 48" and 72° 35' 38" west longitude [9].

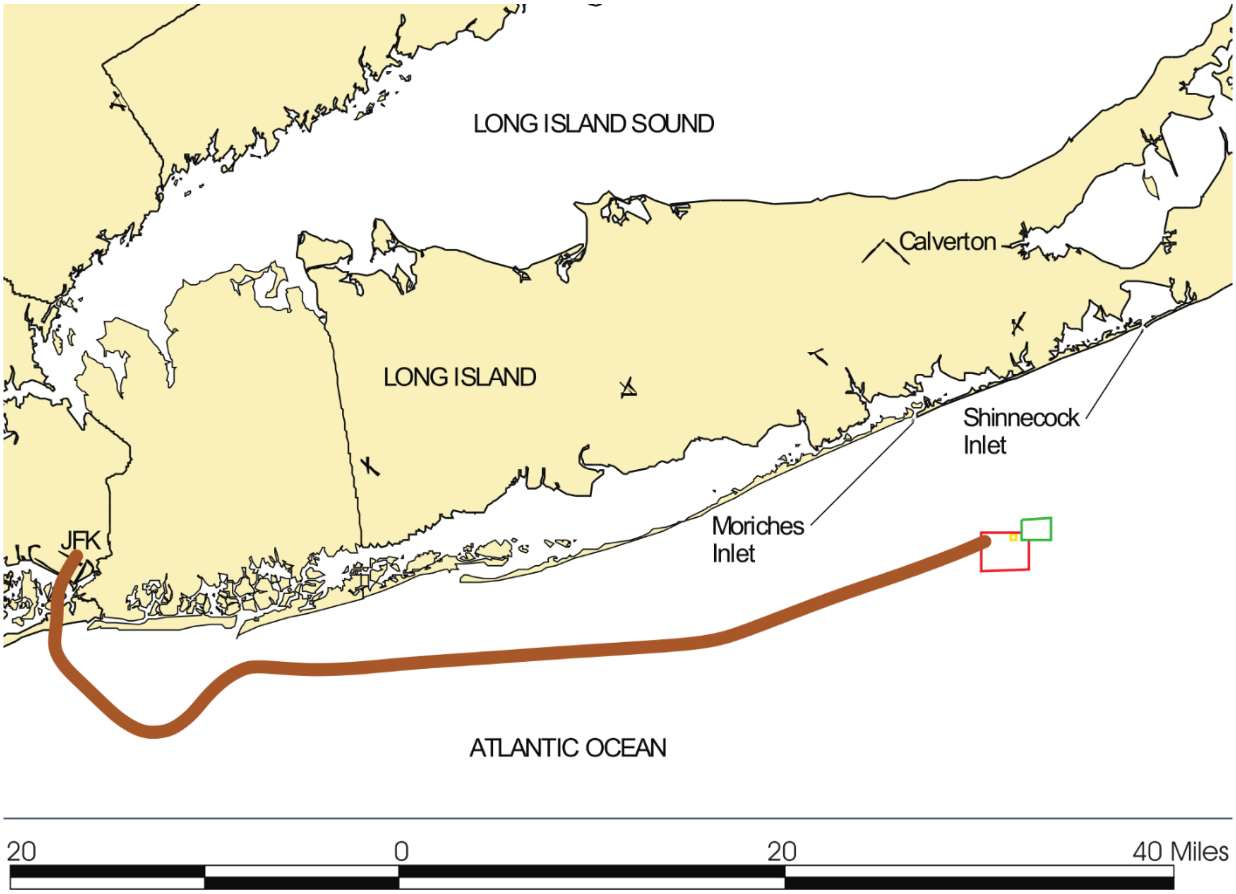


Figure 3: Location of Airplane Wreckage [9].

## 1.5) The Brief Reason of the Accident

According to the reports, the planes had several structural failures. The failure started from the fuel tank at the center wing. The breakout of the tank happened due the overpressure event. The Sequencing Group came to the conclusion that the breakup started because "spanwise beam 3 fractured at its upper end and that overpressure within the CWT caused it to rotate forward about its lower end." [9] Although this statement is the first of many structural damages that occurred, the events that led to the overpressure and started the sequence of failures will be extensively discussed in Section 3. Besides, the investigation was continued at Bruntingthorpe Airfield, in England. They found that an explosion in the fuel/air tank can create enough pressure for structural breakdown, so it is verified that the crash happened due to the explosion in the fuel/air tank. The question then becomes, what led to the overpressure and what was the reason of ignition within the fuel tank? To understand these and to be able to comment on the findings, the system that failed will be discussed first in Section 2 and then the specific chain of events will be displayed following the prior. Problems regarding witness testimonials such as exaggeration, inaccuracy, blurry memory etc. aside, it is noteworthy that a crash witness, described the plane as a fireball, which was falling over the ocean because this observation is not used as evidence or a lead regarding the cause of the accident, but it is used to understand and visualize the magnitude of the explosion through the analogy of a fireball.

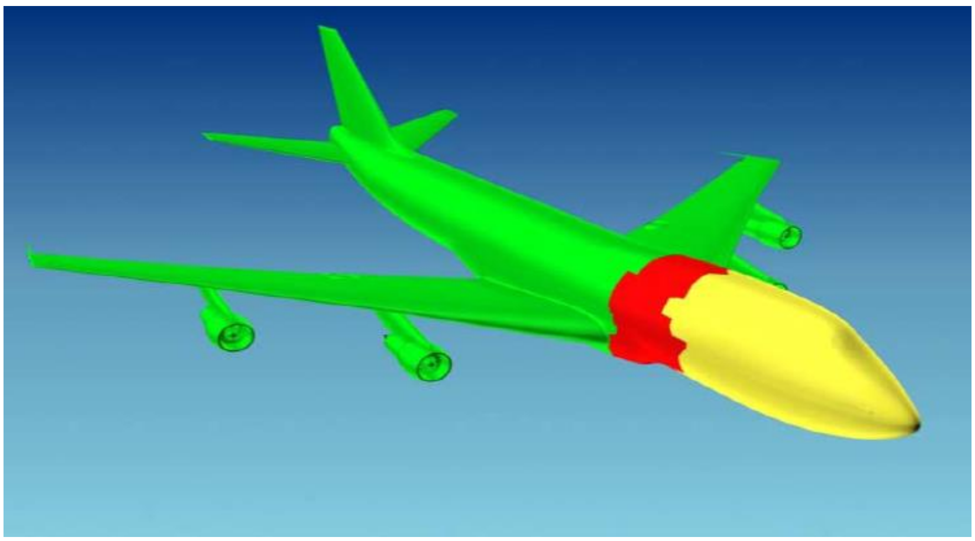

Figure 4: Failure point shown in the Simulations [9].

## 2) Performance & Design

The crash report of TWA800 discloses the three components of the plane that played an important role in the crash: cabling (electronic cables around center fuel tank), fuel and the fuel tank. Thorough research of performance and design are presented in **Section 3 - Specific Accident Characteristics.**

### 2.1) Fuel performance Analysis

> "Look at that crazy fuel flow indicator there on number four... see that?"[

The inquiry showed that, on the day of accident, the generators were playing a major role in heating the mixture of air and kerosene fumes. Before take-off, while the airplane was parked, its air conditioners were running for several hours. Which then resulted in a two-hour delay. Investigators' tests revealed that the internal temperature of the central wing fuel tank may have reached 52 degrees. Note that the combustion threshold for kerosene is 35 degrees. [1]

To elaborate more on the fuel of aircrafts, it is known as aviation kerosene (JetA). JetA is often used in military and civil air crafts. Aviation kerosene is convenient to use in commercial airplanes due to its low viscosity, higher flash point and low cost. An elaboration on these terms is made below.

### 2.1.1) Flash Point

Flash point is defined as the temperature point that a flammable chemical substance gets ignited and converted into vapor. In comparison to its gasoline counterparts, kerosene holds a higher flash point, therefore it offers higher octane ratings to achieve better power and efficiency. That is the main reason why commercial aircrafts prefer using kerosene fuel. [3]

The flashpoint of the aviation kerosene is between 29°C (84°F) and 74°C (165°F). The flashpoint of the fuel can be changed. The temperature of flashpoint is highly affected by the critical value of the fuel-air mass ratio at the flammability limit. Also, based on Le Chatelier's rule for flammability limits.  Shepherd, J. E, et. al. investigated the fuel ignition in the fuel tanks, and they found that in a typical commercial craft 0.3J energy is enough to ignite fuel which can be an ignitable spark from the broken electronic cables. The Aviation kerosene is also found to be a more flammable in gas form rather than the liquid fuel form. So, to decrease flammability in fuel tank and increase high flash point, the nitrogen is used in fuel tanks. It leads to sustain pressure in the fuel tank and decrease flammability.

### 2.1.2) Viscosity

Kerosene has lower viscosity than the old commercial fuels such as gasoline. The lower viscosity provides an easier flow of kerosene to the airplane's engine and connected components. Due to its low viscosity, bubbles are created in fuel during the transportation and the created bubbles result in decreasing the cavitation in the fuel flow components, fuel tank and engines.

### 2.1.3) Cost

Kerosene is cheaper than the old commercial fuels such as gasoline, for per gallon of fuel. Kerosene with the mixture of air JetA, is the commercial fuel used in the airplanes as kerosene has a higher flash point, lower viscosity, and a lower cost.

## 2.2) Fuel Tank and Fuel System Analysis

Fuel system is one of the essential systems to give power to engines, and also it helps in balancing the aircraft. The fuel system is an interaction of the fuel to store (Fuel Tank) the fuel and transmit to fuel to the engine at a specified flow rate pressure and temperature. A specified temperature is needed to protect the fuel from not getting frame and explode. Typically, in a commercial aircraft fuel system consist of fuel tanks, pumps, filters, valves, metering systems and monitoring devices. Since the weight of the fuel plays an important role in the center of mass of the plane, it also used for balancing the airplane [4].

One of the essential parts of the fuel system is fuel tank which plays an important role in weight of the airplane. It must be resistive to various conditions on the plane or on the air considering the large amount the fuel it shelters inside. Consequently, fuel tank has several requirements; Federal Aviation Authorities (FAA) stated that every fuel tank produced, needs to withstand the effects of inertia, vibration, fluid, and structural loads which could be effective in the operation of the aircraft [4].

The fuel tanks usually position at wings, however in larger aircrafts there are additional fuel thanks which is the central wing tank (CWT). The main accident happened in this tank of the Boeing 747's TW800 flight.

### 2.2.1) The design parameters of the fuel tank and fuel system

As mentioned in the previous paragraphs, the weight of the fuel directly affects the center of mass and consequently it affects the plane's maneuver abilities, stability, and flight characteristics. The center of mass of the airplane is constantly changing as the fuel is used and decreased. The fuel system pumps help the airplane to balance the center of mass. So, it can be said that the fuel system is also used for the stability and the control of the plane when a disturbance occurs or when plane should maneuver. Overall, the fuel system is crucial in stabilizing and controlling the aircraft.

In flight mechanism, determining aft and location of the center of the gravity are essential for the stability and balance of the aircraft. The center of the gravity is depending on the weight distribution. The importance of the location of the center of gravity is illustrated in the figure below.

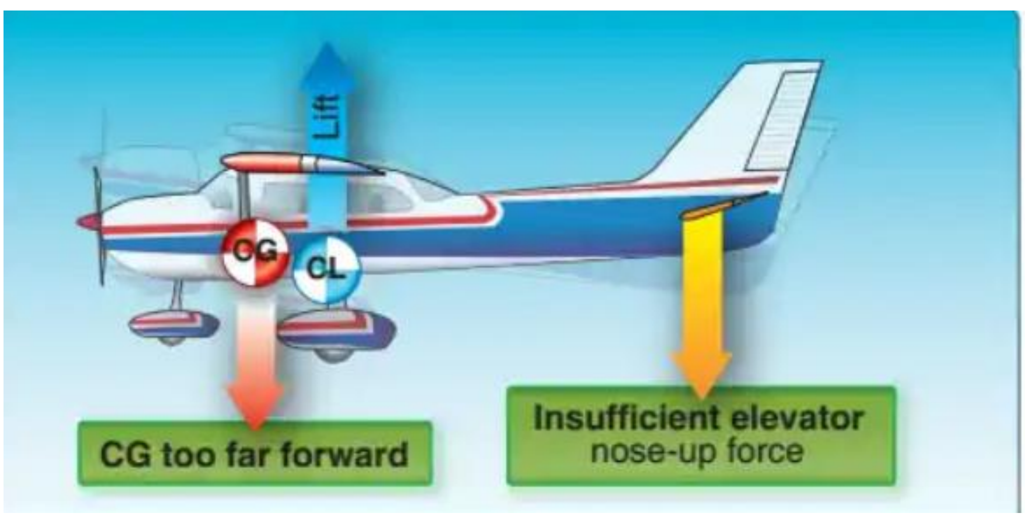


Figure 5: Pilot Handbook of Aeronautical Knowledge [5].

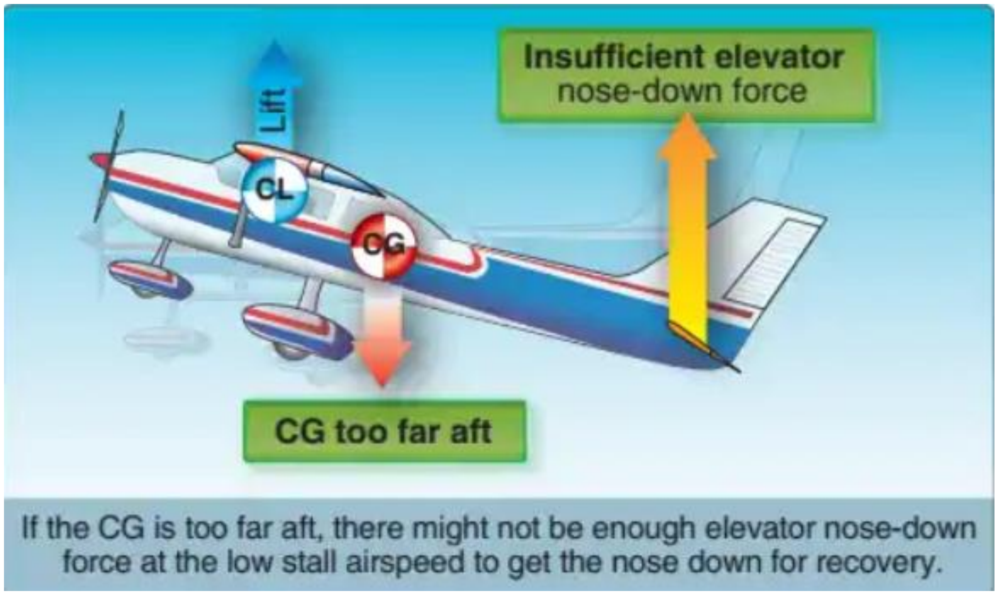


Figure 6: Pilot Handbook of Aeronautical Knowledge 2 [5]

Both the fuel consumption and fuel tank position have an impact on the location of the CG point. The fuel tanks on the wings can affect the lateral balance of the aircraft. When the fuel consumption occurs more on the one wing and less on the other wing, the lateral balance fails. This leads to changes in the location of the CG point which then triggers wing heaviness as shown in the upcoming figure. This unbalance gives also additional lift and drag forces on the wings as illustrated in figure 4. The center of gravity is not automatically calculated during flights of old planes such as Boeing 747's TW800 flight. The pilots should be aware of this unbalance situation. The aircraft designers have also taken precautions against the balance problem. The balance problem can be controller with the aileron trim tab that consumes the fuel from the heavy side of the wing. Additional lift is occurring on the heavy side by the aileron, but the deflection process leads additional drag and range, therefore efficiency and the endurance of the engine decreases due to additional drag.

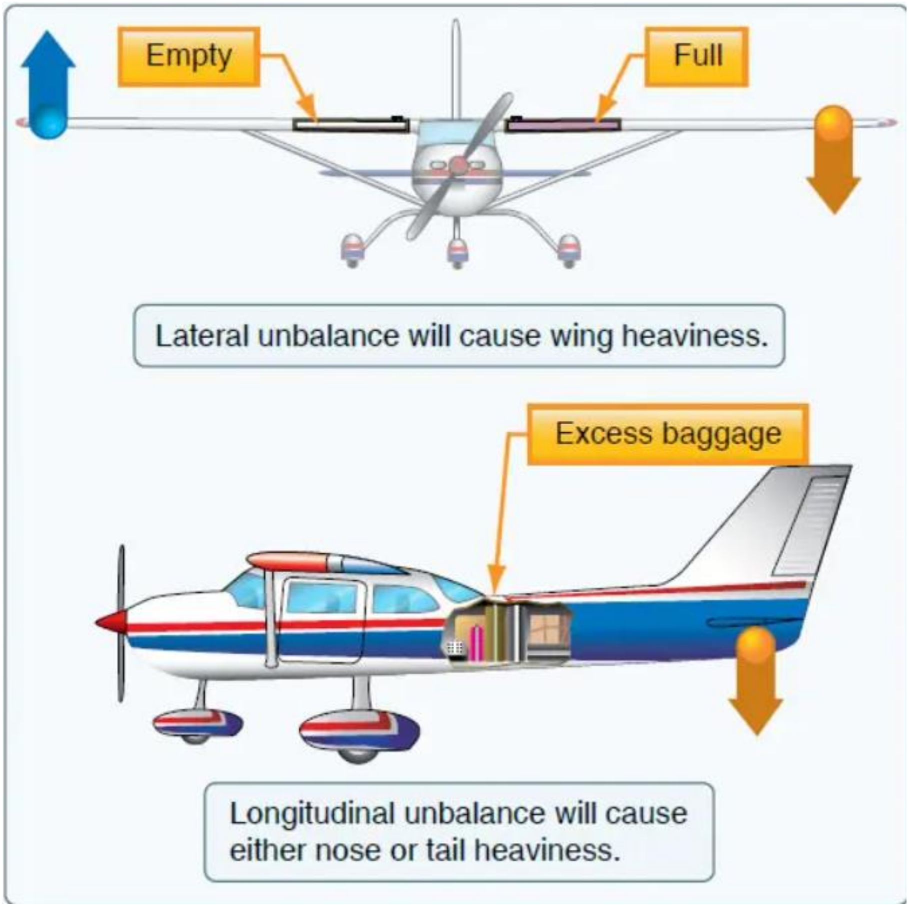


Figure 7: Lateral and longitudinal unbalance [6].

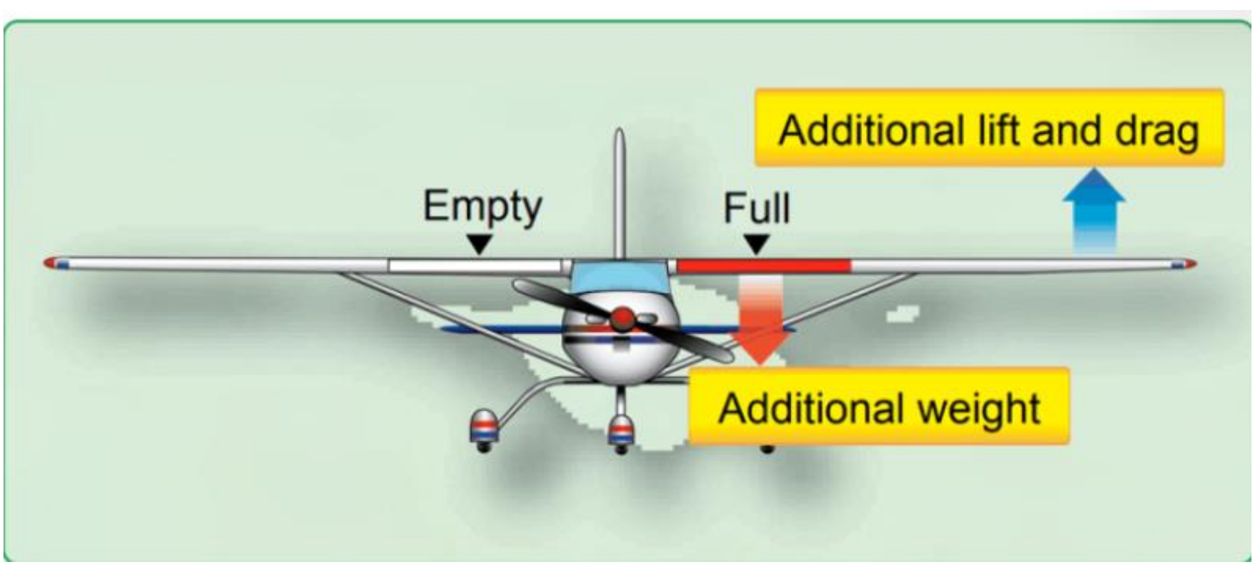


Figure 8: Occurrence of the additional lift and drag [7].

To conclude, the aircraft fuel systems have some precautions to protect fuels and systems are also used to balance the airplane. After the accident, the fuel tanks also got several precautions. First, the filling ratio of the tanks are increased since the liquid kerosene has higher flash points then the gassed version and empty space lowers the pressure of the air in the tanks. So, the pressure acting on the kerosene increases to increase the flash point. Second precaution is the filing some amount of the fuel tank with nitrogen that decreases the flammability of the kerosene in the plane. This is applied to all aircrafts produced after 2005. The fuel system schema of the Boeing 747 is presented below.

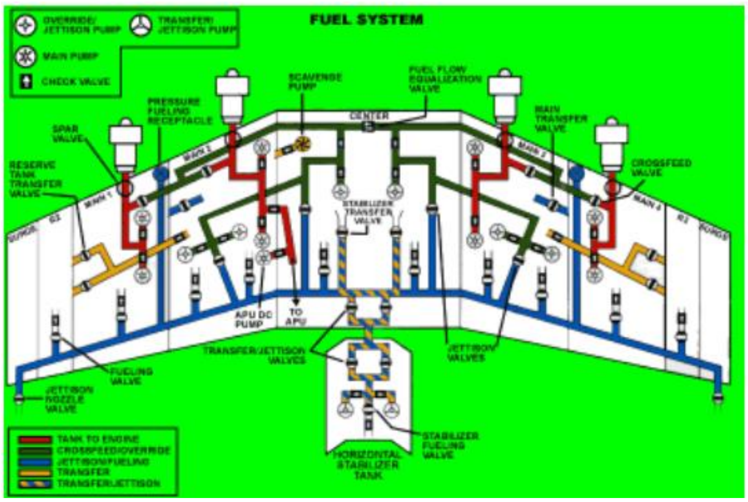


Figure 9: Fuel system schema of the Boeing 747-400 [8].

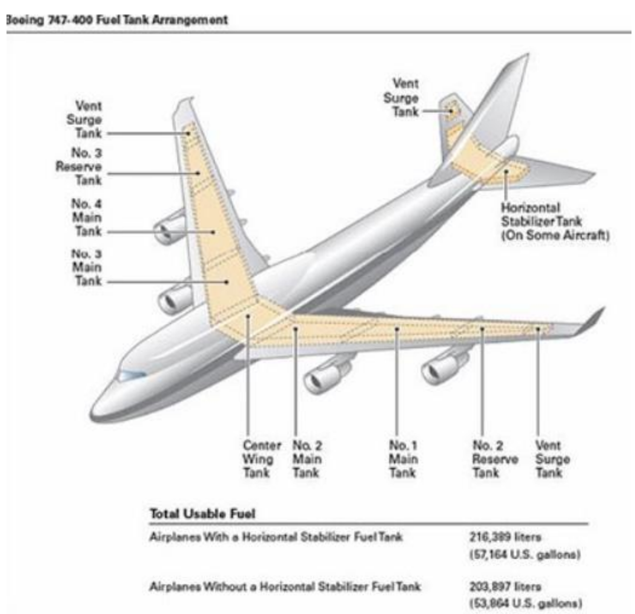


Figure 10: Fuel system schema of the Boeing 747-400 on the plane [8].

## 2.3) Aircraft Electrical Wire

The aircraft wires also take important weight and space on the plane. Such as in Boeing 747 uses approximately 750,000 feet (about 225308 meter) of wire, weighing about 3,500 pounds (1587.573 kg.). The one of the essential concepts on the airplane design is weight reduction, there are several methods to decrease the weight of the wires. One of the methods is to decrease the weight by developing wires with higher temperature rating, which allows less copper content. Second method is to decrease the weight of the insulation by developing better materials that can safely be used in smaller thickness. After the accident of Boeing 747, some performance criteria are applied to the wires which are; cables should withstand abrasion and other mechanical abuse, should maintain circuit integrity in case of current overload, should not propagate flame/fire, should no hazard due to arc tracking susceptibility should occur, should not generate large amounts of smoke if overheated or involved in a fire, should withstand influence of moisture, UV, fluids, cleaning compounds, etc. Additional to these criteria, the wires should be sufficient in terms of weight, size, and combability. The aging also another important on the wires. The wires of Boeing 747 were 24 years old; aging should be applied to wires to sustain their bending, fatigue, vibration, scrape, and flexure behaviors. Aging should be applied also to sustain their resistance on chemical, hydraulic attacks, thermal degradation, and UV or sunlight effects. Considering that the wires of Boeing 747 were 24 years old; despite already having fractures on, they could've also changed during the flight [9].

After the Boeing 747 accident, the wire designs have undergone a major change. The association of wire designs and their insulations with the specific accident will be explained in Section 3. The vulnerability of the system as it pertains to our case is also explained in that section. Observe the below figure to see the new designs of the wire to isolate circuits.

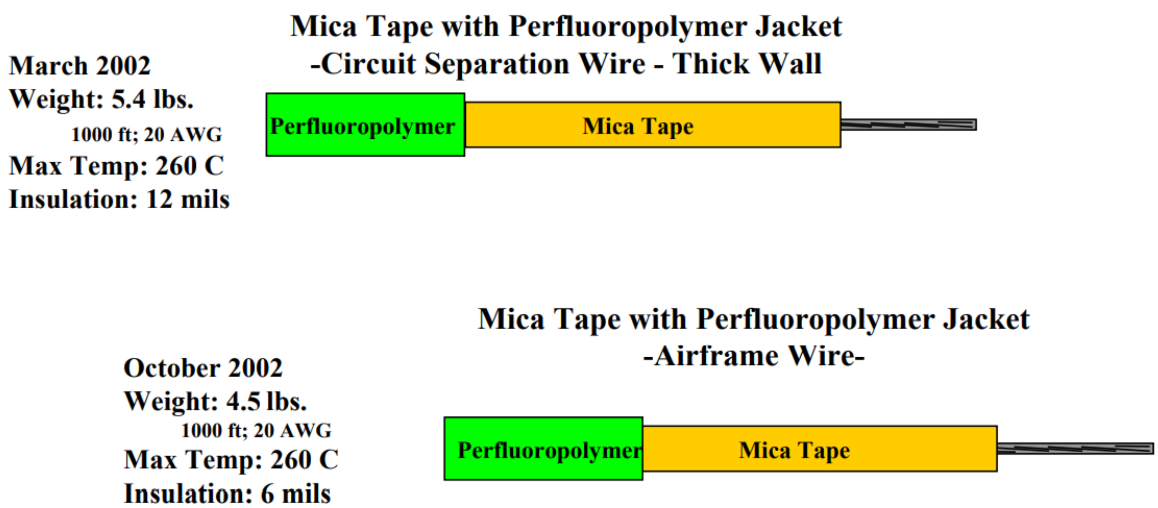


Figure 11: The Applied Circuit Separation for Better Isolation on the Wires [8].

## 2.4) Statistical Reliability

In 1996, TWA800 flight the Boeing 747 exploded in mid-air, launching a highly publicized four-year National Transportation Safety Board (NTSB) investigation. The NTSB concluded the probable cause was the explosion of flammable fuel/air vapors in the center wing fuel tanks. Although, the root cause has never been determined precisely, the report concluded that it was likely due to a short circuit inside the tank [9]. After that, there were some statistical methods applied to the reliability of the fuel tank system. One of them was the Fault Tree Analysis (FTA). This is an analysis method that is compliant with the safety certification of aircraft fuel systems due to its logical approach to factoring in different and many risks. Probabilities of basic events are determined based on historical data and testing of new materials and designs. Combinations of events that can lead to a system failure are managed, analyzed, and subsequently documented using fault tree analysis [10]. It uses a schema to analyze the fault distribution. An example of the FTA is shown below.

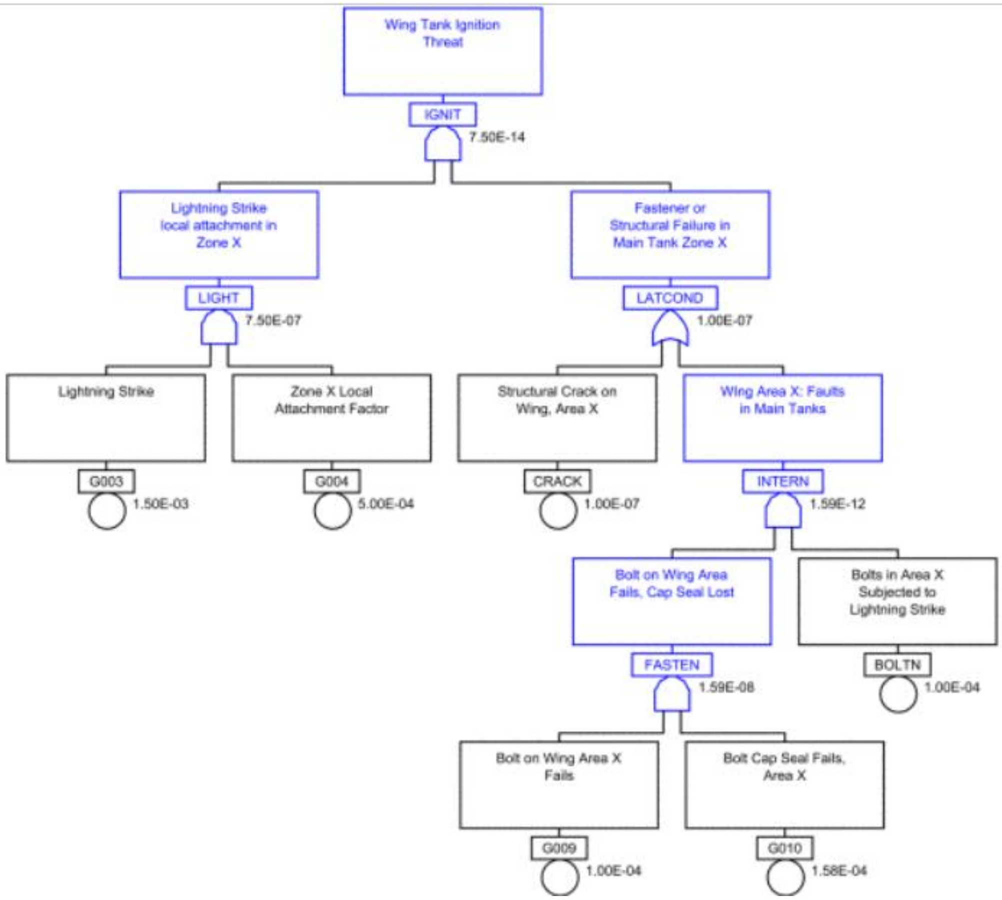


Figure 12: Notional Fault Tree Analysis (with fictional numbers for illustration purposes only) for structural bond path. Image output of CAFTA™, courtesy of Electric Power Research Institute (EPRI) [10].

After the Boeing 747 accident, The Federal Aviation Administration (FAA) responded by establishing a series of regulations for the design process, analysis, and support of the fuel systems. These new regulations are implemented in FAR 25.981. In 2014, M. E. Hill and L. E. Bechtold investigated the failure probability of the fuel system with the FTA method. They assumed that the airplanes are complied with FAR 25.981. Their concluded probability of the failure is $1{\times}10^{-7}$ which is trivial [10].

To conclude, back in 1996 there were very little regulations on the fuel system and electronic wires. After TWA800 flight with the additional requirements, failure probability significantly decreased. In today's commercial airplanes, the failure probability of the fuel system is $1\times10^{-7}$ as mentioned [10].

## 3) Specific Accident Characteristics

Determining the root cause of the accident has been an arduous process involving different federal and institutional investigations. However, the end result proved to be decisive enough that we now have sufficient factual information to reason the accident step by step. Although the root cause of the accident has been pinpointed in a general sense, there still remains an ambiguity as to what may have caused the specific system involved in the accident failed the way it did.

As discussed in the previous sections, the part that led to the catastrophe was the Center Wing Fuel Tank. However, before diving into the problem that emerged within the CWT, the other possible root causes that were considered during the investigation should also be explained. In any mid-air breakup scenarios, a structural damage that has occurred before the flight is always considered. In this case, the recovered parts of the airplane and the fact that they were spaciously distributed all over the ocean hinted at a very probable in-flight breakup. Also, the occurrence of an in-flight breakup was consistent with the witnesses' observations. Upon the examinations, the only structural damage found was corrosion which was cited as "minimal". The amount of corrosion and the fatigue and mechanical damage, or lack thereof, meant that the in-flight breakup could not have been caused by any structural damage that was already in existence. Apart from the minimal corrosion, some cracks were also observed alongside minor manufacturing errors in certain joints of the fuselage however as stated they were not significant enough to have caused the breakup. Also, there has been no indicator that the said parts experienced any failure prior to the crash.

Moreover, the possibility of a terrorist act being involved in the accident has also been investigated. However, this possibility never gained enough credibility and remained a speculation in light of the investigation. The investigation revealed that although minor traces of explosives on three different parts of the recovered airplane were detected, the traces did not point to an explosive material that may have caused the accident. Since %95 percent of the fuselage has been recovered, the investigators concluded that there isn't any evidence indicating the explosion of a bomb or a missile. However, there have been findings of small holes over the fuselage that might have hinted at a missile attack had they been larger. Nevertheless, the size of the holes led the investigators to dismiss this possibility and they came up with alternative causes to the observed holes. It has been later announced that the said holed may have been formed during the period when the wreckage was already under water. [9]

To understand the initiator of the in-flight breakup, the investigators analyzed the parts landed closest to the JFK airport. These parts were believed to be the first ones to depart from the airplane and are the most likely to be the failed parts. Most of the parts found, including "the Wing Center Section front spar and spanwise beam, the manufacturing access door, the two forward air conditioning packs, large pieces of a ring of fuselage structure just in front of the wing front spar, and main cabin floor beams and flooring material from above the WCS and from the fuselage in front of the WCS" [] belong to the wing center section. The metallurgy structure/sequencing group conducted research and reported that the first item to leave the assembly was the Spanwise Beam #3. More importantly, their research revealed that there has been an overpressure within the central wing fuel tank judging by the fracture in the upper end of the third spanwise beam. The events following the overpressure are believed to be sequenced as following: [9]

- Forward rotation of the spanwise beam #3 with respect to its bottom
- Impact on the front spar and fractions on its upper chord caused by the spanwise beam's rotation
- Front spar bulged forward on both sides, caused by overpressure escaping from the central wing fuel tank
- The upper skin of the WCS and the upper end of the front spar were disconnected from one another completely

- Overpressure that remained in the CWT caused both forward end of the keel beam and the WCS lower skin to move downward

- The stress in the fuselage skin adjacent to the front spar and in the ring chord significantly increased by the downward loading of the forward end of the keel beam

- As this downward loading increased, cracking continued through the ring chord and the lower pressure bulkhead, and immediately entered the fuselage skin (at the stringer 40 right)

- This crack propagated and then branched to the left and right, circumferentially, then it propagated back to the lower left side of the front spar

- Propagation of this large crack caused a large piece of fuselage skin to have only a small part that is adjacent to the lower pressure bulkhead to remain attached to the main body.

- Cabin pressure and the overpressure from CWT vent on the weakly attached fuselage piece transferred the downward loading to the keel beam's forward end, causing WCS lower skin panel and the keel beam to separate.

- Due to the separation of this large piece, a large hole was opened on the fuselage, near the front spar.

According to the sequencing study, break up sequence was caused by an overpressure inside the CWT, which is assumed to be caused by a fuel/air mixture explosion, since there was no evidence for a missile or bomb, or any similar high-energy explosive device detonation, in any area of the airplane. Further investigations, tests and evidence showed that the temperature and the pressure conditions were in the range that Jet A fuel is flammable, and a simple spark can cause the explosion. (Note that Jet A fuel is not flammable or explosive under room temperature). It was also investigated that if the fuel-air explosion can create enough pressure to break apart the fuel tank, which will initiate the event sequence that will split the airplane. Using an out of service 747, tests show that fuel air explosion can fail the tank structure due to overpressure. However, the test was done with propane instead of Jet A fuel, but it was concluded that Jet A fuel explosions also can break apart the fuel tank therefore causing the airplane destruction. Further investigations simulating the TWA flight 800's altitude, pressure, temperature, fuel mass conditions showed that the loadings exceeded the limitations, therefore showing the situation was sufficient to initiate the failure of CWT structure. [9]

Upon the conclusion that there has been an understandable fuel/air explosion inside the central wing fuel tank, the question became: "What caused the explosion and what was the igniter?". To answer this question, different possible scenarios have been considered. The point of interest was finding the canal through which energy entered the central wing fuel tank and the first consideration was that it had entered through the fuel quantity indication system. However, there were many other theories that proved to be false. All of the possible ignition sources have been listed below: [9]

- Lightning Strike
- Meteorite Strike
- Missile Fragment
- Small Explosive Charge
- Auto Ignition or Hot Surface Ignition
- Fire Migration Through the Vent System
- Uncontained Engine Failure or Turbine Burst
- Malfunctioning Jettison/Override Pump
- Malfunctioning Scavenge Pump
- Static Electricity

All of the above causes have been disregarded on the grounds that they are not supported with sufficient evidence. Especially the meteorologic events were disproved fairly quickly with the help of weather data relating to the day of the accident. Possible fires in the air conditioning pack or the landing gear wheel well were seen as a viable reason for a hot surface ignition to happen inside the central wing fuel tank with elevated temperatures. But this idea was also later abandoned since there was no evidence indicating that the temperatures were that increased within any of the mentioned parts.

The focus shifted towards an explosion caused by the Fuel Quantity Indication System (FQIS) since it is the only present wiring system that is located within the CWT. The accident report states that Boeing has precise discharge limits for this specific wiring system and that any explosions caused by this system must've happened due to energy provided from the outside. Also, this energy that came from the outside should be over a certain threshold in voltages to cause an explosion. Lastly, the way which the excess energy was discharged into the tank must be ignition-causing.

The outside source of excess voltage, if related to electromagnetic intervention, could be related to three things: [9]

- Radiofrequency Transmitters coupling to the wiring system of FQIS: Deemed to create insufficient energy, hence not the cause of ignition.
- Personal Electronic Devices coupling to the wiring system of FQIS: Deemed only enough to create 10% of the voltage that can cause an explosion, hence not the cause of ignition.
- Transient voltage spike from other systems with higher voltages on the aircraft: Deemed "unlikely" because of multiple analyses.

Then, with the understanding that an electromagnetic interference was not the case, the investigation turned to the possibility of a short-circuiting problem. It is known that short circuits can create the voltage surplus especially when the wires are particularly close to each other. This surplus of voltage is usually transferred from the short circuit that has high voltage to the nearby wiring system that has low voltage. A critical information is that Boeing design specifications do not explicitly or implicitly state that the FQIS wiring system cannot be near high voltage circuits. The wiring system is shown below.

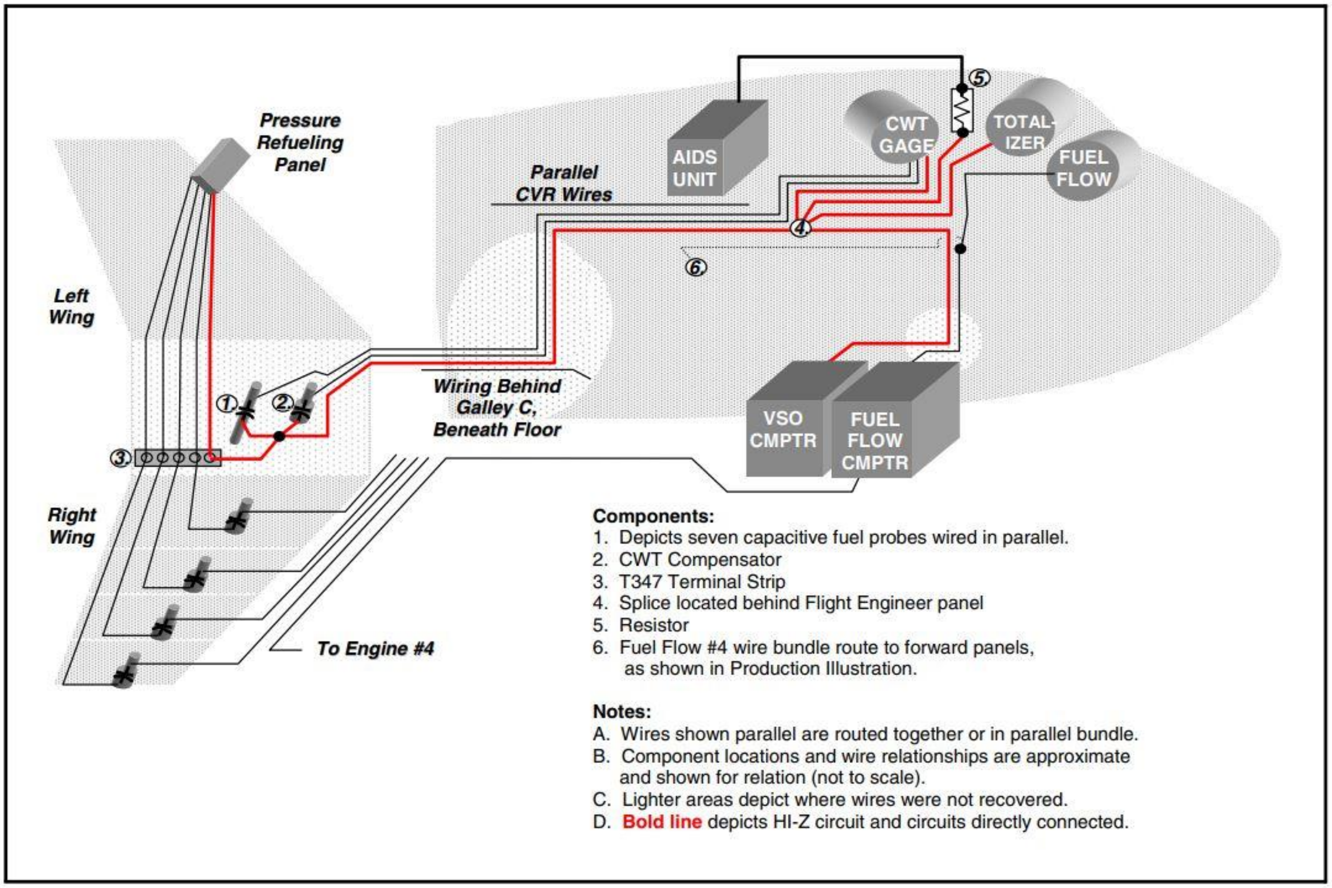


Figure 13: Wiring System Schematized [9]

To elaborate on the possibility of a short circuit event, the findings revealed that the wiring systems on the airplane had damaged insulators. Wires with damaged insulators are more prone to short-circuiting and the damage was not directly associated with the accident, but it was noted that at least some of the damage could have existed prior to the explosion. Arcing was also detected in some of the wirings including ones going to the right main wing tank fuel flow gauge and right wing FQIS wiring that all would've been involved with the central wing fuel tank at point 3 in the figure above. The authorities deemed any short circuiting involving these parts would indeed be able to carry the necessary ignition energy into the FQIS.

As a result of the physical evidence coupled with the electrical anomalies reported by the captains shortly before the explosion, the Safety Board determined that the high energy released into the central wing fuel tank fuel quantity indication system must have been caused by a short-circuiting event in one of the aircraft's systems. [9]

As for how that energy was released into the CWT, there are different schools of thought.

## 3.1) Arcing

Damage due to mechanical contacts or cold flow exposed wires on FQIS wiring that is in the fuel tank. These exposed conducting wires can easily create an electric arc, which will be the source of all the destruction happened. The electric arc inside the fuel tank can cause the ignition of the vapor of air-fuel mixture. The same mechanism of ignition inside the fuel tank is suspected to be the cause of CWT explosion for the 1990 Philippine Airlines 737 crash and the 1972 Navy C-130 crash. The collected pieces had only very small fraction of the CWT FQIS wiring, therefore it was not possible to assess the degree of damage on the wiring before the explosion. On the other hand, examination of other 747 aircrafts' CWTs resulted that some of the 747s has damaged CWT FQIS wirings. Also, damage occurred before the accident was found by the investigators, which includes exposed conductors, inside the wing tanks of TWA800 flight. The arcing on the FQIS elements could have also occurred due to the other conductive components, which is present in the fuel tanks, for example safety wires or metal shavings. The investigations could not show clear and certain evidence in the recovered pieces, the damage caused by the explosion and fire is most likely the reason we couldn't find such evidence, due to its severity.

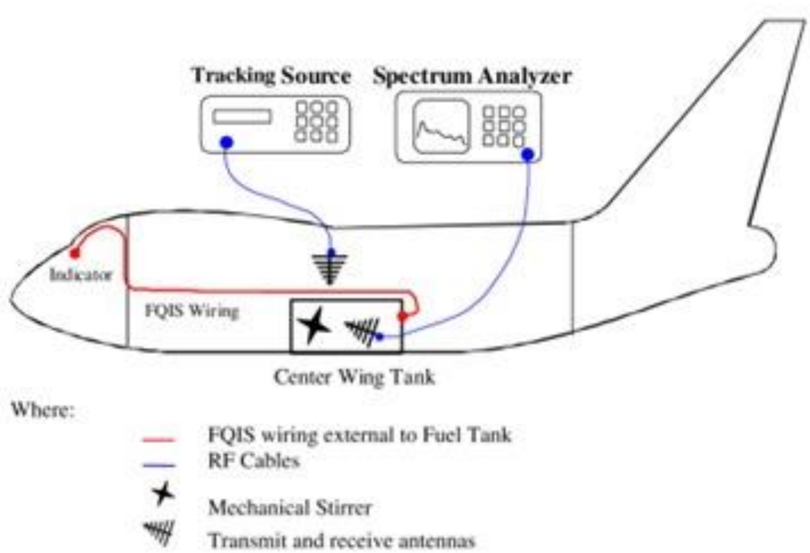


Figure 14: The relative locations of the CWT and FQIS [18]

## 3.2) Resistance Heating

Another unevidenced, but potential reason for the CWT explosion is thought to be a filament, which is heated up and became the source for combustion energy by being in contact to a conductive wire, compensator or probe that is under high voltage. No filament was found in the TWA800 flight’s collected pieces, it could have been obscured by the fire damage or lost.

## 3.3) Silver-Sulfide Deposits on Fuel Quantity Indication System Wiring and Components

Another potential mechanism for combustion inside the TWA800’s fuel tank is the silver-sulfide deposits that are developed on the silver-coated copper components in the fuel tanks. Silver-sulfide deposits are semiconductive. Semiconductive materials have lower resistance than insulators, therefore creating a situation that can cause electric arcing. In fact, silver-sulfide deposits were apparent on the TWA800 airplane, on the compensators, wiring, and FQIS probes. Other airplanes, including military and commercial airplanes, especially other 747s, found to also have similar silver-sulfide deposits on FQIS parts. According to research, these deposits happen due to the exposure of the component to the jet fuel (or jet fuel vapor) over time, and since the jet fuel contains sulfur, and the wires are silver coated, the accumulation occurs.

Another laboratory research that is conducted by the University of Dayton Research Institute resulted that at higher temperatures the accumulation of these deposits is faster, and fuel washing slows down the formation of silver-sulfide deposits. This outcome is very important for the CWTs, because, while wing tanks are filled with fuel fully more frequently, CWTs are less often filled to the top, making the CWT fuel probes and its terminal block not covered by fuel more often, which decreases the fuel washing therefore increases the silver-sulfide accumulation on them.

AFRL’s investigation resulted that probably the silver sulfide deposits accumulate after a long-term corrosion or degradation process. Which means that more failures can be expected if the probes are older. Yet on the other hand, this issue is not observed on only the older airplanes. A 757 that is as young as 750 hours of flight also had silver-sulfide deposits, which could cause FQIS problems.

### 3.4) Verdict

Silver-sulfide deposits on FQIS parts appears to be the most probable source for the ignition energy mechanism in TWA 800's CWT. There were FQIS anomalies observed during the maintenance of this aircraft, which is in line with these deposits being the source of ignition energy in CWT explosion.

## 4) Related Accidents

### 4.1) Thai Airways International Flight 114, 3 March 2001

A horrific accident took place in Thailand, the Bangkok International Airport to be more specific on 3rd of March 2001. The aircraft involved in the accident was a Boeing 737-400 belonging to the Thai Airways International Public Company Ltd. also known as Thai Airways. A notable difference from our accident is that the airplane was stationary, waiting at Gate 62 of the Bangkok International Airport for a flight to another city in Thailand, Chiang Mai. The apparent similarity is that the accident involved an explosion in the central wing fuel tank. The intricacies of the accident will be explained in the upcoming section. As for the analysis of the accident and its probable causes, the governing body when it comes to aviation accidents, The Thailand Aircraft Accident Investigation Committee (AAIC) communicated the issue to the US to request assistance regarding the investigation. The US officials sent an “Accredited Representative” to meet their needs. [11]

Figure 15: State of the Aircraft After the Accident [11]

### 4.1.1) Findings

In terms of fatality, the accident was not as deleterious as our accident. One crew member lost their life, and several others were severely injured. Needless to say, this difference is caused by the fact that the aircraft was not in air. The investigation revealed that all the necessary measures regarding the critical parts of the plane were in accordance with the regulated standards. Additionally, the immediate aftermath of the explosion was handled appropriately and precluded the fire to spread out to the different parts of the airplane, or the terminal for that matter. The air temperature at the time has been decided to have an effect on the explosion by increasing the fuel-air mixture temperature and making it flammable at the time the explosion took place. An exact correlation with our accident, an overpressure event is believed to take place. This deduction was made due to the far away location of the central wing fuel tank's surfaces from the center. The CVR sound spectrum is reported to be very similar to the accident featured in this report and a Philippine Airlines accident also involving a Boeing aircraft. As for the probable causes, initiation by a high-energy explosion device, fuel tank flow switch, electromagnetic energy from a radar in the surrounding area or an electrostatic discharge from the vent valve have all ben disregarded due to a lack of sufficient evidence. One probability that was not convincingly rejected was that the explosion could be ignited by the Fuel Quantity Indicator System. However, all the possibilities listed aside, metallic debris found on the right- and left-wing fuel pumps pointed towards the explosion being caused by “dry running” by the left-wing fuel pump. [11]

### 4.1.2) Conclusion on Thai Airways Accident

As a result of the investigation, the AAIC concluded that the root cause of the explosion of the central wing fuel tank cannot be pinpointed. Although the explosion can be linked to the ignition of the flammable fuel/air mixture just as TWA Flight 800 Boeing 747, the exact reason of the ignition still holds ambiguity. However, the prevailing understanding is that there is a decent chance that the explosion took place because the central wing fuel pump was run alongside metal shavings and the fuel-air mixture. [11]

The suggestion from the investigators as to what measures should be implemented to prevent this issue from recurring was that the State of Design needed to increase the amount of research projects on fuel tank explosion and the associated vapor. They also called for additional standards to be set in light of the new research to come. Lastly, they wanted the response time to be improved meaning that the fire extinguishers to arrive to the scene considerably more quickly. [11]

## 4.2) Philippine Airlines Flight 143, 11 May 1990

Philippine Airlines Flight 143 was planned as a domestic flight, starting from Ninoy Aquino Airport in Manila to Mandurriao Airport on Iloilo City, on May 11, 1990. The aircraft was a Boeing 737-370 operated by the Philippine Airlines, with 120 occupants, 6 of which were the crew. Luckily, there were 112 survivors. Luckily, the accident happened while the plane wasn’t on air, and therefore many of the passengers were able to leave without fatal injuries. Passengers fleet the aircraft via chutes. It is also worth mentioning that the aircraft had been in use for 9 months at the time of the accident. The aircraft was suspected of a bomb attack at the time and was concluded that a bomb or any other issue was the cause. The reason is that the explosion took place just after the pushback, forcing officers to consider the chances of bad intensions. [17]

Regarding the accident, the air temperature was above average, 35 degrees Celsius. This is in fact normal for Philippines. Considering the outside temperature, the air conditioning packs, placed just underneath the center wing fuel tank, had been in use for approximately 40 minutes. The center wing fuel tank had not been filled in the last 60 days, but there is a possibility that it still contained some fuel vapors and traces of fuel. The explosion happened on the central wing fuel tank, pushing the cabin floor upward. Then, the Boeing aircraft burst into flames as the wing tanks ruptured. The engines of the aircraft were not running at the time of explosion, and several passengers reported hearing multiple explosions.

Below is the map showing the planned route. The Distance from Manila-Ninoy Aquino International Airport to Iloilo-Mandurriao Airport is 451 km (282 miles).

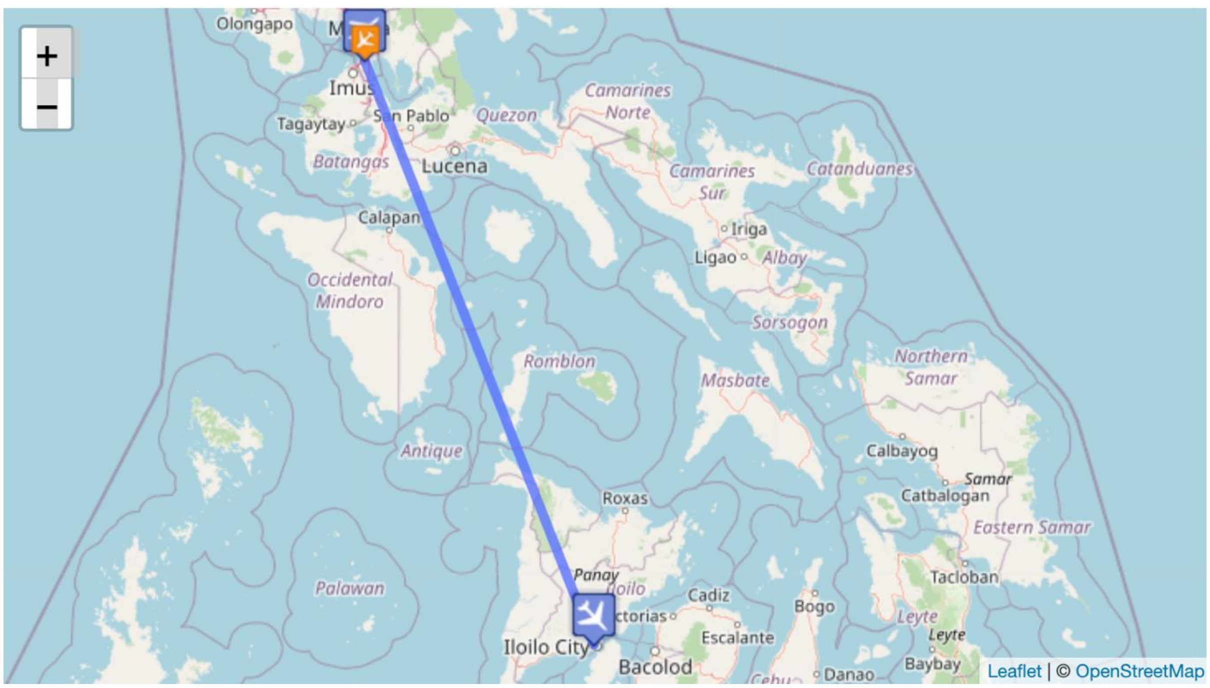


Figure 16: Map Showing flight route [15]

After receiving the aircraft from the factory, the airline decided to add logo lights to the plane. Unfortunately, they have damaged the vapor seals by doing so as it required passing additional cables and wires through the fuel tank vapor seals. [17]

The National Transportation Safety Board (NTSB) suggested to the FAA that an "Airworthiness Directive" to be created for inspections of the fuel boost pumps, float switch, and wiring looms as there were signs of chafing on the wiring looms and fuel boost pumps. An Airworthiness Directive was not issued by the FAA at the time. [17]

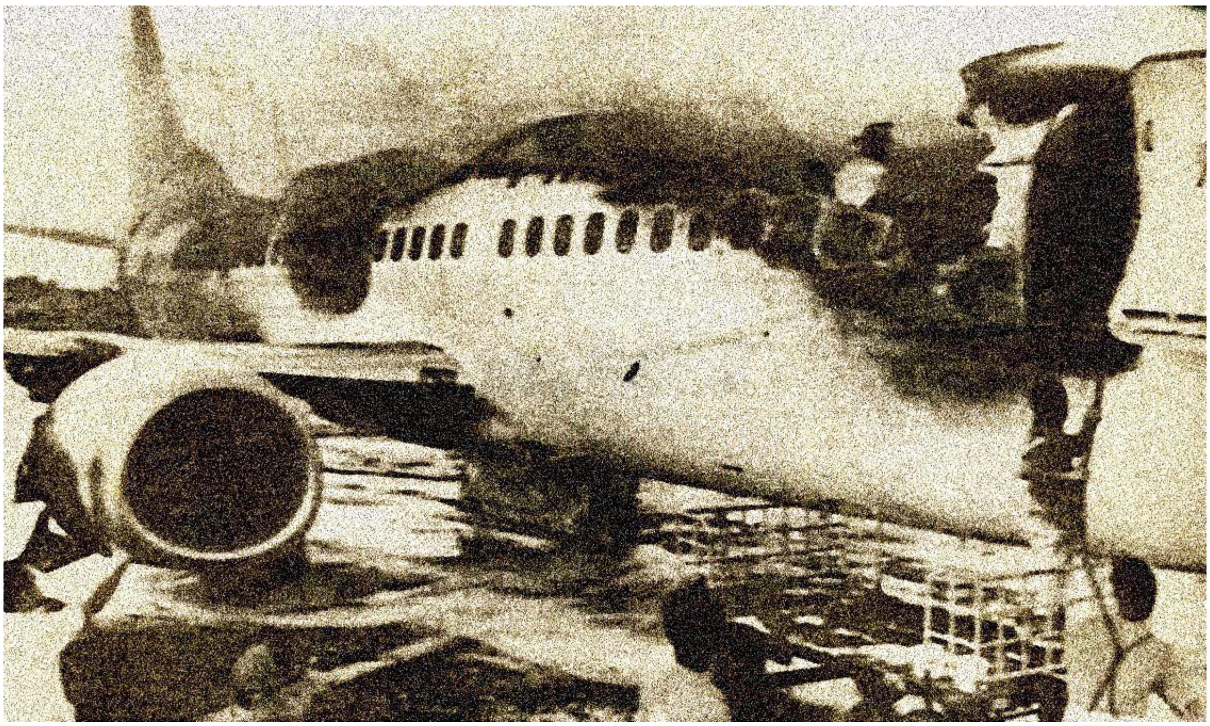

Figure 17: Image of the Aircraft After the Accident [16]

## 5) Corrective Measures

Obviously, following the accident, many safety recommendations have been made and a considerable amount of them have been activated. The Safety Board activated these corrective actions in three different occasions, the first one being on December 13, 1996. In the first iteration of these changes in regulations, the first proposal included better insulation for fuel tanks. The conspicuous solution that first came to our mind is to have additional insulators between the fuel tanks and heat-generating systems in aircrafts that are yet to be manufactured. This idea was adopted by the Safety Board, and they too suggested and demanded better insulation for systems that are close to the fuel tanks, the central wing fuel tank being the most prominent. Also, the Safety Board stressed the importance of nitrogen-inerting systems to prevent explosions within tanks. Apart from the fact that these measures were to be taken by airplane manufacturers, it was also recommended that these changes be made to suitable existing airplanes. Secondly, the Safety Board focused on the quantity of the fuel-air mixture and how it is being deployed into tanks. Their suggestions included filling up the tanks from cooler tanks on the ground while the temperature is being monitored instantaneously. As a group, we also came up with the idea of cooling the canals which transported the fuel-air mixture on the ground to the plane to have a lower temperature fuel-air mixture in early stages of flight. Although the idea behind these suggestions is the same, the Safety Board opted for the former. Finally, they called for the revision and modification of other Boeing 747's that have similar close geometries around the CWT area between the tanks itself and other wirings. [9]

The second iteration of modifications came on February 18, 1997. This time the focus was not on the failure itself but on other explosives and how they could be regulated. The Safety Board called for a checklist to be put in place that controls aircraft contamination by effectively detecting K-9 explosives. [9]

Lastly, the third batch of solutions were implemented on April 7, 1998. The measures were primarily designed to target the existing airplanes. The Safety Board called for the detailed inspection of both the FQIS wirings and Fuel Tanks to detect any damage that has been caused by similar factors to replace those parts. The terminal blocks used on Boeing 747's was also changed under the condition that they had "knurled surfaces or sharp edges". These terminal blocks were Honeywell Series 1-3 probes, and their adequacy was also put to test. Different FQIS systems were examined that did not have these specific terminal blocks to see if the issues faced were similar. Finally, circling back to the issue that is the most probable cause of ignition, silver-sulfide deposits on FQIS parts, a recommendation has been made to increase the amount of research on how hazardous these deposits can get in what quantities and how to relieve the parts of these deposits. If cleaning is not an option, at what point the parts of the FQIS should be changed should also be researched. [9]

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