BOEING

Submission to the

National Transportation Safety Board

for the

TWA 800 Investigation

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from The Boeing Company

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GLOSSARY

A/C	air-conditioning
AAIB	Air Accidents Investigation Branch
AAPA	Air Atlantic Pilot's Association
AD	Airworthiness Directive
AEA	Association of European Airlines
AECMA	Association Europeenne des Constructeurs de Materiel Aerospatial
AFB	Air Force Base
AFM	air-fuel mixture
AIS	Aerospace Industry Association
AMM	Aircraft Maintenance Manual
AMOC	alternate method of compliance
APU	auxiliary power unit
ARAC	Aviation Rulemaking Advisory Committee
ASTF	Aging Systems Task Force
ATA	Air Transportation Association
ATC	air traffic control
ATSRAC	Aging Transport Systems Rulemaking Advisory Committee
AWG	aircraft working group
CVR	cockpit voice recorder
CWT	center wing tank
DOD	Department of Defense
DWV	dielectric withstanding voltage
ECS	environmental control system
EE	electrical and electronics
EMI	electromagnetic interference
EQA	equipment quality analysis
FAA	Federal Aviation Administration
FBI	Federal Bureau of Investigation
FDR	flight data recorder
FE	flight engineer
FIM	fault isolation manual
FMEA	failure modes and effects analysis

FOD	foreign object debris
FQIS	fuel quantity indicating system
FQPU	fuel quantity processor unit
FTA	fault-tree analysis
FTHWG	Fuel Tank Harmonization Working Group
GBI	ground-based inerting
HIRF	high-intensity radiated frequency
Hi-Z	high impedence
HST	horizontal stabilizer tank
IR	insulation resistance
LN	line number
Lo-Z	low impedence
LRU	line-replaceable unit
MΩ	megohm
NASA	National Aeronautics and Space Administration
NPRM	Notice of Proposed Rulemaking
NTSB	National Transportation Safety Board
OBIGGS	onboard inert gas generating system
OBOGS	onboard oxygen generating system
P/N	part number
RFC	Request for Comment
RMM	Ramp Maintenance Manual
rms	root mean square
RTCA	Radio Technical Commission for Aeronautics
SAE	Society of Automotive Engineers
SB	Service Bulletin
SFAR	Special Federal Aviation Regulation
STA	station
STC	Supplemental Type Certificate
TFE	tetrafluroethylene
TSD	transient-suppression device
TWA	Trans World Airlines
V	volt
VSO	volumetric shutoff
WCS	wing center section

OVERVIEW

INTRODUCTION

On July 17, 1996, Trans World Airlines Flight 800 departed New York's John F. Kennedy International Airport en route to Paris, France, carrying 212 passengers and 18 crewmembers. The aircraft was a Boeing 747-100 that had been delivered in November 1971 and had accumulated 93,303 flight-hours and 16,869 cycles prior to this flight. It departed JFK about 8:16 p.m. eastern time and was climbing through 13,760 feet when, 14 minutes into the flight, it exploded and fell into the Atlantic Ocean approximately 9 miles off Long Island. All 230 people onboard were killed.

INVESTIGATION—BOEING SUPPORT

This tragic accident launched the most complicated and comprehensive wreckage recovery, aircraft reconstruction, and accident investigation in the history of commercial aviation. The NTSB led this difficult challenge with the support of several parties to the investigation. As part of the TWA Flight 800 accident investigation, the NTSB has requested that all parties to the investigation:

- Submit proposed findings to be drawn from the evidence revealed during the course of the investigation.
- Identify, if possible, a probable cause.
- Propose safety recommendations designed to prevent future accidents.

Boeing has responded to the NTSB's request with this document, which:

- Provides an assessment of the evidence and other pertinent data.
- Identifies the knowledge gained from the investigation and related activities.
- Describes the actions taken by Boeing to enhance the safety of the in-service fleet.
- Identifies actions to further enhance systems safety:
    - Preclude the potential for ignition sources in fuel tank systems.
    - Reduce the center wing tank (CWT) exposure to flammability.

Boeing Participation

Over the nearly four years of the TWA 800 accident investigation and subsequent activities, Boeing has devoted enormous resources, effort, and expertise, and more than $32 million toward wreckage recovery and reconstruction, the inspections of other aircraft, and exhaustive testing, analysis, and research. As the manufacturer of the 747-100 aircraft, our specific role in this investigation has been to:

- Provide technical information regarding aircraft design to assist the NTSB in the investigation.
- Change aircraft designs, develop service bulletins, and provide maintenance and operational recommendations to the air carriers.
- Support carriers in implementing changes in the fleet.

These activities have led to changes in design practices, the development of service bulletins supporting FAA airworthiness directives (AD), and maintenance recommendations.

EVIDENCE ASSESSMENT

Boeing’s assessment of the evidence is based on extensive observations of the wreckage, analysis of possible failure modes, observations of the wreckage reconstruction, analysis and simulation of explosion scenarios, and review of other pertinent data gathered during the investigation. Based on a review of this information, Boeing believes that there was an ignition of the flammable vapors in the CWT resulting in a loss of structural integrity of the aircraft. Although there has been significant analysis of the wreckage and potential failure modes by some of the best minds in aviation, the government and academia, the investigation, to date, has not determined the ignition source.

See appendix A, *Investigative Evidence—TWA 800 Airplane*, for details of the Boeing evidence assessment.

KNOWLEDGE GAINED DURING INVESTIGATION

The extensive scope of the TWA 800 investigation has prompted a worldwide review of fuel systems for all large commercial transports. This review of design practices and service experience on individual aircraft models identified improvements that could be applied across other aircraft models. As a result, service bulletins to incorporate changes to virtually all aircraft in the fleet have been—and are continually being—released. Many of these changes have been mandated by the FAA for incorporation by ADs. Some details of these ADs for Boeing aircraft are provided in appendix D.

In addition to design and service experience reviews, in October 1997, the air transport industry launched the most comprehensive effort ever undertaken to examine the physical condition of airplane fuel tanks and associated components. The Air Transport Association coordinated the industrywide Fuel Systems Safety Program using aircraft working groups composed of representatives from the aircraft manufacturers and major operators.

A sample inspection program was conducted to gather data on the physical condition of fuel tanks in the in-service fleet. Through this activity, the industry has examined the fuel systems of more than 850 turbine-powered commercial transports built by six manufacturers and operated by 35 airlines worldwide. In general, these physical inspections have shown that the design and components inside fuel tanks maintain their intended safety measures very well over time. Some minor issues, which do not affect the continued airworthiness of the fleet, have been identified and are being addressed by each manufacturer by service bulletins, maintenance programs, or both, as appropriate.

Altogether, the investigation and the industry efforts have revealed:

- **A sound design philosophy—**The industry approach to fuel tank system safety through the preclusion of ignition sources within fuel tanks is sound.
- **Opportunities for further improvements**—Although the specific ignition source within the CWT of the TWA 800 airplane has not been identified, the investigation has identified opportunities to further enhance overall fuel tank system safety in general.
- **Additional enhancement based on flammability reduction**—An additional level of fuel system safety may be achieved by reducing the amount of time that flammable fuel vapors are present within fuel tanks.

Boeing has supplied an enormous quantity of engineering information to support the TWA 800 investigation. However, the unprecedented scope of the TWA 800 investigation has underscored the benefit of greater cooperation throughout the industry and improved processes for identifying and sharing pertinent information in a timely manner. Late in the TWA 800 investigation, for example, the Boeing team learned that the company had previously analyzed the effect of temperature on 747 fuel systems under a U.S. Air Force contract to assess fuel system pump performance under prolonged ground operations of the E-4B airplane—a military version of the 747. Because none of the Boeing Commercial Airplanes team members involved in the TWA 800 investigation was aware of that 1980 military study by the Boeing Military Aircraft and Missiles division, this information was not discovered or shared with the NTSB earlier in the investigation. Boeing accident-investigation processes have been revised in light of this oversight to include an online document search of technical libraries throughout the company. This process change identified additional documents that were supplied to the NTSB. Boeing has offered the NTSB direct online access to this information system.

The TWA 800 accident investigation also has shown that improved cooperation industrywide can contribute to the overall enhancement of safety. The industry Fuel Systems Safety Program, described above, has provided a forum for open exchange of fuel system safety issues between all manufacturers, operators, and government agencies. Another example is the Aviation Rulemaking Advisory Committee (ARAC) Fuel Tank Harmonization Working Group (FTHWG), which brought together a worldwide group of experts to complete a comprehensive study of fuel tank flammability reduction.

BOEING ACTIONS

In response to the information gathered during the investigation, and as a result of inspections of the in-service fleet and scrapped and retired airplanes, Boeing has taken the following actions in an effort to further enhance the safety of fuel systems:

Precluding Fuel System Ignition Sources

The fundamental design philosophy for fuel system safety is to diligently preclude the presence of ignition sources. This philosophy is sound and has served the industry well, providing safe air travel for millions of passengers every year. The industry must continue to maintain its vigilance to preclude the presence of ignition sources within the fuel system as it continues to enhance the safety of the in-service fleet.

The extensive and comprehensive investigation of TWA 800 has identified areas to further enhance fuel system safety. These lessons learned have resulted and continue to result in aircraft design and maintenance changes. See appendix B, *Investigative Evidence—Other Airplanes,* and appendix C, *Design Review, Tests, and Inspections,* for further details of analyses and inspections of the in-service fleet, including activities directly associated with the TWA Flight 800 investigation, Boeing support of FAA aging system programs launched by the Gore Commission, Boeing support of the worldwide aviation industry Fuel Systems Safety Program, and the application of lessons learned from 747 activities to other Boeing aircraft.

Actions Taken

Specifically, Boeing has taken a number of actions and participated in various industry activities as follows:

- Released 17 service bulletins calling for inspections and modifications of the 747 fleet. Another two service bulletins presently are scheduled for release.
- Released 31 service bulletins on other Boeing model airplanes. Another nine service bulletins presently are scheduled for release.
- Participated in FAA-sponsored ARAC FTHWG to study fuel tank flammability reduction.
- Evaluated fuel flammability and potential options for reducing flammability, including:
    - Pack bay ventilation.
    - Duct insulation.
    - Heat shield installation.
    - Metal air-conditioning pack bay doors.
    - Use of ground-based conditioned air.
    - Unusable fuel quantity reduction.
    - CWT fuel redistribution.

  - Cold wing fuel recirculation.
  - Ullage sweeping.
  - Nitrogen inerting.
  - Foam.
- Provided technical support and an airplane for FAA tests of ground inerting systems.
- Provided technical support and equipment for NTSB electromagnetic interference (EMI) ground tests.
- Working with airline customers to reduce flammability exposure by modifying operational procedures.
- Participated in the industrywide response to the FAA Notice of Proposed Rulemaking (NPRM) 99-18.
- Participated in the industrywide response to the FAA Request for Comment titled, "*Fuel Tank Ignition Prevention Measures*" dated April 3, 1997.
- Held airline maintenance and engineering conferences to exchange information on airplane inspection and modification activities.
- Conducted a sampling of in-service aircraft for all Boeing models to evaluate (1) the integrity of the fuel system wiring and grounding straps, (2) the condition of fuel system components, fuel lines, and fittings, and (3) the electrical bonding on all equipment after prolonged service.
- Performed audits of the manufacturing processes associated with the fuel system bonding and grounding for current production Boeing aircraft.
- Performed engineering drawing reviews and historical data reviews for aircraft fuel systems to validate that the design was acceptable and to verify from a historical perspective that all issues are being addressed.
- Developing improved maintenance practices.

See appendix D, *Airplane Changes;* appendix E, *Maintenance Changes;* and appendix F, *Operational Changes*, for further details of Boeing actions to preclude ignition sources in fuel systems.

FURTHER ENHANCEMENTS

The industry continues to actively pursue enhanced fuel tank system safety in the wake of the TWA 800 accident. This unprecedented level of effort being expended by the manufacturers, the airlines, the FAA and the NTSB, and other parties will result in further enhancements to airplane safety.

Aviation Rulemaking

The FAA recently released NPRM 99-18, which includes a Special Federal Aviation Regulation (SFAR) calling for analysis of the fuel systems of the turbine-powered commercial fleet and modifications to aircraft designs and maintenance programs. NPRM 99-18 also proposes revisions to the Federal Aviation Regulations (FAR) for ignition source protection and the addition of flammability requirements for new models. The industry has provided its comments to help make this pending regulation as practical and effective as possible.

Industrywide Efforts

As described above, the industry has been assessing the fuel system condition of the world's aircraft fleet. Boeing is a major participant in this cooperative industry effort, which includes reviewing fuel system designs and collecting maintenance information for the fleet of Boeing-manufactured aircraft. This data is being used to enhance maintenance programs to ensure that design features to prevent ignition sources are maintained.

In addition to the investigation efforts led by the NTSB, the Gore Commission launched the FAA's Aging Systems Program. Like the industry's Fuel Systems Safety Program, this FAA program will identify potential design and maintenance program changes.

Boeing endorses the intent of both the FAA's SFAR and aging systems activities. We will participate in achieving their objectives by making appropriate changes in our designs, providing service bulletins to our customers, and recommending changes to maintenance programs.

Reducing Flammability Exposure

To date, the commercial aviation industry's fundamental fuel tank system design philosophy has been to diligently preclude ignition sources. This philosophy makes the conservative assumption that the vapors in the fuel tanks are always flammable, whereas these vapors are in fact flammable only a fraction of the time.

Over the past 30 years, the aviation industry has explored several technologies to reduce flammability exposure, but practical solutions for commercial aviation have not been viable.

At the recommendation of the NTSB in the aftermath of the TWA Flight 800 tragedy, the industry and the FAA have launched a renewed effort to evaluate flammability reduction in commercial aviation. This focus will ensure that the commercial fleet benefits from updated operational practices and advances in technology. Although the military has developed complicated systems to reduce loss of combat aircraft from hostile munitions designed to penetrate fuel tanks, practical solutions have not been available in the past for commercial applications. Potential advancements in flammability reduction for commercial aircraft require significant analysis to ensure that changes in operational practices and the application of technology will not adversely affect the overall safety level of the commercial fleet.

To this end, Boeing was a major participant in the ARAC team that, in 1998, evaluated several alternatives to reduce the exposure of fuel systems to flammable vapors. Boeing also established an internal fuel system safety team to better understand fuel flammability issues and develop solutions. While some flammability reduction for the existing fleet may be achieved through the use of conditioned air from a ground source, the ARAC goal of reducing the exposure of the CWT flammable vapors to a level approaching that of the wing tanks has remained, at best, practical only for future designs. NPRM 99-18 addresses the reduction of fuel tank exposure to flammable vapors for new type design aircraft. Boeing will supply an aircraft and technical support for the FAA technology validation program for ground-based inerting systems. Boeing will continue to support FAA-led activities to reduce the exposure of CWTs to flammable vapors.

Over the past two years, the Boeing Military Aircraft and Missiles division has been working with aviation suppliers to refine military versions of inerting systems. Boeing Commercial Airplanes is working with their military counterparts to determine if a commercially viable application can be developed. The FAA also has been working with these suppliers and is preparing to enter into a technology validation program.

See appendix G, *Flammability Summary*, for details of Boeing efforts to understand flammability reduction and consider the application of technology and appendix F, *Operational Changes*, for operational practices to reduce exposure to fuel tank flammability.

BOEING ACTIONS TAKEN ON NTSB RECOMMENDATIONS

The NTSB issued several recommendations during the course of the TWA 800 investigation. Actions taken by Boeing on those recommendations are addressed throughout this submission. The following table shows where the comments on specific recommendations are located.

Recommendation	Subject	Page
A-96-174	Precluding Flammability—Long Term	G-6
A-96-175	Precluding Flammability—Short Term	G-7
A-96-176	747 Handbook Changes for Center Tanks	G-7
A-96-177	Temperature Gages for Heated Tanks	G-8
A-98-34	747-100, -200, -300 In-Tank FQIS Wire Inspection	D-3
A-98-35	Replacement of Series 3 747 FQIS Components	D-3
A-98-36	Survey In-Tank FQIS Wires in Other Airplanes	D-9
A-98-37	Copper-Sulfide Research	C-9
A-98-38	Wire Separation	D-6
A-98-39	FQIS Tank Surge Protection Systems	D-6

SUMMARY

Since the TWA Flight 800 tragedy, significant effort has been made to understand this accident and to implement changes to further enhance the safety of the in-service fleet. While the investigation has been unable to determine the ignition source that led to the explosion of the CWT in TWA Flight 800, significant effort has been made to further preclude aircraft-generated ignition sources and to reduce the exposure of the CWT to flammable vapors.

The fundamental philosophy of precluding aircraft-generated ignition sources has been validated as the primary means of ensuring the safety of the in-service fleet. Significant action has been taken to understand the effects of aging on aircraft systems, both inside and outside the fuel tank. Changes are being implemented to new aircraft designs, in-service aircraft, and airline maintenance practices to ensure that this fundamental design philosophy is consistently achieved. Additional activity is underway to identify aging-aircraft systems issues that potentially affect the safety of the in-service fleet. Boeing is supporting these programs and is taking appropriate action as issues surface that might further enhance the safety of the in-service fleet.

The reduction of CWT exposure to flammable vapors is an industrywide effort. The FAA has taken the lead in developing industrywide solutions, and Boeing will continue to support the FAA in this endeavor.

Toward this end, Boeing is committed to enhancing aviation safety and welcomes the opportunity to continue working with the NTSB, the FAA, and the industry.

APPENDIX A: INVESTIGATIVE EVIDENCE—TWA 800 AIRPLANE

The investigation of the TWA Flight 800 accident involved detailed examination and study of all of the recovered wreckage and data provided by other sources such as the flight data recorder, cockpit voice recorder (CVR), air traffic control, maintenance records, and so forth. All airplane systems, structures, and engines were examined in great detail for evidence that could lead investigators to the cause of the accident or to something that may have contributed in some way to the accident. All of the evidence is documented in great detail in various factual reports.

This document addresses only those primary areas of wreckage, data, testing, and analysis on which the NTSB focused its efforts to determine whether an aircraft component or system may have been the initiating event for the accident. No attempt is made to address other areas or systems.

STRUCTURAL FINDINGS, SIMULATIONS, AND MODELING

Boeing engineering representatives began participating in the TWA 800 accident investigation soon after the investigation began. Initially, Boeing representatives provided the NTSB with technical assistance to help map the debris field and identify wreckage. The investigation soon determined that a fuel tank explosion and fuselage failure occurred early in the sequence of events. Preliminary evaluation was unable to establish a relationship between a fuel tank explosion and fuselage failure. However, the continuing NTSB-led investigation and computer modeling at Boeing later confirmed that an overpressure-induced failure of the center wing fuel tank would be capable of initiating a structural failure sequence that could culminate in separation of the forward fuselage.

Structural Breakup—Preliminary Evaluation

Early in the TWA 800 accident investigation, Boeing engineering representatives assisted the NTSB by applying detailed knowledge of the 747 airframe to the complex exercise of mapping the debris field and identifying pieces of wreckage. This effort, and the subsequent recovery of pieces of wreckage from the “red zone,” revealed within weeks of the accident that a fuel/air explosion in the nearly empty center wing tank (CWT) and a failure of the fuselage forward of the wing front spar bulkhead occurred relatively early in the sequence of events.

As a result of the early observations, a preliminary evaluation of a CWT overpressure event was conducted by Boeing in an attempt to determine if there was a rational basis for predicting whether the apparent type of fuselage failure could be linked to an overpressure event. As a part of the preliminary evaluation, the only other well-documented incident of a CWT fuel/air explosion in a Boeing commercial airplane, a 737-300 in Manila in 1990, was studied for comparison purposes.

The preliminary evaluation did not establish a rational linkage between a CWT overpressure event and a concurrent or subsequent failure of the forward fuselage. Consequently, Boeing launched a much more rigorous and exhaustive effort to model a CWT fuel/air explosion. The goals of this analysis were to identify a link between the overpressure of the CWT and the subsequent failure of the forward fuselage and to determine a likely ignition location within the CWT. That effort was initiated in August 1996 and continued through the remainder of the year.

Structural Breakup—Final Conclusions

By December 1996, with the wreckage recovery effort approximately 90 percent complete, the NTSB chartered the Metallurgy and Structures Sequencing Group to "address the wing center section breakup sequence and any potential interaction or relationship with the fuselage 'red area' breakup sequence." Boeing contributed three members to the group and provided essential expert knowledge of the 747-100 structural characteristics, loads, stress, and metallurgical considerations.

The group reached its initial conclusions in February 1997 and documented a sequence of events that initiated with an overpressure-induced failure of the CWT end rib (spanwise beam 3), progressed to failure of the front spar bulkhead, and then propagated to failure of the fuselage forward of the front spar bulkhead. The failure propagation sequence in the red area (pieces recovered from the red zone) was mapped to the point where complete separation of the forward fuselage would have occurred. The Boeing Structures representatives agree that while there may be unexplained aspects with regard to certain observations, "the facts and data on the whole support the sequence documented" in the Sequence Group Report. The group also determined that none of the structural fatigue cracks documented as part of the investigation were contributory to the breakup sequence of the airplane.

While the Sequence Group activity was underway at the reconstruction site in Calverton, New York, the effort in Seattle to model a CWT fuel/air explosion was winding down. Two primary considerations led to the decision to terminate the activity in February 1997. First, it was determined that the problem was essentially unworkable with the state-of-the-art methodology and computing capability available at Boeing. More importantly, the activity of the Sequence Group already had succeeded in establishing the relationship between a CWT overpressure event and subsequent fuselage failure.

Boeing continued to use the structural models that had been developed to validate incremental stages of the failure sequence documented by the Metallurgy and Structures Sequencing Group. In every case in which Boeing was able to perform such a validation analysis, the results confirmed the group's findings.

Additional Support

Throughout the remainder of 1996 and intermittently for approximately the next two years, Boeing continued to provide support as requested for the NTSB-sponsored activity to have selected third-party organizations model a CWT fuel/air explosion in a 747-100.

Structural Examination—Criminal Investigation

In addition to supporting the NTSB, Boeing also provided support to the FBI investigation to determine whether a bomb or missile may have caused the accident. Boeing specialists examined the airplane structure and engines for evidence of bomb damage or missile impact. With regards to the physical evidence, Boeing's examination of the recovered wreckage did not reveal any evidence of bomb damage on the structure or damage that could be expected from a missile impact.

In addition, Boeing was represented on the NTSB Witness Group that was formed to review and study the eyewitness reports. With regards to the eyewitnesses, Boeing is in agreement with the information documented in the Witness Group Chairman's Factual Report and the information and conclusions reached and presented in the Witness Group Study Report.

SYSTEMS FINDINGS

Electrical Components

No evidence was found to support a conclusion that a specific electrical system or component of the 747-100 fuel quantity indicating system (FQIS) ignited a fuel/air explosion and initiated an event sequence such as the one suspected in the TWA 800 accident. The 747-100 FQIS is designed specifically to preclude fuel tank vapor ignition. The FQIS is designed to tolerate environmental factors that could contribute to conditions that might cause electrical shorting or grounding. Exhaustive lab testing for potential ignition sources were essentially negative. Rigorous initial qualification testing by Boeing and its suppliers demonstrated regulatory compliance. Boeing has thoroughly tested the FQIS system as part of the NTSB accident investigation without detecting electrical event conditions that would cause an explosion aboard TWA 800.

Recovered FQIS Components

Indicators. There were seven fuel quantity indicators mounted on the flight engineer panel of TWA 800:

- Center wing tank.
- No. 1 reserve tank.
- No. 4 reserve tank.
- No. 1 main tank.
- No. 2 main tank.
- No. 3 main tank.
- No. 4 main tank.

Each indicator displays the quantity of the fuel in its fuel tank using both an analog (pointer) and a rotating counter. The indicators also supply a quantity signal to the volumetric shutoff (VSO) unit, the fuel quantity totalizer, and the Airborne Integrated Data System.

There is also a fuel quantity totalizer mounted on the flight engineer panel. The indicator monitors a quantity signal from each fuel tank quantity indicator, sums all the tank quantities, and indicates the total fuel quantity as well as the gross weight of the airplane.

There was no evidence of electrical stress on any components in the recovered indicators. The CWT indicator was disassembled and the components were inspected and analyzed. All component damage was attributed to either high impact or saltwater contamination. None of the parts failed due to an electrical stress. In fact, some parts were fully operational once the salt contamination was removed.

Under the direction of the NTSB, the recovered FQIS indicator for the CWT was taken to the manufacturing facility in Coon Rapids, Minnesota, and analyzed for the type of damage that made it inoperable. It was found that only a few components were damaged or missing. As a check of the indicator's health, the electronic portion of the indicator was made operational by adding three components that were missing and by removing and replacing five others that were damaged. The five components that were damaged were sent to an independent lab for analysis. It was found that all five of these components had failed either because of saltwater exposure or because of impact. One of the transistors was brought back to its operational specifications by removing salt that had built up under its casing.

From inspections and tests of the flight deck fuel quantity indicators conducted by the NTSB as part of the accident investigation, there was no evidence of a failure or damage found that would contribute to, or be evidence of, excessive energy being introduced into the center fuel tank of the accident airplane.

Probes. The tank unit (probe) is a capacitance-sensing element mounted in the fuel tank. The tank unit consists of two concentric tubes (electrodes), two mounting brackets attached to the outer electrode, and a terminal block consisting of three terminals and a strain-relief clamp stud. The mounting brackets have two mounting holes to bolt the unit to the airplane structure. The two electrodes form the plates of a capacitor with the inner electrode made of nickel and the outer electrode made of anodized aluminum. The inner electrode is coated with a polyurethane varnish to shed water. The inner and outer electrodes are spaced and insulated from each other at intervals throughout their length by Teflon spacers. The number of tank units in each fuel tank depends on the tank size and shape. The tank units are used to determine the depth of the fuel in the fuel tank. Their capacitance varies with respect to the amount of fuel covering each tank unit, thereby providing a comparative value to determine the amount of fuel in the tank.

The compensator is used in both the FQIS and also with a fuel system VSO unit. It is used to determine the dielectric constant of the fuel, which is used to "compensate" for the varying density of the fuel due to varying fuel loads and temperatures. The compensator consists of four concentric anodized aluminum tubes (electrodes) mounted on one end of a tube. Teflon spacers separate the electrodes. The opposite end of the tube contains mounting brackets and wiring terminals to connect the compensator to the airplane wiring. The compensator is mounted in the tank at the lowest usable fuel level and is normally covered with fuel.

There was no evidence of arcing on any of the pieces and fragments of fuel probes, compensators, and in-tank FQIS wiring recovered from the accident airplane. There was evidence of soot from the burning fuel on various fragments, and there was damage related to the breakup of the airplane. The complete details of the findings from the examination of these parts are contained in the NTSB Factual Report.

Cable Assemblies. Wiring in accordance with Specification Control Drawing 10-60875 is used between the flight engineer's panel and the fuel quantity probes. These are environmental-resistant cables suitable for immersion in fuel. They are constructed of wire conforming to MIL-W-16878, type EE, 200C, with silver-plated copper conductor wire insulated with 0.015 inch of TFE Teflon (polytetrafluroethylene).

An NTSB System Subgroup meeting was held at Wright Patterson AFB on August 21, 1997, to review the results of an engineering analysis of fuel probes wiring. Anomalies such as holes in the insulation due to abrasion, residue deposits, and insulation cold flow were noted. Specifically, wire insulation damage was noted for fuel probes configured with a steel wire bundle strain relief clamp combined with a knurled antislip probe surface to help hold the wire bundle in place. Insulation damage was observed as exposed Hi-Z shield strands, exposed shield termination conductors, and deformed Lo-Z insulation due to pressure. Copper, sulfur, and silver were present in fuel residue deposits on fuel probe terminal block components and wire where the metal conductors were exposed.

Some of the insulation damage and wear were not readily visible until the wire was moved and viewed at approximately 35X magnification.

A similar meeting was held in the NASA Laboratories to review the CWT FQIS wire. The wiring was in accordance with the specification described above with an overall lacquered-nylon jacket. The following summarizes the findings and observations on the CWT FQIS wire bundle:

- No deformation or flattening of the Lo-Z wire was observed.
- Some kind of deformation was found on the Hi-Z wire (cold flow).
- There were signs of damage at STA 388. Further investigation revealed damage to the Hi-Z wire caused by the accident impact.
- There was no sign of electrical arcing.
- There were signs of corrosion on the FQIS wire. It was determined that the corrosion was caused by damaged wire insulation under the cable jacket. However, it was concluded the damage to the insulation was caused by impact-type fracture.

General-Purpose Wire

The wire was identified as BMS 13-42A, Alkane-Imide (known as Poly-X) type insulation.

The wiring from the scavenge pump relay associated with the flight engineer panel on TWA 800 was found to have deeply hot-stamped wire markings and a crack propagating from a numeral "1." It was found that the crack penetrated the inner layer of the insulation to the core conductor. No evidence of electrical arcing was observed.

Other observations on the general-purpose wire were as follows:

- Most of the cracks were on wire bundle W480 and within 5 feet of the aft end of the bundle (STA 570-900).
- Significant variation was observed on the depth of the different letters within the same marking.
- Insulation of the wires marked as W42A/8/1-(varied) was found cracked. In one case, there were six cracks in a 1-foot section (at about STA 320).

No. 4 Fuel Flow Indicator

The transcript of the cockpit voice recordings produced in the NTSB Factual Report (Docket No. SA-516, Exhibit 12-A) contains the statement by the captain of TWA 800, "Look at that crazy fuel flow indicator there on number four."

As part of the investigation, the NTSB examined the components of the fuel flow indication systems for engine No. 4, reviewed the maintenance records of the airplane for maintenance activity that occurred on this system, analyzed the wire routing in the airplane, and examined the airplane wreckage for the fuel flow wiring for engine No. 4.

The fuel flow system is an independent and separate system from the fuel quantity system and provides a redundant backup for the fuel quantity information. The fuel flow system and the fuel quantity system do not share any wiring or equipment. Whereas the fuel quantity system has sensors in the tank that directly measure the amount of fuel, the fuel flow system has a fuel flow transmitter mounted in the fuel line to each engine. The signal from each engine is provided to the fuel flow module in the electronics bay. The fuel flow module processes the signal from each transmitter and sends it to the flight deck.

There are three indications in the cockpit that display fuel flow for each engine. The pilot's center instrument panel contains an integrated display that shows the fuel flow rate for all four engines. The fuel flow signals that drive the center instrument panel display are also sent to four separate fuel flow indicators on the flight engineer's instrument panel. There are also separate signals provided for each engine to four indicators on the flight engineer's instrument panel that show the fuel used by each engine, as calculated from the flow rate.

In reviewing the NTSB's Maintenance Group Report, Docket No. SA-516, Exhibit 11-A, there are approximately nine maintenance actions related to the fuel flow system on the accident airplane that occurred between July 1, 1994, and July 17, 1996. Five of these were related to engine No. 1 fuel flow, one was related to engine No. 2 fuel flow, and three were related to engine No. 4 fuel flow. Various maintenance actions are identified, including replacement of the flight deck indicators, cleaning of connectors, and replacement of the actual fuel transmitter, the sensor located in the fuel line that measures the flow rate.

The NTSB's report on the condition of the fuel flow equipment recovered and analyzed from the accident airplane states that there was no physical evidence of an internal failure of the engine No. 4 fuel flow indicator or the fuel flow electronics module.

The NTSB also focused on determining where the wiring of the engine No. 4 fuel flow system and the fuel quantity system wiring were routed together or in close proximity to each other. The examination of the airplane drawings showed that there were three locations where this wiring was routed together.

The wire bundles from the accident airplane were examined to ascertain if any damage had occurred in these areas that may have accounted for the fuel flow indications just prior to the center tank explosion. Of the wiring that was found, there was no indication that any damage occurred that might account for the erratic fuel flow indication. There was no evidence of arc or heat damage other than that caused by the accident itself.

CVR Dropouts

As part of the accident investigation, the NTSB examined the CVR to document any unusual or abnormal occurrences. Besides the signature of a very loud sound, which terminates the end of the recordings, two events were found only on the captain's CVR channel. At time 0.73 seconds before the end of the recording and again at 0.68 seconds before the end, the NTSB notes that the normal 400-Hz background noise signal with its associated harmonics changed. The NTSB stated that this change consisted primarily of a lack of the upper harmonics of the 400-Hz frequency. At these two different areas on the recording, the signal contains only the 400-Hz component, without any added harmonics. The NTSB examined the last 15 minutes of the recording in an attempt to document any additional or similar occurrences and none could be found.

Examination of the captain's CVR channel trace printout contained in the NTSB Factual Report (Docket No. SA-516, Exhibit 12-B) shows that the entire signal, the 400-Hz component and all of its harmonics, was reduced significantly, not just the harmonics. The 400 Hz component in figure A in the report is approximately at the 100,000,000 level (the Y-axis is not labeled for these figures). In figure B, the 400 Hz is at level 1,800,000, or 1.8% of the figure A level. The higher order harmonics have also been reduced significantly in figure B. This shows that the entire signal had been reduced and not just the upper harmonics.

It should also be noted that the signal that is picked up by the CVR could be influenced by any changes in the signal in the adjacent wires that run from the cockpit to the CVR. It is Boeing's assessment that there could be three reasons for the change in signal measured by the CVR (Chart 2 of the NTSB report):

1. The most likely causes in this instance may be a local flaw in the recording media. This flaw may be visible or reproducible. Another possibility may be head-to-tape contact (dust

particle) either during recording or during playback. This contact is more likely to occur on an outside track and may affect high frequencies more than low frequencies.

2. Another less likely possibility is that a major load change in the airplane power system (e.g., large numbers of equipment or systems being switched on or off) occurred that influenced the measured signal. There was no indication from information collected from the investigation that such switching was initiated or occurred in the accident airplane.

   In testing that the NTSB performed in Roswell, New Mexico, to try to replicate the signal changes noted on the captain's CVR from TWA 800, the harmonic spectrum that was measured in figures A, B, and C of the NTSB report, Chart 2, could not be duplicated on the test airplane. The airplane that was tested at Roswell had a very different configuration of loads and equipment compared with the TWA 800 airplane, which resulted in a different harmonic signature.

3. Lastly, an electrical fault might have occurred that caused the CVR signal to be dropped at Point B of Chart 2. Once the fault was cleared, the signal was restored at Point C. The spectrum at Point C is different from Point A, which indicates that once the system was restored, the system configuration had changed. This scenario seems unlikely because the other channels did not show a change in the 400-Hz magnitude and the harmonics. The charts contained in the NTSB Factual Report do not show any changes in the other channels' noise signal (Chart 3). If an electrical fault of this magnitude had indeed happened, it should have shown on all channels, unless the other channels' noise signal magnitudes were significantly lower than the captain's channel. This is difficult to discern from the NTSB Factual Report because it does not show any spectrum of the other three channels and the signal strength compared to captain's audio channel.

Mechanical Components

Boeing engineers participated in the identification of recovered parts and in the detailed tear-down inspection and analysis of components. Fuel system components within the center wing section were examined for evidence of a possible ignition source. The following paragraphs provide a summary, by part, of the investigation findings contained in the Systems Factual Report, Docket No. SA-516, Exhibit 9-A.

Scavenge Pump

The scavenge pump was not recovered from the TWA 800 wreckage. However, various parts of the scavenge system were recovered. Normal procedure for the fuel load at dispatch would be for the scavenge pump to be off. Review of TWA flight crew training procedures, the CVR transcript, conclusions reached from electrical failure analyses, and laboratory analyses of recovered equipment (Systems Factual Report, Docket No. SA-516, Exhibit 9-A) indicate that the system was in normal operating condition, switched off, and not powered through the potential failure scenarios investigated. Although the scavenge pump switch position in the air at the time of the accident could not be conclusively determined, evidence indicates that the pump was not powered at the time of the accident.

The scavenge pump switch and control relay were recovered and analyzed. The switch was found in the OFF position. The position of the switch in flight could not be confirmed, but there was no evidence of forced movement to the OFF position. The switch and control relay showed no signs of electrical stress or failure.

The piece of the scavenge pump inlet line that was recovered did not indicate sooting or flow patterns on the internal surface. The scavenge pump circuit breakers were recovered and analyzed. There was no evidence of electrical stress or abnormal conditions noted.

Override/Jettison Pumps

Both override/jettison pumps were recovered from the CWT and were examined at NASA Laboratories in Huntsville, Alabama. There was no evidence of arcing or any other pre-accident anomalies found in the motor sections of either pump. Nothing unusual was noted on either pump. Evidence of some impeller contact with the housing was identified, but it was determined to be insignificant. Previous testing has shown that this type of contact will not ignite fuel vapors.

Normal fuel management procedures for the dispatch fuel load with an empty CWT would be for the override/jettison pumps to have been turned off. The tank was empty except for the residual fuel that cannot be scavenged out of the tank. The flight deck switches were examined, and found in the OFF position. It could not be confirmed that they were in the OFF position at the time of the accident, but there was no evidence to indicate that there was forced movement of the switches to the OFF position.

Other Fuel Pumps

Portions of all other fuel pumps were recovered, and there was no evidence of an overheated motor or indication of internal fire in any of them. Pumps inspected in detail were the No. 2 main aft boost pump, the No. 2 main forward boost pump, the No. 4 main forward boost pump, the No. 4 main aft boost pump, the No. 2 main outboard jettison pump, and the No. 3 main inboard jettison pump. Recovered fuel pump wiring conduits to the No. 1 and the No. 4 main tanks were inspected and found to have the Teflon sleeving intact with only minor surface chafing on the outer layer. There was no evidence of arcing or burning found in the recovered parts.

Surge Tank Protection System

The surge tank protection system has canisters that discharge Freon into the surge tank to prevent an external ignition source from entering the tanks. All of the canisters were recovered and found full (not discharged). The optical sensor from the right wing was recovered and found to have a light coating on the window. This finding is not unusual because the tanks are constantly breathing past this sensor.

Tubing

Various degrees of crushing, internal and external soot, heat damage, bursting, and collapsing were found on the recovered tubing taken from different areas of the tanks. Damage to the tubing was typically representative of the damage in the same area of the tank. For example, heavy sooting on the tubes could be tied to a fire in the tank where there was also heavy sooting on the tank structure. There was no evidence of arcing damage on any of the recovered pieces.

Volumetric Shutoff Unit Tests

Under the direction of the NTSB, the VSO unit from the accident airplane was taken to the manufacturing facility in Coon Rapids, Minnesota, for analysis. The following is a portion of the summary of the NTSB field notes titled, "Volumetric Shutoff Box Systems Sub-Group," dated September 18, 1997.

> The Volumetric Shutoff (VSO) avionics unit was recovered and examined by a safety board Sub-Group for evidence of an electrical event that may have affected the VSO from fuel quantity indication system (FQIS) wires, or evidence of a power input to FQIS wires from the VSO. No evidence of arcing was found in the unit. The circuit cards for the CWT shutoff (card A9) and fuel density computation (card A2) were found physically damaged. The A2 card had enough damage to prevent operational checks. The A9 card had 5 parts replaced and broken tracks bridged. The A9 card functioned within tolerance at room temperature. No short circuits were found in the primary or secondary circuits of the power supply card (card A4) that has transformers which supply power to the ground fueling panel (P42). The shutoff cards for the CWT and tank 3 had broken components replaced were found to operate when placed in a serviceable unit.

SUMMARY

None of the recovered fuel system components inspected and analyzed showed any evidence of being the ignition source that initiated the accident. The two CWT override/jettison pumps would have been turned off, and when they were inspected, they did not show any signs of arcing or other anomalies that could be suspected of being the ignition source.

The CWT scavenge pump that was not recovered would have been turned off. The switch did not indicate that it was turned on, and there was no evidence of electrical stress or failure of the switch, control relay, or circuit breakers. Review of TWA flight crew training procedures, the CVR transcript, conclusions reached from electrical failure analyses, and laboratory analyses of recovered equipment indicates that the system was in normal operating condition, switched off, and not powered through the potential failure scenarios investigated.

Similarly, there was no evidence of electrical stress or arcing found on any of the FQIS indicators, probes, or wiring.

APPENDIX B: INVESTIGATIVE EVIDENCE—OTHER AIRPLANES

INSPECTIONS OF IN-SERVICE, RETIRED, AND SCRAPPED AIRPLANES

Airplane Inspections

As part of the NTSB investigation, from May 19, 1997, through July 29, 1998, Boeing participated in inspections of 18 transport airplanes built by three manufacturers. Boeing also reviewed reports and NTSB safety recommendations encompassing 71 airplanes from various manufacturers. Fifteen of the 18 airplanes inspected by the NTSB were built by Boeing Commercial Airplanes Group, including thirteen 747s and two 737s.

The inspections consisted primarily of visual inspections with a limited amount of electrical and physical tests conducted on the airplanes. Laboratory tests were conducted on some parts removed from a few of the inspected airplanes.

The condition of the airplanes in open storage or scrap holding was generally poor. Most had the doors and windows closed and other openings sealed and covered with foil. A couple of the airplanes were derelict with doors and windows open and with holes in the fuselage. In these airplanes, the group tried to limit wire inspections to areas that were enclosed and covered. Electronic boxes and modules and other parts were missing from most of the airplanes. Center tank entry was made in only two of the airplanes, and these tanks had been open prior to the inspection. Fuel quantity probes from only one airplane were observed in these inspections. The probes from the other center tank inspected had been removed, along with about 2 to 3 inches of wire that had been attached to the probes prior to the inspection.

The visual inspections of the out-of-service airplanes found physical (mechanical) damage to wire insulation. Metal shavings were found both on and between wires in bundles, as well as next to the cooling holes on the tops of avionics boxes. The inspections found accumulations of foreign materials on wires that included lint (fiber particles and dust), hardware, structural corrosion preventive compound, grease, blue and brown fluid stains, and paper. Wire bundles were found adhered into solid masses with added wires strapped to existing bundles. Crumbled rubber cushions were found in clamps, cracked O-rings were found, and cracks were found in the insulation of wires in five airplanes. The inspections found wire installations (workmanship) that did not comply with standards contained in the Boeing Standard Wiring Practices Manual (SWPM D6-5446).

Findings in these out-of-service airplanes were relatively common to all the types of airplanes inspected and were not unique to a particular manufacturer or operator. Many of the conditions noted could be attributable to the derelict state of the airplanes inspected. Some of the information obtained from these inspections may be useful in enhancing existing maintenance practices, but more useful and pertinent information is being collected by the FAA's Aging Systems Program described below.

The findings in the newer airplanes inspected showed a few cases of one or two isolated shavings and minor accumulations of dust or lint in some areas.

In relation to the accident investigation, it is difficult to directly relate any of the findings from the inspections of these airplanes to any condition that may have contributed to the ignition of the center fuel tank on the accident airplane.

AGING SYSTEMS INSPECTIONS

The Aging Systems Task Force (ASTF) was formed in 1998 by the Air Transport Association to accomplish the following:

- Define and document airline best practices with regard to aging systems.
- Prepare and implement a specialized sample inspection, by aircraft type, of aircraft systems wiring that is more than 20 years old.
- Collect and analyze the inspection findings.
- Evaluate the data and devise an action plan as indicated by those findings.
- Initiate longer term program revisions to better prepare for potential problems with aging wiring.

The release of the "FAA Aging Transport Non-Structural Systems Plan" in October 1998 and the formation of the Aging Transport Systems Rulemaking Advisory Committee (ATSRAC) in January 1999 resulted in the ASTF being requested by the ATSRAC to undertake these additional tasks:

- Establish the criteria for selection of service data, and then review service data and service experience.
- Review existing regulatory actions with repetitive inspections to determine if terminating action is appropriate.

Nonintrusive Inspections

Each ASTF model working group was tasked with establishing, conducting, and summarizing results of a nonintrusive inspection of the wiring of a representative sample of one affected airplane model. The intent of the survey of a portion of the fleet using nonintrusive methods was to assess the overall condition of the fleet with regard to wiring and to identify any airplane model-unique areas of concern. Each model working group was to determine, zone-by-zone or by another logical sequence, an exhaustive list of potential or unforeseen problem areas, by paying particular attention to:

a. Wiring, connectors, grounds, circuit breakers, conduits, terminations, and so forth and associated hardware in the following areas:
    - Flight-critical areas.
    - Areas normally hidden from view.

- Areas in close proximity to flammable liquids and gases (e.g., fuel vapors, oxygen).
- High electric current draw areas.

b. Aging caused by:

- High vibration.
- Harsh environments.
- Corrosion.
- High maintenance traffic.

Sample Fleet

The ASTF working groups conducted nonintrusive inspections of 81 airplanes representing 8 affected models as a representative sampling of an active domestic fleet of 3,073 airplanes. The following table summarizes the sampling size for each affected model.

Model	Sampling	Fleet %
B-727	9 of 660 active domestic* airplanes 26,744 to 72,661 hours, 20,502 to 59,749 cycles	1.4
B-737	9 of 1,125 active domestic* airplanes 50,500 to 68,300 hours, 25,400 to 72,700 cycles	0.8
B-747	7 of 203 active domestic* airplanes 57,784 to 81,965 hours, 8,633 to 19,363 cycles	3.4
DC-8	14 of 133 active domestic* airplanes 70,200 to 71,800 hours, 23,900 to 46,900 cycles	10.5
DC-9	15 of 450 active domestic* airplanes 31,600 to 87,000 hours, 36,133 to 91,800 cycles	3.3
DC-10	14 of 212 active domestic* airplanes 32,700 to 82,400 hours, 9,600 to 30,400 cycles	6.6
L-1011	3 of 48 active domestic* airplanes 59,231 to 72,699 hours, 14,567 to 27,874 cycles	6.3
A300	10 of 242 total worldwide airplanes inspected 21,000 to 42,700 hours, 15,900 to 31,000 cycles	4.1

Summary of Sampling Size for Each Affected Model
*(*Domestic fleet data provided by the Air Transport Association)*

Nonintrusive Survey Results and Conclusions

No wiring safety-of-flight concerns were identified that would require immediate action on any of the inspected airplanes.

The majority of observed wiring installation discrepancies were found to be in areas of frequent maintenance activity, or related to housekeeping. Fluid contamination and dust and dirt accumulations were seen on most airplanes. Overall, wiring installations on all aircraft were found in good condition, showing little or no evidence of deterioration, particularly those installations undisturbed since manufacture. The working groups did not note any direct correlation between the condition of the wire and the actual time in service.

Hardware. After reviewing more than 3,000 individual discrepancies found during the survey, each working group independently concluded that none of the discrepancies appeared to be wire-type dependent. Degradation such as insulation breakdown and cracking was found on existing and original wire types. It is the consensus of the working groups that most or all of the deterioration was because the wiring had not been protected from environmental conditions, accidental damage, or both. Neither time in service nor the systems that they supported seemed to have any appreciable bearing on the condition of the wiring. Wiring installations in areas and zones that are subject to a high level of maintenance activity show more evidence of being disturbed than those in areas not regularly frequented by maintenance personnel. Items such as improper clamp sizing, inadequate clearance to structure, and accumulation of dust or debris were common.

Maintenance. Existing maintenance programs may benefit from providing additional wiring inspection detail. Existing inspection training programs and current criteria should be enhanced to improve detection of wiring installation degradation, especially in unprotected areas. These programs should also be enhanced in the area of wiring maintenance practices, such as protection of wiring from debris or fluid and chemical contamination. There appears to be some lack of understanding and appreciation for the impact of wiring installation techniques on the durability of that installation and on the reliability of related systems.

SUMMARY

In general, the condition of wiring found on airplanes at or exceeding 20 years of age is satisfactory. Noted items that were not deemed to be flight-safety issues, but required further analysis, were provided to the airframe manufacturers for evaluation. Typical items undergoing closer scrutiny included dust and lint buildup, inadequate clearance to structure, indications of cracked wire insulation, and improper clamp condition, spacing, and size. All the significant items noted during the nonintrusive wiring inspections were corrected on the airplane prior to reentry into revenue service. Results will be provided to the ATSRAC during its July 18–19, 2000, meeting on the evaluations of what the impact of each of the significant items would have been if left unchecked on an airplane.

APPENDIX C: DESIGN REVIEW, TESTS, AND INSPECTIONS

In an unprecedented effort that has spanned the time since the accident, Boeing has studied the design characteristics of the 747 Classic fuel system in an attempt to uncover any issues that could result in an ignition source in the fuel tanks. Boeing conducted tests to evaluate the various proposed methods by which the inherent safety features might have been compromised and conducted inspections to collect data on the in-service fleet to determine if there were any significant issues that would affect fleet safety. The industry Fuel Systems Safety Program, the latest significant element of this effort, will conclude with the release in mid-2000 of summary reports of inspection findings from the affected manufacturers and airlines.

The Boeing conclusion from the reviews, tests, and inspections is that there is no obvious malfunction or defect that can be identified as an ignition source for the TWA 800 accident. Shifting from the obvious to the more implausible explanations, Boeing again finds that, even when using ignition scenarios involving a series of unlikely events and conditions, testing performed to replicate the conditions does not reveal a plausible explanation for the existence of an ignition source.

DESIGN FEATURES AND STANDARDS

The following paragraphs summarize the significant safety features of the fuel quantity indicating system (FQIS) and the center tank scavenge pump that were installed on TWA 800. The review of these features was done to provide a baseline for evaluating parts from the accident airplane to see if any of these features had been compromised. To date, no such evidence has been found.

FQIS Safety Features

The FQIS installed in the flight engineer's panel on the TWA 800 airplane, like those on every 747 Classic airplane and all other commercial transports, is designed to preclude the possibility of an internal ignition source both during normal operation and with any failure that might be expected to occur during the life of the fleet.

Examples of some of the FQIS design features that safeguard against in-tank ignition sources are described in the following paragraphs.

FQIS Indicators

The FQIS indicators on the 747 Classic airplane house the electronics that determine the amount of fuel in the tanks. The FQIS indicators supply very low power to the fuel probes and compensators inside the tanks. The energy level is limited to 10 times less than the industry-standard minimum energy required to ignite a fuel/air mixture.

These restrictions are accomplished through careful layout of electronic components and wiring in the indicator as well as by redundant devices to limit the electrical current in the indicator outputs to the fuel tanks. If a wire short were to occur inside a fuel tank, an arc of sufficient energy to ignite fuel vapors would not be expected to occur because the energy to the wire and components in the tank is limited at the source (i.e., the FQIS indicator). An electrical short would be indicated by erroneous system performance, which would be identified and corrected.

FQIS indicator design characteristics that ensure the integrity of the unit for the life of the airplane include:

- **Insulation resistance between parts.** The insulation resistance between all mutually insulated parts must be greater than 20 MΩ at 500 V dc, except for the insulation resistance between the lighting circuit and case, which must be greater than 100 MΩ at 500 V dc.
- **Low-current leakage.** The dielectric withstanding voltage of the unit is 500 V ac rms at either 60 Hz or 400 Hz (60/400 Hz) with less than 0.5 mA of leakage current.
- **Hermetic sealing.** The indicators are hermetically sealed to prevent moisture and contaminants from damaging the electronics.

FQIS Wiring—Outside the Tank

The FQIS wire from the connector on the rear of the FQIS indicator in the flight engineer's panel to the flight engineer's panel disconnect is general-purpose wire. This segment is approximately 4 feet in length. The length of wire from the indicator disconnect to the first bundle clamp is sleeved with Raychem RT876, BMS 13-52 Type 1B or Type V, a polyester (tight-weave) sleeve to protect against chafing. This portion of wiring is in a stable low-vibration area.

The FQIS wire bundle that runs from the flight engineer's panel disconnect to the wing tank spar disconnects is specified as MIL-W-16878C. MIL-W-16878C is rated as a high-temperature wire that can operate continuously at 200°C and 1,000 V ac rms. The inner conductor is silver-plated copper wire. This wire bundle is protected against wire-to-wire abrasion with a varnish-impregnated nylon sleeve. The insulation resistance is specified at greater than 2,000 MΩ at 500 V dc with a dielectric withstanding voltage specified at less than 2.0 mA of leakage per connector plus 2.0 mA of leakage per 100 inches of cable at 1,500 V rms at 60/400 Hz. The wiring from the flight engineer's panel to the wing-to-body disconnect panels and the rear spar is covered with a varnish-impregnated nylon jacket for additional abrasion protection. Starting with airplane line number (LN) 244, the FQIS wiring incorporates an electromagnetic interference (EMI) shield on the bundle from the flight engineer's disconnect to the spar disconnects, while the FQIS wiring starting with airplane LN 455 incorporates an EMI shield on the bundle in the flight engineer's panel. This shielding was added to reduce EMI-induced fuel quantity signal fluctuations.

Wiring from the flight engineer's disconnect down to the volumetric shutoff (VSO) unit in the electrical and electronics bay, and from the VSO unit to the spar-mounted connectors, is general-purpose wire.

All FQIS wiring along the wing leading edge incorporates an overall lightning shield to provide lightning protection.

FQIS Wiring—Inside the Tank

Wiring within the tank is the same MIL-W-16878C wire used external to the fuel tank. FQIS wiring in the tanks is affixed to the structure by clamps that prevent the wiring from contacting structure. This configuration reduces the likelihood of abrasion of the wire insulation. Penetration points through the structure are lined with plastic grommets to prevent abrasion during installation or by incidental contact with the hole edges. A drip loop in the wire is provided at each probe and compensator to shed moisture.

FQIS Probes and Compensator

The mounting of the fuel probes within the tank ensures positive spacing from the structure. The ends of the probes employ plastic endcaps to keep the wiring from inadvertent contact with the structure that could result in an electrical short and cause erroneous system performance. These measures further reduce the likelihood that an electrical short can occur in the tank.

The dielectric withstanding voltage of the probes is 1,500 V ac rms at 60/400 Hz with less than 0.5 mA of leakage current, and the insulation resistance is specified to be greater than 200 MΩ at 500 V dc. Every new probe assembly is tested for these two standards to verify the integrity of the part after assembly. The insulation-resistance test is conducted on probes that have undergone repair or refurbishment. These tests provide a high level of confidence that the mutually insulated parts within the probe do not break down over the life of the part.

The probe inner electrode is coated with polyurethane varnish to prevent moisture adhesion, and the outer electrode is anodized to prevent corrosion. Because the anodizing is nonconductive, it provides an additional layer of protection against short circuits between the inner and outer electrode and the outer electrode and structure.

The design of mutually insulated parts protects against sulfide contamination on the probe assembly. There are limited copper or silver parts on the probes and compensators. There is a copper braze (weld) between two joints on the terminal block. The minimal exposure of brazing material to fuel is inconsequential. There is little or no sulfide contamination. There is a small solder joint in the compensators, but there has never been a reported degradation of compensator insulating capability or performance due to this solder joint as a result of sulfide contamination.

Summary

The 747 Classic FQIS is designed to preclude the ignition of fuel vapor in the tanks. The FQIS incorporates design features that tolerate the fuel tank environmental factors such as vibration, corrosion, and contamination. In turn, these features provide extended life expectancy and tolerance to conditions conducive to shorting or grounding.

Bonding Guidelines

During the course of the investigation, Boeing was asked to define the criteria used to bond components in the fuel tank to protect against static buildup and discharge, specifically related to MIL-B-5087 and the “3-inch bonding rule” identified in this specification.

For purposes of electrostatic charging, the 3-inch bonding rule is a general guideline that metallic components not exceeding 3 inches in the largest linear dimension are not required to be bonded to structure, except where they act as a portion of the ground path. Applicable Boeing design requirements for the 747 airplane program do not specifically require electrical bonding of equipment and components that exceed 3 inches in the largest dimension. Even though there was no formal program requirement to bond components larger than 3 inches, attention was given to conductive parts that might be electrically isolated from basic structure. Incidental and inherent bonding were taken into account even where no deliberate attempt was made to isolate a component. Program engineers are familiar with the 3-inch rule and use MIL-B-5087 as reference material. These guidelines are communicated with designers when clarification is requested.

To revalidate this approach as a good design practice, Boeing conducted electrostatic testing in late 1996. The FAA and the NTSB provided comments on the test procedures and observed the testing. The issue at that time was whether a leak in the crossfeed manifold spraying on unbonded equipment could produce an electrostatic discharge. Other issues were investigated as the testing evolved. Eight major groups of tests were accomplished, many of which were performed on a mockup of the center wing tank (CWT) fuel plumbing using the same fuel pumps and tubes as those found on the 747-100. Components that were tested include Wiggins couplings with diameters ranging from 1.75 to 4 inches, tube sections with diameters from 1.75 to 4 inches and lengths greater than 1 foot, 1.75-inch Teflon-sleeved clamps, 2-inch Nitrile-sleeved clamps, and 12- by 12-inch aluminum plates. Voltage accumulation and streaming current was measured for fuel flowing *through* electrically isolated tubes and couplings, as well as for fuel leaks and fuel sprays *onto* clamps, aluminum plates, sections of fuel tubing, and Wiggins couplings. Test variables included fuel temperature, pressure, conductivity, water content, and fuel pressure source. In addition, fuel “slosh” testing was conducted on electrically isolated clamps, couplings, and tube sections that were placed in a partially filled test tank. This tank then was oscillated to measure any voltage buildup. From test results, the stored electrostatic energy was calculated to compare with the maximum allowable energy in fuel tank electrical equipment design specified by Boeing (0.02 millijoules).

In reviewing the basic bonding criteria and in reestablishing the soundness of that approach through testing, Boeing concluded that the basic bonding design for the fuel tanks prevents the development of an ignition source related to static buildup and discharge.

Center Tank Fuel Pumps

Boeing Letter B-B600-16593 to the NTSB, dated January 20, 1999, described in detail the evaluations conducted on the safety features of the scavenge system, including inspection of the recovered hardware and a thorough failure analysis of the scavenge pump electrical system. The failure analysis included potential abnormal conditions and their impact on system safety. The purpose was to investigate the possibility that the scavenge pump may have been operating without having been selected to operate by the crew and discover the effect of such inadvertent operation. Following is a summary of the above letter and that investigation.

Failure Analysis

The investigation analyzed components including the pump; relays; circuit breakers; low-pressure light; switches; and wiring; as well as failure modes such as open wires or wires shorted to ground or power, whether contacts were open or closed, burned-out indication light, and degraded components.

Four of a total of 79 potential faults were found to result in pump operation when the pump was not selected to operate. They included:

- An internal short between relay contacts.
- An internal short of the relay coil to its power input.
- An internal short in the pump selector switch.
- 3-phase shorting directly to 3-phase wiring on the power side of the pump.

Correlating the failure analysis with other factual evidence, including cockpit voice recorder (CVR) review and analysis and testing of recovered equipment, revealed no evidence of any of the four possible failure modes and, as a result, they were classified as extremely unlikely to have occurred. In addition, none of these four extremely unlikely failure modes alone would have created an ignition source in the CWT.

Recovered Hardware

Wright-Patterson AFB laboratory analysis of the indication light, control relay, and switch showed no signs of electrical stress or failure. The section on component tests, below, provides greater detail. It was concluded that the system was in normal operating condition, switched off, and not powered. The NTSB factual report states, “No evidence was found that the scavenge pump in the accident airplane had been powered at the time of the accident.”

Pump Design Features

The pump has built-in thermal protection in the motor, as do all 747 fuel pumps, to remove power from the pump motor automatically when internal temperatures in the windings reach a specified temperature below the autoignition temperature of jet fuel. The design also includes flame-quenching passages required for motor and bearing cooling and lubrication. Initial qualification tests of the pump, and additional testing at Environ Labs, confirmed that the scavenge pump meets all design requirements for being explosion proof.

In summary, the investigation since the accident, combined with an extensive records search of Boeing and airline service history for unselected operation of the system, indicates that the combination of circumstances did not exist that could have allowed the pump to be operating when not selected and become a potential source of ignition.

FAULT TREE

Boeing developed a TWA 800 fault-tree analysis (FTA) as a tool to help guide the investigation. The objective was to identify all the possible scenarios that could have led to the CWT explosion. Boeing believes that the fault tree served this purpose.

Data gathered from the investigation eliminated some events from the Boeing FTA and identified others to be investigated. There were instances where additional events were identified that were not included in the FTA. The NTSB reviewed the FTA and commented on several items, requesting Boeing to revise the FTA to include additional items and change certain probability assessments. At that point in time, a significant portion of the investigation was already completed, and the key issues were identified and were already under close scrutiny in the investigation.

Boeing advised the NTSB that revising the fault tree at that point in the investigation would not help to identify any new areas to investigate and would not help to identify the cause of the accident. Boeing believed that it was more productive to concentrate on the open issues in the investigation and pursue the various inspection and modification programs that were underway, rather than work through the paper exercise of revising the FTA.

It is important to note that there are various methods and practices used by the FAA and the type certificate holders to evaluate and substantiate the design of airplane systems and equipment. An FTA is a tool that is commonly used and is usually built from a failure modes and effects analysis (FMEA) (see FAA AC 25.1309A). There are many guiding industry documents by the Radio Technical Commission for Aeronautics (RTCA) and the Society of Automotive Engineers (SAE) on the development of these types of analyses.

Boeing developed the TWA 800 FTA specifically to aid in the early stages of the accident investigation, not as a document to support certification of the airplane. The process used to develop this type of documentation for certification of systems and equipment is rigorous and thorough. This is not to say that the Boeing TWA 800 FTA was not rigorous or thorough. The focus was to support the accident investigation, and as such, it did not go through the iterative review process with the FAA normally associated with certification of a system, nor were the underlying FMEAs developed that normally would be the source of data to build the FTA.

TEST FINDINGS

Boeing, in cooperation with the NTSB, participated in and conducted various tests to evaluate the effectiveness of various protective features or to determine the feasibility of proposed failure scenarios that would result in an ignition source in a fuel tank. The following is a summary of some of the more significant tests conducted.

Component Tests

Center Tank Fuel Pumps

There is no evidence of an ignition source related to a fuel pump. Early in the investigation, a thorough review of fuel pump design, certification, and qualification testing was conducted. Both center tank override/jettison pumps were recovered and thoroughly analyzed. No anomalies were found. The review of the design, certification, and qualification testing and the analysis of the override/jettison pumps and portions of various other pumps in the recovered wreckage lead to the conclusion that the pumps are of robust design, and that an ignition source related to a fuel pump could not be found.

Although the scavenge pump was not recovered, various parts of the scavenge system were recovered and analyzed. There is no evidence that the center tank scavenge pump was powered at the time of the accident. The scavenge pump normally would not have been turned on, based on the fuel load at dispatch. Review of TWA flight crew training procedures, the CVR transcript, conclusions reached from electrical failure analyses, and party laboratory analyses of recovered equipment (Systems Factual Report, Docket No. SA-516, Exhibit 9-A) indicate that the system was in normal operating condition, switched off, and not powered by any combination of the multiple failures that were investigated.

The following components of the scavenge system were recovered and analyzed:

- **Scavenge pump switch and control relay.** The switch and relay were recovered and analyzed. After its recovery, the scavenge pump switch was documented as being in the OFF position. There was no evidence of forced movement to the OFF position. The scavenge pump normally would not have been in use, given that the CWT was not fueled for the flight. The switch and control relay showed no signs of electrical stress or failure.
- **Scavenge pump inlet line.** The piece that was recovered did not indicate sooting or flow patterns on the internal surface.
- **Scavenge pump circuit breakers.** The circuit breakers were recovered and analyzed. There was no evidence of electrical stress or abnormal conditions.

A scavenge pump was recovered from an aircraft salvage yard by the NTSB and found to have the fuel lubrication tube missing. This tube is a flame-quenching passage. The pump was explosion-proof tested at Lear in this configuration and passed the test (i.e., no flame propagated into the tank side of the pump). No other anomalies were noted, except small amounts of lint, which were not unusual.

Wire Space Dielectric Tests

It has been postulated that two bare wires with their exposed conductors lying very close together, but not shorting, may result in an undetected ignition path in the fuel tank. Boeing conducted testing at sea level to determine the voltage required to create an arc across two exposed conductors lying very close together. In this testing, one wire had all of its insulation removed and the other wire had its insulation removed in a small area to expose the conductor.

The “damaged” area of the second wire was placed facing the exposed conductor, separated by only the width of the wire insulation jacket of the second wire. Under this condition, the voltage required to bridge the air gap (approximately 10 mil, or 10/1000 of an inch) and create an arc was more than 1,100 V ac rms, 60 Hz. This gap must be reduced to approximately 1-mil distance (1/1000 of an inch, or about one-quarter of the thickness of a piece of paper) before the breakdown voltage approached 350 V ac rms, 60 Hz.

Similar tests were conducted at 13,000-foot altitude with the following test results: The breakdown voltage required to bridge a 10-mil gap and create an arc was over 800 V ac rms, 60 Hz, and this gap must be reduced to approximately 4-mil distance before the breakdown voltage approached 350 V ac rms, 60 Hz. These tests conclude that the scenario necessary to develop an ignition path as a result of damaged wiring in the tank is highly unlikely because the spacing of the two exposed surfaces must be held extremely close together over an extended period of time without actually being in a short or intermittent short condition.

Debris

It has been postulated that conductive debris bridging the inner and outer tubes of a fuel probe without causing a hard short circuit (a detectable failure) may result in an ignition path in the tank. Boeing has also conducted testing to determine the voltage required to create an arc when conductive debris is bridging the inner and outer tubes of a fuel probe. Even with the protective varnish layer removed from the inner electrode of the probe, a voltage level greater than 350 V ac was required for a breakdown between the electrodes with conductive debris (steel wool) between them. This is due to the anodize coating on the outer electrode, which broke down at a minimum of 516 V ac rms, 60 Hz in tests conducted at Boeing. Anodize coatings are very stable and do not generally degrade over time unless subjected to abrasion. Therefore, it is Boeing’s opinion that this does not represent a plausible undetected ignition path in the tank.

Sulfidation

The theory was advanced that silver- and copper-sulfides may act as a possible means of creating an undetected ignition path within the tank. Silver- and copper-sulfides are the result of the sulfur component in jet fuel reacting with the exposed silver and copper metals on FQIS wiring in the fuel tank. It has been postulated that a sufficient buildup of these contaminants across two damaged wires on the terminal block could lead to an electrical bridge of the exposed wiring. Unless the buildup of these sulfide contaminants is so severe that fuel quantity indication is affected, the buildup could go undetected by the flight or maintenance crews. The damaged wiring observed on a fuel probe with a Series 3 terminal block is cited as an example of the potential for damaged wiring.

The mechanism of silver- and copper-sulfide buildup is understood and recognized by Boeing. This is not new information as a result of the TWA 800 investigation. The extent of contamination and the coupling of that contamination to ignition sources in the fuel tanks is a new theory. This theory is based on Air Force experience regarding a military aircraft that encountered problems associated with copper- and silver-sulfide deposits. The design of the probes on the military aircraft caused it to be susceptible to these deposits due to the large amount of exposed metal shielding present in the design and the spacing of mutually insulated conductors (conductors that must remain insulated from one another).

NTSB Recommendation A-98-37 requests further research into copper-sulfide deposits. The exact wording of the recommendation follows:

> *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.*

Presently, the FAA is conducting a fuel system copper-sulfide research program using the Stanford Research Institute. The initial plans for this research program are structured into the following tasks:

- Identification of film properties.
- Conditions for deposit formation.
- Diagnostics and deposit removal.

As noted above, evaluations have been conducted by Boeing that confirm that sulfide deposits do accumulate during service life. The deposits can reduce insulation resistance of wiring or components, but levels that might result in a hypothetical ignition source (in conjunction with other necessary faults and conditions) have not been observed. The results of these studies have been documented in laboratory reports and shared with the NTSB.

Boeing is also supporting the FAA-sponsored study by Stanford Research Institute and will respond to any recommendations that may result from that activity.

Equipment Tests

Center Tank Probe, Wire Harness Insulation, and Dielectric Withstanding Test—Altitude

Boeing obtained center tank fuel quantity probes, compensators, and wiring that had been in-service for 23 years. The in-tank wiring harness from the bulkhead connector into the tank was subjected to abnormally high voltages through a range of altitudes from sea level to 50,000 feet. Breakdown values were virtually the same for new wires and probes as they were for wires and probes that had been in-service for 23 years. Breakdown always occurred at the terminal block.

The breakdown at sea level was always greater than 3,100 V ac (4,300-V peak). The breakdown values at the accident altitude of 13,700 feet were always greater than 1,700 V ac (2,400-V peak).

The FQIS uses voltages below 30 V ac and has the inherent safety features noted previously that limit energies and currents in the tank to safe levels. The airplane has two main types of power, 28V dc and 115 V ac, both of which are well below the breakdown voltages of these FQIS parts. There are instances where the 115-V ac power can be stepped up to voltages up to 350 V ac for use in the lighting system of the airplane, but again, this is well below the breakdown voltages of this equipment. What this means is that if some failure did occur that conducted these airplane voltages into the fuel tank, the integrity of the in-tank wiring and the equipment would prevent any ignition source from developing. In the event that this type of failure did occur, damage to the flight deck indicators would result in an obvious indication of the failure, and the fault would be removed and the equipment repaired. No indicator damage of this kind was noted on the TWA 800 airplane.

Indicator Resistor Stress Test

The Honeywell fuel quantity indictor has circuitry dedicated to limiting the current into the fuel tanks. A bridge circuit was designed so that should a short circuit occur in the tank unit circuit or compensator circuit, either from the unshielded lead to ground or between the two leads, the resulting current would be less than 0.01 amp. This limiting is accomplished by a diode-resistor-biasing network. A test was conducted as part of the NTSB investigation in which over-voltages were applied external to this circuitry, simulating a short of airplane power to the FQIS wiring coming from the indicator to the fuel tank. It was noted that if voltage greater than 85 V ac was applied, it would have a permanent functional and visible effect on the resistors in this circuit. The effect is characterized by a change in the red color band on the resistor, a drift in the value in the resistor outside its specified limit, or both. The greater the voltage, the less time it takes for the resistors in the current-limiting circuit to exhibit this effect. The recovered CWT indicator had neither of these indications.

Probe Arc Path Analysis

During altitude testing, a total of 14 probes and two compensators had potentials from 850 V ac up to 3,400 V ac applied from Hi-Z to Lo-Z with the shield generally grounded. When the shield was floating, no significant changes in breakdown voltage or arc location were noted. Following this series of altitude tests, two of the new -14 probes were tested at sea level with changes in humidity from 9 percent to 99 percent. Over 75 high-energy arcing breakdowns were generated (estimated 4 millijoules) from a piece of test equipment referred to as a high pot tester. The following delineates the arc path on the fuel probe (60B92010-14).

On one test sample, arcing occurred between the outer (Lo-Z) tubular electrode and the electrostatic shield, leaving carbon traces on the exterior of the probe adjacent to the Hi-Z access hole. The edge of the terminal block at that location was charred, the arc path was evident on terminal insulator, and the edge of the insulating film in which the electrostatic shield was encapsulated was destroyed where the arc penetrated from the electrode to the metallic shield element.

No other areas of the probe were affected by the arc. There was no indication that arcing occurred between the internal (Hi-Z) tubular electrode and any other component. The arc path was essentially identical on both affected probes with different orders of magnitude reflecting the different number of events each probe was subjected to during the humidity testing that was conducted.

The purpose of this test was to purposely overstress the fuel probes and compensators to determine the most likely location of a failure. This information was useful in determining the overall integrity of the parts but also in helping to provide guidance in the inspection of the parts recovered from the wreckage when looking for similar types of damage in similar locations on the parts.

Probe Saltwater and Fuel Soak Tests

Salt. Fuel quantity probes were taken from a 747 after 23 year of service. These probes were used in altitude-arc testing, and then analyzed for arc paths. Part of this activity included a chemical profile of any chemical deposits on the probe. These probes were then soaked in Puget Sound saltwater for four weeks. Trace amounts of copper-sulfide were identified before and after this four-week soak. This test provided evidence that if copper-sulfide were present on a fuel probe, it would be detectable even after soaking in saltwater for several weeks. According to the notes from this test:

> *Pre-saltwater exposure electron microprobe survey of dark deposit from the Hi-Z terminal block of the tank unit showed that sulfur was present. Upon removal of the terminal assembly, the dark deposit was still visible, although new deposits have been added. Also, arcing damage that was present prior to soak test has not been obliterated by the seawater exposure.*

This note suggests that an arcing event would not necessarily disappear and would have still been visible on the parts examined from the wreckage of TWA 800. No such evidence was found on the center wing tank FQIS components or wiring, in-tank or out-tank.

Fuel. Two fuel quantity probes with initial traces of copper-sulfide already deposited on the terminal block were exposed to a one-month cycled soak in Jet A with an elevated sulfur concentration. Two containers of Jet A were sulfur-saturated by adding 0.3% sulfur by weight to the fuel. The value of 0.3% is the maximum allowable sulfur content of Jet A, as listed in ASTM D1655. The probes were placed in solution sufficient to cover the entire terminal block. They were removed from the fuel twice daily for roughly two hours, excluding weekends. During this abbreviated test, there was no measurable buildup or increase of copper-sulfide or any sulfur compound found anywhere on either probe.

The purpose of this test was to take probes that had been in-service and subject them to an environment conducive to the accelerated buildup of sulfidation. The results showed that the probes themselves contain little material that would be susceptible to the buildup of sulfur/sulfide contamination. This supports other findings and inspections that show the in-tank wiring, and not the probes and compensators, is most susceptible to sulfidation due to the presence of copper and silver in the wiring.

Airplane Tests

Laboratory EMI Test

Boeing conducted laboratory testing to evaluate what would be required to cause excessive energy to be induced into the tank through the FQIS wiring, and then what subsequent in-tank failures would be required to result in an ignition path.

It was postulated that an electrical voltage transient (voltage spike) of sufficient strength, induced onto FQIS wiring, might result in an arc in a fuel probe if the probe were contaminated with conductive debris. Voltage transients in wiring are generated when power to equipment is switched from one state to another state, like turning a light from OFF (0 V ac) to ON (115 V ac). These transients can greatly exceed the normal voltage in the wire for very short periods of time. When other wires are close or adjacent to the wire that is undergoing switching, these transients may be coupled onto the adjacent wiring by what is referred to as electromagnetic interference (EMI). When voltage and current are present on a wire, electromagnetic fields are established around the wire. When the voltage or current in the wire changes, the fields around the wire change. If there is other wiring adjacent to the wire that is switching from OFF to ON, these fields cause a similar, but reduced, change in the adjacent wiring (i.e., the voltage transient was "induced" onto the adjacent wiring).

The FAA expressed concern when the results of Boeing laboratory tests demonstrated that, given high enough levels of voltage transients (over 800 V in laboratory conditions) induced onto the FQIS wiring outside the fuel tank, an arc could be generated on a fuel probe that had been purposely contaminated with conductive debris.

These tests were designed to "stress test" the system and were not intended to reflect the actual airplane environment. The purpose of testing was not to determine the performance of the FQIS in accordance with established airplane EMI requirements. Also, the insertion of conductive debris is not a normal part of this type of test. The test configuration and procedure were derived from a generic equipment test intended to demonstrate the resistance of a piece of electronic equipment to EMI. The test configuration was never intended to be used as a dielectric-breakdown evaluation.

Airplane EMI Test

Testing conducted by Boeing and coordinated with both the NTSB and the FAA on two operational 747 airplanes configured similar to the TWA 800 airplane demonstrated that voltage spikes induced onto the FQIS wiring and into the tank (83-V peak) were far below that required to create a potential ignition source. This testing demonstrated that the available energy levels would not result in an arc in the fuel tank even with debris present in the probe. The earlier laboratory testing referred to above, which did create an arc, required extremely high voltage spikes and carefully placed debris to obtain this result. Boeing has also completed laboratory testing that assessed the effects of other EMI sources, internal and external to the airplane, that might induce voltage on the FQIS wiring and might have resulted in excessive energies being conducted into the fuel tank. This testing indicated that high-intensity radiated frequency (HIRF) radiated directly onto the FQIS wiring did not result in voltage of sufficient magnitude to result in an ignition source in the tank during normal and failure conditions. The findings of these tests have been provided to the NTSB.

INSPECTION FINDINGS

FQIS Equipment Removals—Other Boeing Models

Boeing removed all of the FQIS wiring and probes from three in-service 737 Classic airplanes and all the FQIS probes and wiring from three fuel tanks on a 747-400. This allowed Boeing to conduct detailed analyses and tests of this hardware to determine if there were any similarities to the FQIS probes and wiring from the 747 Classic.

The 737 Classic and 747-400 use a totally different FQIS probe design from that of the 747 Classic. Therefore, there were no issues associated with the terminal block and wire damage as a result of a knurled surface. The only similarity was that some sulfidation was noted on the wiring from these airplanes. Tests demonstrated that the level of buildup was less than the amount that could contribute to any known or plausible ignition fault scenario. Boeing is working with the FAA sulfidation study to determine what, if any, issue sulfidation poses. The FAA study also will provide recommendations on the prevention and removal of sulfidation, if required.

Bonding and Grounding Design Review

To develop the detailed inspection instructions used to conduct the fuel tank inspections of all models in the Boeing-built fleet, a comprehensive review of the fuel system design was conducted for each model. Various revisions were made to the detailed assembly drawings to address any issues associated with the bonding or grounding of a part or component. The design reviews did not reveal any issues that would result in an ignition source in the fuel tank and compromise the safety of the airplane.

Factory Inspections

In addition to the fleet inspections, each model underwent a series of special inspections in the factory to ensure that the design and build instructions contained on the engineering drawings were being properly implemented in the factory. Minor discrepancies were identified and corrected, but there were no issues that would affect the airworthiness of the affected model.

747 Classic Fuel Tank Inspections

Boeing Service Bulletin 747-28-2205, “Fuel—Fuel Tanks, Center Wing Fuel Tank Inspection,” details an inspection for the 747 center wing fuel tanks. This is a sample inspection program undertaken by Boeing and the airlines to collect data on the in-service condition of CWT fuel systems. The purpose of the inspection is to confirm the intended condition of the fuel tank and fuel systems components in the tank and identify what actions may be required to ensure continued airworthiness of the airplane. In addition, the results of the inspection may result in corrective action service bulletins or maintenance programs to ensure the continued airworthiness of the fleet.

Data from 424 747 CWT inspections has been reviewed to date, and no unsafe conditions have been identified. For a small set of parts, corrective action and maintenance programs are being developed to ensure that continued airworthiness is maintained.

APPENDIX D: AIRPLANE CHANGES

SERVICE BULLETINS AND AIRWORTHINESS DIRECTIVES

The following paragraphs summarize some of the service bulletins (SB) issued in the aftermath of the TWA 800 accident and associated airworthiness directives (AD) issued by the FAA.

Main Tank Boost Pump Conduit Wiring Inspection

Boeing Service Bulletin 747-28A2204, released in December 1996, affects all 747 airplanes. This SB required the periodic inspection of the fuel pump wiring routing through conduits in the fuel tanks. Although there was no evidence on the accident airplane that this was an ignition source, the precaution was taken to inspect this installation to ensure that the double layer of protective sleeving and the wiring were not damaged. The FAA has issued AD 96-26-06, which requires compliance to the inspection instructions in this SB.

Boost Pump Conduit Sleeving Inspection

While completing Boeing SB 747-28A2204, one operator noted that the protective sleeving on the fuel pump conduit wiring was missing on one airplane. As a precautionary measure, the FAA released a telegraphic AD in May 1998 that required inspections within 60 days of all 747s that had not yet completed SB 747-28A2204 to verify the presence of the sleeving material. Boeing provided the inspection procedure to the airlines. No other instances of missing sleeving were found as a result of this inspection.

Scavenge Pump

Connector Inspection

During the teardown and inspection of older 747 scavenge pumps as part of the accident investigation, it was noted that some of the grommets installed in the connectors of the pumps were deteriorating. Boeing Service Bulletin 747-28A2206, which affected 747s with electric scavenge pumps, was released in September 1997. It provided instructions to operators for inspecting the scavenge pump connector and replacing the affected grommets. The FAA issued AD 97-25-06 in December 1997 requiring the inspection and replacement detailed in the Boeing SB. All inspections were completed by March 1998.

Connector Inspection and Rework

Boeing Service Bulletin 747-28A2215 recommended reinspection of the scavenge pump connectors that were reworked under Boeing SB 747-28A2206 after it was discovered that the replacement grommet did not fit as precisely as the original grommet and allowed the internal pump wiring to be compressed. SB 747-28A2215 corrected the compression condition. The

FAA released AD 98-14-17 in July 1998 requiring the new SB to be completed. All inspections were completed by September 1998.

Scavenge Pump Flame Arrestor Installation

Boeing Service Bulletin 747-28A2210, released in May 1998, provided a kit of parts and instructions for installing a flame arrestor at the inlet tube for the scavenge pump. The FAA issued AD 99-08-02 in April 1998 requiring installation of the flame arrestor by May 2001.

APU DC Pump Connector Inspection

The auxiliary power unit (APU) dc pump used the same connector as the scavenge pump. Boeing SB 747-28A2209 addressed the same issue on the APU dc pump connector grommet as was addressed on the scavenge pump connector in SB 747-28A2206. The FAA issued AD 99-08-19 in April 1999, and all inspections were completed by July 1999.

CWT Override/Jettison Pump Inlet Check Valve and Inlet Adapter Inspection

Boeing Service Bulletin 747-28A2212, issued in April 1998, affects all 747 airplanes. The FAA issued AD 98-16-19 in August 1998 requiring the center wing tank (CWT) override/jettison fuel pumps to be switched off at 7,000 lb until the inspection instructions in the Boeing SB were accomplished. The FAA AD also required inspection of the inlet check valve and the pump inlet adapter within 90 days of the effective date of the AD. Initial inspections were required of all airplanes with more than 10,000 flight-hours, and repeat inspections were required every additional 10,000 flight-hours. Boeing is in the process of designing a new inlet check valve and adapter, which will eliminate the need for the periodic inspection mandated by the AD.

Main/HST Tank Override/Jettison Transfer Pump Inlet Check Valve and Adapter Inspection and Replacement

Boeing Service Bulletin 747-28-2222 provided an inspection of the main or the horizontal stabilizer tank (HST) override/jettison pump inlet check valve similar to the inspection detailed in SB 747-28A2212 for the CWT override/jettison pump inlet check valve. Boeing is in the process of designing a new inlet check valve and adapter, which will eliminate the need for this periodic inspection.

Override/Jettison and Transfer Pumps Operational AD and Thrust Washer Inspection

Boeing released two SBs regarding the HST and CWT transfer and purge pumps. Boeing Service Bulletin 747-28-2225 called for inspecting the HST transfer pumps to measure axial play of the impeller shaft on pumps with suspect thrust washers manufactured or overhauled between July 1996 and November 1998. Boeing Service Bulletin 747-28-2226 called for inspection and modification of the HST and CWT pumps to purge pumps with the suspect thrust washers. The FAA also released a telegraphic operational AD 98-25-52 requiring CWT pumps to be switched off with sufficient fuel remaining to cover the pumps. As an interim measure until the SBs were performed, airlines were not allowed to operate the horizontal stabilizer tank. Both Boeing SBs provided an alternate method of compliance for AD 98-25-52 fuel management procedures.

RECOMMENDATIONS—AIRPLANE CHANGES

To ensure the continued safety of current production aircraft and the in-service fleet, Boeing has changed its design standards requiring the separation of fuel quantity indicator system (FQIS) wires and wires supplying electrical power. Boeing prepared service bulletins to separate FQIS wires and to retrofit FQIS instruments to ensure that the proper separation is provided with fuel tanks. Because the detailed technical knowledge for developing transient-suppression devices resides with the FQIS suppliers, Boeing has provided technical assistance to our suppliers to help them develop and certify these devices. As soon as these transient-suppression devices are certified by the FAA, Boeing will issue service bulletins advising customers to install them.

Furthermore, Boeing has reviewed the bonding and grounding specifications on its design drawings and has verified that Boeing aircraft-build processes ensure proper grounding and bonding. Boeing released a service bulletin to verify bonding and grounding of the in-service fleet and has also released service bulletins for repetitive inspection and modification of fuel tank wiring and connectors, as well as a service bulletin requiring repetitive inspection of the fuel scavenge pump.

747 Classic FQIS Probes and Wiring—NTSB Recommendations A-98-34 and A-98-35

NTSB Recommendations A-98-34 and A-98-35 recommend inspection, replacement, and repair of FQIS in-tank wiring and probes on 747 Classic airplanes. The exact wording of the recommendations follows:

> *Issue, as soon as possible, an airworthiness directive to require a detailed inspection of fuel quantity indication system 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 fuel quantity indication system wiring. (A-98-35)*

During the investigation, the NTSB identified the following as potential hazards relating to the FQIS probes and wiring found in Boeing 747 fuel tanks during the investigation:

- Terminal blocks with knurled surfaces and squared edges (Honeywell 747 Classic probes only).
- Terminal blocks with a metal strain-relief clamp (Honeywell 747 Classic probes only).

- Cold flow of wire insulation and points of chafing and potential chafing between FQIS wiring and structure.
- Inappropriate repairs, such as:
  - Adhesive tape and lacing tape used to repair an in-tank wire bundle.
  - Oversized P-clamp on terminal block; wiring looped multiple times through clamp.
  - Chafed wire coated with fuel tank sealant.

In response to these recommendations, Boeing has taken the following actions that we believe address the above issues:

- Boeing issued Service Bulletin 747-28-2205 (currently at Revision 2, issued March 11, 1999). This SB contains instructions to the operators for the inspection of in-tank FQIS wiring of 747 Classic center wing tanks. Subsequently, the FAA has released AD 99-08-02 that requires the complete inspection instructions of SB 747-28-2205 to be accomplished. This AD was issued May 11, 1999, with a two-year compliance period. This SB contains bonding and grounding measurements of the fuel systems components, an examination of all bonding jumper installations, a condition check for all mechanical and electrical components (including FQIS components and wiring), and an inspection for foreign object debris.
- The airlines have voluntarily provided Boeing inspection reports from approximately 437 inspections using SB 747-28-2205. These inspections represent approximately 39 percent of the worldwide 747 fleet and 42 percent of the U.S.-registered 747 fleet. Reports from these inspections detail one instance of minor damage to an FQIS wire (which was repaired per the instructions in the SB) and one instance of a loose connection to a fuel probe. There have been no issues identified that would affect the continued airworthiness of the 747 Classic. Note that the number of airplanes on which the inspection has been conducted per the requirements of the FAA AD noted above may actually be much greater than suggested by the voluntary data provided to Boeing.
- Boeing also issued Service Bulletin 747-28A2208 on May 14, 1998 (presently at Revision 1, dated August 26, 1999), which is applicable to all 747 Classic airplanes (747-100, -200, -300, -SP, and -SR). This SB provides instructions to remove and replace those fuel quantity probes and compensators that have the knurled-surface terminal block. The SB further specifies that all wiring that was attached to such a probe or compensator is to be replaced. This replacement can be accomplished either through the retermination of the existing wiring or by replacing the entire affected wire bundle in the center tank. (Note: for those airplanes known to be delivered with probes and compensators with knurled-surface terminal blocks, the SB requires the replacement of the center tank wire harnesses). Boeing believes that this SB addresses the NTSB concern regarding “concealed...very small” damage points on the wiring attached to knurled-surface terminal blocks in that all of this wiring is removed from the airplane, which is the first issue noted above. Also, the new terminal blocks being used to replace the knurled-surface terminal blocks have been improved to eliminate the square edges. This improvement addresses the second issue noted

above for reworked or refurbished parts. For existing non-knurled-surface terminal blocks, the probe wire routing enhancement described below addresses the third issue.

- The 747-28A2208 SB also requires that all wiring attached to any terminal block on probes or compensators is to be rerouted as shown in the SB. The routing shown in the SB ensures that there is no inadvertent contact of the wiring to the edges of the terminal block, eliminates any excessive routing of wiring through the clamp on the terminal block to prevent compression damage, and provides improved separation between the mutually insulated Hi-Z, Lo-Z, and Hi-Z shield wires. Boeing believes this new routing addresses the second and third issues noted above in that the new wire routing prevents contact with the edge of the terminal block, addresses the issue of over-compression of the wiring by detailed illustrations of wire routing and clamping design, and minimizes contact between mutually insulated wires (Lo-Z, Hi-Z, Hi-Z shield), thereby eliminating concerns regarding any "arc gaps" between "very small" damage points in the wiring that may escape inspection. It should be noted also that the rerouting of the wiring on the terminal blocks enables an inspection of that wiring, including any wiring that may have been retained under the terminal block clamp, which addresses the issue of compression damage. Boeing believes that the enhancement in the terminal block wire routing incorporates the best practices of the Boeing Standard Wiring Practices Manual and will not result in any wiring damage.

The SB also specifies that all the FQIS wiring and components in the center fuel tank are to be inspected. Although the SB does not require the removal of all clamps retaining the wiring to inspect for damage under the clamps, it is Boeing's belief that the SB addresses the areas of concern most noted by the NTSB (i.e., the wiring at the terminal blocks and exposed sections of wiring with chafing potential).

- Lastly, SB 747-28A2208 provides instructions to perform a low-level insulation resistance (IR) test of the FQIS center tank wiring from the flight deck to the center fuel tank. The purpose of this test is to determine if there is any significant compromise in the insulation of the FQIS wiring throughout the airplane. The test checks the IR between the Lo-Z, Hi-Z, and Hi-Z shield wire and each wire to ground.

The FAA has issued AD 99-08-02, which, among other things, requires the accomplishment of SB 747-28A2208. The AD was issued May 11, 1999, with a 24-month compliance period.

In addition to these mandated actions, Boeing is modifying the maintenance documentation for the 747 Classic to incorporate additional instructions and illustrations on the removal, replacement, and repair of components and wiring in the tank to ensure that the service bulletin information is applied throughout the fleet. In addition, the FAA issued Notice of Public Rulemaking (NPRM) 99-18 on Oct. 29, 1999, titled "*Transport Airplane Fuel Tank System Design Review, Flammability Reduction, and Maintenance and Inspection Requirements*," which is now under comment review. One of the proposed actions required by the NPRM of the affected airplane manufacturers and airlines is the establishment of maintenance and inspection processes and plans for fuel systems. Boeing is evaluating additional maintenance and inspection criteria that would ensure that improper repairs or alterations are identified and corrected. These actions will address the fourth issue noted above.

To date, Boeing has received voluntary reports on 72 airplanes owned by seven operators that have accomplished SB 747-28A2208. The data provided by these operators indicates that the intent of the SB is being met (i.e., that the knurled-surface terminal blocks are being removed and replaced with terminal blocks that do not have the knurled surface, that the FQIS wiring is being inspected and replaced or reterminated as required, that the wiring at the terminal block is being repositioned, and that the insulation-resistance tests are being conducted).

As a result of the NTSB inspection findings, the NTSB has raised the issue of a life limit for FQIS components and wiring in the fuel tank. With respect to the wiring, the significant issues are wire damage and copper-silver sulfur corrosion (or sulfidation) products and their effect on the insulating integrity of the wiring and the potential for the introduction of a spark gap should sufficient energy be inadvertently introduced into the fuel tank through the out-tank FQIS wiring.

The FAA has initiated research into sulfidation, led by SRI International, through the FAA's Center of Excellence program. This program will address the identification of film properties and the conditions for the deposit formation and provide diagnostic and deposit removal methods that would be the basis for recommendations on any life-limit for the in-tank wiring.

Boeing has not seen any significant issues associated with any of the other in-tank FQIS components (i.e., the compensators or probes). Boeing removed, inspected, and tested two full shipsets of 747 Classic FQIS wiring and components. The NTSB has received these reports that describe all analyses, tests, and inspections that were performed on the removed wiring and components. In summary, the results showed that damage to wiring was insignificant and was mainly related to removal of the wiring from the airplane for this study. Sulfide contamination was evident on the Hi-Z wiring near the terminal blocks, but test results showed the dielectric strength of the wiring had not been compromised to a point to be considered hazardous. There was some minor degradation of the Hi-Z ground shield under the terminal block of one probe. Once again, however, the dielectric strength of the probe had not been compromised to a point to be considered hazardous. In addition, three shipsets of 737 Classic and one partial shipset of 747-400 FQIS in-tank hardware have been removed, inspected, and tested. There were no issues with the 737 Classic or 747-400 in-tank FQIS hardware. The fuel tank wiring was again the primary source of issues that were related to sulfidation, damage, or wear.

Boeing, at this time, does not see the need for any life-limit on FQIS in-tank components (probes and compensators). As sulfidation is related to the in-tank FQIS wiring, Boeing is open to reviewing the results of the FAA study on this issue and will respond to any recommendations or mandates issued by the FAA at that time.

FQIS Wire Separation and Transient Suppression—NTSB Recommendations A-98-38 and A-98-39

The NTSB Recommendations A-98-38 and A-98-39 recommend that actions be taken to separate and shield FQIS out-tank wiring and install surge-protection systems on all applicable transport-category aircraft. The purpose of these recommendations is to prevent excessive energy from getting into the fuel tank via the FQIS wiring to the tank. The exact wording of the recommendations follows:

Require in Boeing 747 airplanes, and in other airplanes with fuel quantity indication system (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).

Require, on all applicable transport airplane fuel tanks, surge-protection systems to prevent electrical power surges from entering fuel tanks though fuel quantity indication system wires. (A-98-39).

Wire Separation and Shielding

To date, the FAA has issued AD 98-20-40 for the 747 Classic airplanes, effective November 4, 1998, with a three-year compliance period. The AD requires the installation of shielding and the separation of the electrical wiring of the FQIS located outside the fuel tanks.

The FAA issued a similar AD against the 737 Classic, AD 99-03-04, effective March 9, 1999, with a four-year compliance period that requires, among other things, the separation and shielding of FQIS out-tank wiring.

As stated above, the FAA issued NPRM 99-18 on October 29, 1999, which is titled *"Transport Airplane Fuel Tank System Design Review, Flammability Reduction, and Maintenance and Inspection Requirements,"* and is now under comment review. One of the proposed actions required by the NPRM of the affected airplane manufacturers would be a review of existing FQIS wire installations to determine if they meet the standard imposed in the ADs noted above and to implement any necessary design changes to bring them into compliance.

Boeing has been developing service bulletins to address the ADs noted above. Presently the service bulletins that will address FQIS out-tank wire separation and shielding on the 747 Classic are 747-28-2221 and 747-28-2224. Similar service bulletins are under development for the 737 Classic.

These 747 Classic wire separation and shielding service bulletins, 747-28-2221 through 747-28-2224, incorporate the following design and implementation features:

- **Elimination of older analog FQIS LRUs**. When the design of these LRUs was reviewed with the FAA, it was determined that they could not be made compliant with the AD requirements without extensive modifications. As part of the Boeing wire-separation SB 747-28-2221, the Honeywell analog FQIS is replaced with the next-generation Smiths Industries digital FQIS (all LRUs). (Note: SB 747-28-2221 converts from an analog FQIS, to digital FQIS and then incorporates wire separation and shielding. SB 747-28-2224 incorporates wire separation and shielding on those airplanes that already have the Smiths digital FQIS.)
- **DWV testing**. All Smiths Industries digital FQIS LRUs used with the Boeing wire-separation SBs, 747-28-2221 through 747-28-2224, will undergo a 1,500-V ac dielectric withstanding voltage (DWV) test that will ensure that input power to the LRU (either 115 V ac or 5 V ac) is adequately insulated from the signals going to the fuel tank from the LRU. All parts undergoing this test will receive a new part number so that they are easily identifiable.

In addition to the initial test to substantiate the integrity of the insulation between signal and power traces, the maintenance instructions for these parts will be modified to include an inspection and DWV test whenever the part is opened for maintenance. This will ensure that the insulation between the power and signal traces is not compromised during maintenance.

- **Wire separation.** The basic separation requirement imposed on the FQIS wiring was a 0.25-inch minimum in the pressurized areas of the airplane and a 0.5-inch minimum in the unpressurized areas. It must be emphasized that these are “minimum” separation requirements. In reality, Boeing designers always try to exceed these values where possible. For example, on the 747 Classic wire separation SBs, 747-28-2221 through 747-28-2224, the average spatial separation in most areas of the airplane is much greater than the required minimum separation.
- **Advanced wire type.** In addition to the minimum separation requirements, Boeing is using a BMS 13-58 high-strength arc-resistant type wire for all the affected FQIS wiring. This wire has undergone stringent thermal and electrical (arcing) tests to qualify it for use in critical circuits where wire integrity is essential.
- **Unique identification.** The FQIS wiring has been identified with a unique separation code and a unique color (pink). This information is being included in the maintenance documentation for airplanes that incorporate wire separation to ensure that future modifications to the airplane do not compromise the FQIS wire separation. The unique color designation for this wire will also allow routine inspections to easily identify the FQIS wiring and quickly identify and resolve any installation issues.
- **EMI shielding.** All FQIS wiring is shielded, and all shields are terminated at both ends to ensure maximum EMI protection. The combination of spatial separation with the EMI shielding provides redundant protection against electrical interference from other systems and wiring.
- **Dedicated FQIS wire bundles.** All FQIS wiring is contained within dedicated wire bundles and connectors and does not commingle with any other system or wire bundle.

In summary, it is Boeing’s belief that a wire separation and shielding design such as the one implemented in Boeing SBs 747-28-2221 through 747-28-2224 for the 747 Classic airplane, which complies with the applicable FAA requirements, by itself will provide the necessary level of protection being sought by the NTSB in recommendations A-98-38 and A-98-39.

Transient Suppression

After the 737 and 747 Classic ADs for wire separation, shielding, and transient suppression were released, and Boeing had decided to pursue the mandated wire separation, Boeing approached the affected FQIS suppliers to encourage an independent pursuit of the design and certification of a transient-suppression device (TSD) for their FQISs on the 737 and 747 Classic airplanes through supplemental type certificate (STC).

Since then, Boeing has been in regular contact with the participating suppliers. Boeing has provided technical information to these suppliers regarding the airplane mechanical and electrical interface data requested. Several technical reviews have also been held over the last several months with these companies. In addition, a number of telecons have been conducted to review any issues and status action items. Boeing has also made available our mockup of the 747 FQIS in our fuels lab, which was used for prototype TSD testing. Also, Boeing has had the opportunity to be present during some of the presentations made by the suppliers to the FAA to lend support to the supplier and the FAA in evaluating their TSD programs.

Through these regular meetings and contacts with the suppliers, Boeing has assessed the designs of the TSDs being developed and the program commitments and schedules to which each supplier has performed. From the information that Boeing has received, the design and architecture of these TSDs will accomplish the function of preventing excessive energy from getting into the fuel tank and thereby enhance the safety of the existing FQISs. The modifications necessary to install these devices into the airplane appear to be minimal. The TSDs may provide the airlines a cost-effective and timely solution in complying with the associated ADs once the FAA provides approval of the STCs for their installation. The actual cost-benefit analysis of incorporating a TSD is being performed by the airlines.

At the request of our customers, Boeing is presently evaluating the development of service bulletins that would reference the supplier STCs (once they are approved by the FAA) for the installation of their TSDs. Boeing is presently in discussions with the FAA on the process and plan for accomplishing this.

In summary, Boeing believes that the TSDs that are being developed by and Smiths Industries and certified by the FAA via STC will by themselves provide the necessary level of protection being sought by the NTSB in recommendations A-98-38 and A-98-39.

Boeing does not believe that both wire separation and shielding, and transient suppression, are necessary to comply with the NTSB's recommendations intended to enhance the design of the FQIS to preclude the introduction of unwanted energy into the fuel tank.

Fuel Tank Inspections—NTSB Recommendation A-98-36

This recommendation requests inspection of other transport-category airplanes to determine if there are any issues associated with the fuel system similar to those noted previously in recommendations A-98-34 and A-98-35 on the 747 Classic. The exact wording of the recommendation follows:

> *Conduct a survey of FQIS probes and wires in other transport category airplanes to determine whether potential fuel tank ignition sources exist that are similar to those found in the Boeing 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.*

Prior to the issuance of this recommendation, the airline industry undertook a voluntary fuel tank inspection program affecting the entire commercial fleet. Inspections have been occurring over the last 33 months. This program was first outlined in the industry response to the FAA's request for comment on fuel tanks. The air transport industry, through the Air Transportation Association (ATA), the Association of European Airlines (AEA), the Air Atlantic Pilot's

Association (AAPA), the Aerospace Industry Association (AIA), the Association Europeenne des Constructeurs de Materiel Aerospatial (AECMA), and other consortiums, volunteered to undertake an aircraft fuel systems safety program. This program is being coordinated by the ATA through the aircraft working groups (AWG). Each AWG, made up of representatives from the aircraft manufacturer and various operators, is responsible for coordinating the effort for each type of aircraft. The program includes a sample inspection program and historical data review to gather data on the in-service condition of fuel tanks. The data will be used to confirm the intended condition of the tanks and, where necessary, to identify follow-up activities to ensure the continued airworthiness of these tanks. These additional activities may include updated maintenance programs and corrective-action service bulletins. The results of the inspections will be collected by the manufacturer and shared with the industry to ensure dissemination of data that enhances the safety of all airplane fuel systems. The status of the Boeing inspections is noted in the table below:

Model	**Quantity Inspected**		**Inspection Status**
	Main Tanks	Center Tank	
727	2	2	Ongoing
737	1	52	Ongoing
747	5	437	Complete*
757	5	49	Complete
767	6	41	Complete
DC9	11	--	Complete
DC10	8	--	Complete
MD80	5	--	Complete

*Voluntary inspections complete. FAA AD 99-08-02 requires inspections on all remaining U.S.-registered airplanes.

FAA NPRM AND SFAR

As stated above, the FAA on October 29, 1999, issued Notice of Proposed Rulemaking (NPRM) 99-18, titled "*Transport Airplane Fuel Tank System Design Review, Flammability Reduction, and Maintenance and Inspection Requirements*." Included in this proposed rulemaking is a Special Federal Aviation Regulation (SFAR) requiring the design-approval holders of certain turbine-powered transport-category airplanes to submit substantiation to the FAA that the design of the fuel tank systems of previously certificated airplanes precludes the existence of ignition sources within the airplane fuel tanks. This SFAR would also require the affected design-approval holders to develop specific fuel tank system maintenance and inspection instructions for any items in the airplane fuel tank system that are determined to require repetitive inspections or maintenance to ensure the safety of the fuel tank system. In addition, the SFAR would require certain operators of those airplanes to incorporate FAA-approved fuel tank system maintenance and inspection instructions into their current maintenance or inspection program.

NPRM 99-18 also proposes three amendments to the airworthiness standards for transport-category airplanes. The first would define new requirements, based on existing requirements, for demonstrating that ignition sources could not be present in fuel tanks when failure conditions are considered. The second would require future applicants for type certification to identify any safety-critical maintenance actions and develop limitations to be placed in the instructions for continued airworthiness for the fuel tank system. The third would require means to minimize development of flammable vapors in fuel tanks, or means to prevent catastrophic damage if ignition does occur.

The industry has collectively submitted an extensive response to the FAA urging that the comments summarized in the industry response document be considered and incorporated into the FAA's rulemaking. The industry believes that the alternative methodologies it has proposed will meet the intent behind NPRM 99-18 and achieve its goals by making the proposed rule as effective and practical as possible.

The alternative approach proposed by industry is summarized below:

- Base SFAR No. XX on a *prescriptive* rule (i.e., develop checklists derived from lessons learned) rather than on FAR 25 changes.
- Modify FAR 25 using regulatory language that provides improved requirements, fixes long-standing regulatory deficiencies, maintains technical compliance capability, and preserves precedents that relate to aircraft design and regulatory practices.
- Replace FAR Ops requirements with individual airworthiness directives based on aircraft type and issued upon completion and approval of the SFAR No. XX.
- Furthermore, the industry has recommended that this rulemaking be harmonized within the industry rather than remain a unilateral FAA initiative.

APPENDIX E: MAINTENANCE CHANGES

FUEL SYSTEM MAINTENANCE PROGRAM

As a result of the 747 Classic fuel tank inspections outlined in appendix B, Boeing is developing a fuel system maintenance program for the 747 that will be the baseline for all other Boeing models. The maintenance plan in its present form addresses three main areas of the fuel system:

- Electrostatic bonding.
- Fault-current bonding.
- Visual inspection of systems and components and for foreign object debris (FOD).

The following sections outline the current proposals:

Electrostatic Bonding

The data collected from the extensive 747 fuel tank inspections has shown that once the electrostatic bonds have been correctly installed, there is no degradation that would affect the capability of the bond to protect against electrostatic buildup.

Nevertheless, Boeing is presently developing inspection criteria and processes for periodically inspecting the fuel tank static bonds and grounds. The goal is to limit the number of inspections required to the minimum necessary to substantiate the integrity of these bonds. Experience has shown that the more these systems are disturbed through fuel tank entries, the more likely it is that these bonds and grounds will be negatively affected. In addition, there are a number of personnel hazards associated with working in the confined spaces and with the hazardous vapors of fuel tanks. Therefore, it is desirable to limit the exposure of airline maintenance personnel to these hazards to the minimum extent possible.

Fault-Current Bonding

The inspections of the fuel system components mounted external to the 747 fuel tanks show that fault-current bonds, because of their inherently low bonding values, tend to age over time. Fault-current bonds are installed to ensure that the circuit breaker for a device will pop, airplane wiring will not be damaged, and airline personnel will not be injured in the event of a fault that results in the power to that device being applied to its case or housing. In the case of equipment installed in the fuel vapor areas of the airplane, fault-current bonds are also designed to eliminate potential sparks during a fault-current event. Boeing is presently proposing a periodic check of those components that have extremely low fault-current bonding values to ensure that these low-resistance fault-current bonding values are maintained throughout the life of the airplane.

There are smaller components that do not have low fault-current bond values and have been shown to not have the same aging effects. Therefore, these components will be checked through normal on-condition maintenance activities.

Visual Inspection of Systems and Components and for FOD

The present proposal is to incorporate a list of the fuel system components together with inspection criteria for these components. This list will be included into the structural zonal checks and is also to be used whenever a fuel tank is entered for maintenance. Visual inspection of tubes, clamps, bonding jumpers, FQIS wiring, and probes will be performed to check for damaged or loose parts. A visual inspection for FOD will also be performed.

APPENDIX F: OPERATIONAL CHANGES

GROUND SOURCE CONDITIONED AIR

The NTSB has recommended the development and implementation of short-term design or operational changes that will preclude the operation of transport-category airplanes with explosive fuel/air mixtures in the fuel tanks (NTSB Recommendation A-96-175). Boeing, along with the industry, has studied methods to minimize the temperatures in the center wing tank (CWT). Use of ground source conditioned air for heating or cooling of the airplane while the airplane is on the ground being serviced reduces the heat input into the CWT for those airplanes with air-conditioning packs located below the CWT. Reducing heat input into the CWT will reduce exposure to flammable fuel vapors in the CWT.

Boeing is developing a service letter recommending that operators use ground source conditioned air when available for servicing airplanes in lieu of running the auxiliary power unit (APU) and operating environmental control system (ECS) air-conditioning packs. Boeing plans to revise the Aircraft Maintenance Manual (AMM), the Ramp Maintenance Manual (RMM), and the applicable facilities planning documents to advise operators to use conditioned air from a ground source when available.

CIRCUIT BREAKER RESET PROCEDURE

There is no evidence in the TWA Flight 800 wreckage, maintenance records, or CVR data of any fuel pump circuit breaker being reset during the accident flight or in the recent past service of that aircraft. However, Boeing and the industry have reviewed the overall service history of commercial and military aircraft with regard to incidents involving resetting fuel pump circuit breakers. As a result, Boeing has changed its advice to flight and maintenance crews.

Prior to this change, and not specific to any given system, Boeing aircraft operating procedures allowed one reset of any circuit breaker at the captain's discretion after a short cooling period (approximately 2 minutes). If the circuit breaker trips again, no further attempt should be made to reset it. A revised procedure is being implemented that states that flight-crew reset of a tripped circuit breaker in flight is not recommended and is prohibited in the case of fuel pump and fuel pump control circuit breakers. However, a tripped circuit breaker may be reset once, after a short cooling period (approximately 2 minutes), if in the judgment of the captain, the situation resulting from the circuit breaker trip has a significant adverse effect on safety. The revised procedure also states that a ground reset of a tripped circuit breaker by the flight-crew should only be accomplished after Maintenance has determined that it is safe to reset the circuit breaker. In addition, Boeing is providing troubleshooting guidance to ease in the resolution and improve the safety of related maintenance activity. Maintenance advice has been incorporated into maintenance instructions as revisions to the fault isolation manuals (FIM).

Boeing will issue a service letter in mid-2000 highlighting the revision of the above FIM procedures.

FUEL PUMPS

During the TWA Flight 800 investigation time frame, the following operational actions have been taken regarding specific mechanical failures of fuel pumps on Boeing aircraft. Also included are the design actions associated with each. Although these specific failure modes were considered during the TWA Flight 800 investigation, they were dismissed because of negative findings during the examination of the wreckage.

747 CWT Override/Jettison Pump Shutoff

Following the discovery that pumps were exhibiting failure of the inlet check valve, Boeing ran laboratory tests in which parts of the check valve were ingested into a running pump in an explosive environment. No ignition sources were found. Nevertheless, the following actions were taken.

Boeing Service Bulletin 747-28A2212, issued in April 1998, affects all 747 airplanes. As an interim to pump inspections requested by this bulletin, operational changes were made. Boeing issued an operations manual bulletin, and the FAA mandated it by issuing AD 98-16-19 in August 1998, requiring the CWT override/jettison fuel pumps to be switched off at 7,000 lb of center tank fuel remaining until the inspection instructions in the Boeing SB were accomplished. The FAA AD also required inspection of the inlet check valve and the pump inlet adapter per SB 747-28A2212 within 90 days of the effective date of this AD. Initial inspections were required of all airplanes with more than 10,000 flight-hours, and repeat inspections were required every additional 10,000 flight-hours. Boeing and the pump manufacturer are in the process of designing and qualifying a new inlet check valve and adapter that will eliminate the need for the periodic inspection mandated by the AD. The retrofit hardware will be available in July 2000 and will be incorporated into the airplane production line at line number 1252.

767 Center Tank Override/Jettison Pump Shutoff

Boeing Service Bulletin 767-28A0050, issued in December 1997, affects all 767 airplanes. Because of in-service failure of the inlet diffuser, this bulletin requests inspection of the pump every 1,000 flight-hours and replacement if necessary. As an interim operational measure, a Boeing operations manual bulletin and an FAA AD 97-19-15 were issued to require turning these pumps off at 1,000 lb of fuel remaining in the center tank. The AD also mandates the inspections requested by the SB. Boeing and the pump manufacturer are in the process of designing and qualifying a new pump with a cast-in inlet diffuser that will eliminate the need for inspections. The new hardware is expected to be incorporated into the production line and be available for retrofit in May 2000.

APPENDIX G: FLAMMABILITY SUMMARY

The basic fuel tank protection philosophy used for commercial and military aircraft has been one of precluding ignition sources from fuel tanks. Accidents involving fuel tank explosions are extremely rare events, so the basic philosophy of precluding ignition sources appears sound.

Reducing fuel tank flammability has been recommended by the NTSB and studied extensively by the FAA and the aviation industry. This appendix briefly summarizes the background, research, testing, and status of flammability-reduction efforts by Boeing, the FAA, the NTSB, and others in the aviation industry.

BACKGROUND

As stated above, the philosophy for fuel tank protection in both commercial and military aviation is to preclude ignition sources from fuel tanks. While it has been known that there are times when the fuel tanks are not flammable, the design philosophy makes the conservative assumption that the tanks are always flammable.

Flammability-reduction studies within Boeing and the industry have encompassed numerous areas. We have investigated and are continuing to investigate military designs to determine if any of them can be developed into practical and reliable systems for commercial aviation. In addition, we are studying the factors involved in fuel tank flammability to determine if *practical* flammability reduction can be achieved through temperature reduction, vapor purging, residual fuel reduction, or other means.

Some combat military aircraft use extensive additional measures to survive fuel tank penetration from hostile munitions. These systems introduce new safety risks and other secondary effects that even the military deems acceptable only for combat aircraft. Because the number-one cause of combat aircraft loss is attack by hostile munitions designed to ignite fuel tanks, extensive measures for combat aircraft outweigh the increased risks and other detrimental effects. However, the military, even in more recent acquisitions, generally does not incorporate these measures in aircraft that are not exposed to hostile munitions.

To evaluate proposals for reducing flammability, the complex factors that affect flammability must be understood. Unfortunately, there is no definitive industry standard for assessing the flammability of aircraft fuel tanks. Because past design practice was to conservatively assume that fuel tanks are always flammable, the detailed information needed to assess flammability reduction has not been developed. There has only been sufficient information developed to define the minimum energy level necessary for ignition. This energy level is generally accepted as 0.25 millijoules, to which Boeing applies a significant safety factor. The FAA performed a study of jet fuel flammability and reached the following conclusion:

> *"Th[is] report cannot offer a single definitive answer to the question of when fuel tanks contain flammable vapor, but it does identify the research necessary for a better understanding of fuel flammability in aircraft fuel tanks." (DOT/FAA/AR-98/26)*

RESEARCH

Practical fuel tank flammability reduction requires an understanding of all the factors that influence the limits of flammability and a robust means of gauging the relative benefit between fuel tank enhancement options.

Recent tests have been performed by California Institute of Technology, Southwest Research Institute, FAA William J. Hughes Technical Center, The University of Nevada at Reno, Arizona State University, and the U.S. Air Force in an effort to characterize the relationship between fuel temperature, liquid fuel mass to tank volume ratio (commonly referred to as mass loading), ambient air pressure, fuel vapor composition, and energy required for ignition of the fuel/air mixture. These studies have provided some good data toward establishing a definitive flammability standard.

Boeing has been analyzing the laboratory test data of Jet A fuel chemical characteristics and Jet A fuel vapor ignition. The objective is to determine the factors involved in flammability in an effort to quantify the percentage of time the fleet of aircraft is exposed to flammable fuel tank ullage conditions. Based on these analyses, Boeing has developed computer models—some of which are still under development—that predict:

- Fuel temperature histories for a matrix of Boeing aircraft mission profiles.
- Fuel vapor/air mixture concentrations (namely, the fuel–to–air-mass ratio, or FAR) as a function of fuel flash point, fuel temperature, ambient fuel tank pressure, and mass loading.
- The energy required for ignition of a fuel vapor/air mixture as a function of fuel–to–air-mass ratio, ambient fuel tank pressure, and mass loading.

The outputs to these three models are combined into the Boeing Flammability Exposure Model. The Flammability Exposure Model performs a comparative analysis that quantifies the relative benefits to fleetwide average flammability exposure and specific-risk flammability exposure between different fuel tank enhancement options.

Boeing has completed preliminary thermal analysis of the following options for reducing heat input into the CWT for several Boeing airplanes, including the 747-100.

- Pack bay ventilation.
- Duct insulation.
- Heat-shield installation.
- Metal air-conditioning pack bay doors.
- Use of ground source conditioned air when available at the gate.

These analyses quantify the thermal reduction potentially available for these options. Each option alone provides only a small reduction in CWT fuel temperatures. Although combinations of these options might further reduce CWT temperature, such a reduction may not be significant if flammable conditions would nevertheless occur in the CWT during some portion of the flight.

Boeing is continuing to study the available jet fuel test data and pursue additional data to establish a definitive standard to assess flammability enhancements. Once this awaited definition is available, these thermal reduction options, as well as the following potential flammability reduction measures, will be evaluated for their practical benefit.

- Unusable fuel quantity reduction.
- CWT fuel redistribution.
- Colder wing fuel recirculation.
- Nitrogen inerting (ground based and on board).
- Ullage sweeping.

GROUND AND FLIGHT TESTS

Three aircraft-level tests have been completed that assist in determining the flammability of the CWT on TWA 800 and provide some aircraft test data to assess potential enhancements. The results of these tests confirm that the CWT of TWA 800 would have been expected to contain flammable vapors at the time of the event.

Mojave Flight Test

Boeing conducted a test at Mojave, California, on August 26, 1996, to determine the thermal environment inside and under the CWT under conditions similar to TWA 800. Simulated conditions included fuel loading, ground and flight operation, and ambient conditions similar to TWA 800. The NTSB Fire and Explosion Group's request that the test be run under conditions similar to Flight 800 was generally followed, with the exception that three air-conditioning packs, rather than two packs as in the case of TWA 800, were run for two hours prior to takeoff. The 747-100 test aircraft center tank was instrumented with seven temperature probes. The three air-conditioning packs were run for two hours followed by takeoff and climb. The center tank fuel temperature reached 115°F and the ullage temperatures varied between 80°F and 95°F as a function of location. These temperatures remained approximately in this range throughout the flight.

Conclusion

Based on available data for flammability limits at the time of this test, it was generally accepted that the center tank bordered on the lean limit of the flammability envelope at the TWA Flight 800 accident altitude. This conclusion was based on Jet A fuel with a flash point of 113°F because a fuel sample from the Athens airport was determined to have this flash point.

JFK Flight Tests

In July 1997, nine flight tests were conducted from JFK airport on a leased 747-100. Details of the Flight Test Group's factual reports are found in Docket Items 23A, 23F, and 23H. The primary objective was a flight test to emulate the TWA Flight 800 flight conditions so that center tank temperatures and vapor concentrations could be measured. In addition, three flights with varying pack operation and two flights with additional center tank fuel loads were made to evaluate how these variables contribute to CWT heating. After the six NTSB investigation flights, Boeing leased the airplane to conduct three additional tests to evaluate concepts for reducing pack bay temperatures. For each flight, the configuration (except as noted) and flight profile (except as noted) were intended to duplicate those of TWA 800.

Before the start of the JFK flight tests, the center fuel tank was instrumented with thermocouples, pressure sensors, and vapor sample tubes. The center tank was totally emptied (undrainable fuel mopped out) to allow installation of the instrumentation. After closing the center tank, 50 gallons of fuel, intended for the CWT, were introduced into the aircraft refueling system with the center tank refueling valves commanded open.

The flammability of the center tank ullage is a function of the temperature of the center tank fuel puddle (a thin layer on the bottom of the nearly empty tank) as well as other factors (e.g., fuel composition). Our analysis of the JFK fuel temperature data (spikes that approach actual fuel temperature), together with data from the Marana test (see below), lead us to conclude that the fuel temperature of the puddle of fuel at the time of the TWA 800 event was approximately 130°F to 140°F. Based on this temperature estimate and the jet fuel test data, we conclude the CWT was well within the envelope to be considered flammable.

Two tests with additional fuel in the CWT were also conducted by the NTSB to evaluate the effects of carrying additional fuel in the CWT. The tests show that the partial loading of the CWT with fuel slows the temperature rise of the CWT fuel on the ground but also slows the rate of cooling after takeoff.

The effects of mass loading, as discussed in a study for the NTSB by the California Institute of Technology (Docket No. 20D) and measured with the vapor sample data during the JFK flight tests and the Marana ground tests, show that the addition of this partial load of fuel increases the concentration of fuel vapors in a tank. This increase offsets the desired benefit of temperature reduction from a partial load of CWT fuel. See the Desert Research Institute Factual Report titled, "*Analysis of Vapor Samples Collected From the Center Wing Tank of a 747-100 Aircraft During Ground Tests*."

Finally, Boeing performed three flight tests to evaluate some basic effects of pack bay cooling. The first test was a baseline flight to establish a basis for comparison for flights 2 and 3. The second flight had the No. 2 pack ram air inlet modified to divert the air into the pack bay (instead of feeding the number 2 pack, which was disconnected for this test) to evaluate the CWT temperature reduction with a crude pack bay cooling system. The third flight was with the baseline configuration of flight 1 but with the duct seals in the pack bay replaced to evaluate the effects of reducing air leaks in the pack bay. The tests concluded that ram air cooling would not provide a significant reduction in CWT fuel temperatures due to the heating on the ground prior to takeoff. Once the CWT is heated on the ground, it is difficult to accomplish significant cooling of the CWT by cooling the pack bay. Reducing air leaks in the pack bay also did not significantly reduce CWT temperatures.

Marana Ground Tests

Objective

The purpose of these tests was to evaluate the effectiveness of air-conditioning (A/C) pack bay pneumatic duct insulation in reducing peak temperatures of the 747 CWT. An additional ground test was also conducted to determine the peak temperatures of the CWT and adjacent areas from loading 12,000 lb of fuel in the CWT.

Baseline test. After instrumentation was installed and the tank closed, the CWT was fueled with 150 gallons and the scavenge pump was activated. After the completion of the duct insulation test, the CWT was drained, and it was confirmed the CWT had approximately 50 gallons during the baseline and duct insulation tests.

All three A/C packs were turned on to full cold for three hours. Despite an A/C valve problem, it was determined that the A/C system was operating sufficiently to continue with the baseline test. To maintain consistency between all the tests, no changes to the A/C packs were made. Vapor samples were taken at the end of each hour of the test.

Duct insulation test. The next day, insulation material was placed on the A/C pack bay pneumatic ducts. This test condition was repeated with all three A/C packs selected to full cold for three hours.

12,000-lb fuel loading test. The third test consisted of loading 12,000 lb of fuel in the CWT and operating the packs on full cold for three hours. Post-test results indicate the flashpoint of the fuel loaded was 123°F. The 12,000-lb CWT fuel temperature stabilized at 79°F shortly after fuel loading. All three packs were engaged to full cold and operated for three hours. At the third hour of testing, vapor samples were taken.

Test Results

Baseline and duct insulation test. The duct insulation effect on fuel, ullage, pack bay ambient temperature, and tank structure varied with location and airplane attitude. The peak average fuel temperature reduction, from the applied duct insulation, was 5°F. A/C pack bay average ambient temperature was reduced by approximately 6°F. Inside the CWT, the peak average ullage temperature was reduced 1°F to 2°F.

Baseline and 12,000-lb fuel loading test. The average fuel temperature differences from the baseline and 12,000-lb fuel loading tests at 1, 2, and 3 hours were 22°F, 26°F, and 23°F lower, respectively. A/C pack bay average ambient temperature was approximately 8°F lower. Inside the CWT, the average ullage temperature was 20°F lower.

The vapor samples from the baseline and 12,000-lb test showed that there was a negligible change in fuel vapors between the two tests. The flammability decrease expected due to the temperature reduction was offset by the increase in vapors due to the higher mass loading.

Conclusion

In summary, the addition of duct insulation showed a minimal lowering of the temperature by about 5°F for a nearly empty CWT. The addition of 12,000 lb of fuel showed negligible flammability change because the temperature reduction effect was offset by the increased mass loading effect. A more detailed test summary of the Marana test data and analysis was provided to the NTSB in July 1998.

1996 NTSB RECOMMENDATIONS AND FAA REQUEST FOR COMMENTS

In late 1996, the NTSB issued a series of recommendations as a result of the TWA 800 investigation. These recommendations were related to reducing exposure to operation with flammable vapors in fuel tanks. In 1997, the FAA issued a Request for Comment (RFC) to a series of questions generally based on the NTSB recommendations. Boeing participated with the worldwide aviation industry in submitting an extensive technical response to the questions on August 1, 1997.

In summary, the industry recommended formation of the Fuel Systems Safety Program (discussed elsewhere in this appendix); studies of reducing exposure to flammability, which led to the ARAC FTHWG (also discussed elsewhere in this appendix); and long-term action in the form of NTSB and FAA requests to the petroleum industry that it consider changes to jet fuel properties to reduce flammability (also evaluated by the ARAC FTHWG). The industry response to the RFC also provided specific replies to the questions posed by the FAA, which provided the industry's response to the NTSB recommendations as of July 1997.

The 1996 NTSB recommendations are listed below, together with a summary paragraph on the current actions taken by Boeing and the FAA.

A-96-174 Preclude Flammability in the Long Term

Require the development of and implementation of design […] 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.

As a result of this recommendation, Boeing, the aviation industry, and the FAA have and are continuing to evaluate changes to reduce the flammability of fuel tanks for an additional level of fuel tank safety. Changes evaluated include multiple forms of insulation or pack bay cooling, nitrogen inerting, and other design changes. These actions are detailed throughout in this appendix.

A-96-175 Preclude Flammability in the Short Term

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

(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 B-747, consideration should be given to refueling the center wing fuel tank (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.

As a result of this recommendation, extensive effort has been made to evaluate operational changes to reduce the flammability of fuel tanks. Boeing is developing a service letter recommending that operators use ground source conditioned air when available for servicing airplanes in lieu of running the APU and operating ECS air-conditioning packs (see also appendix F, *Operational Changes*).

Other operational changes evaluated include redistribution of fuel to CWTs, loading of colder fuel, and transfer of cold fuel. Ground and flight tests of redistributed fuel have been conducted. Details and conclusions are provided in this appendix under *Ground and Flight Tests*. Detailed thermal models have been developed and validated though aircraft tests to evaluate cold fuel and ground conditioned air. Details and conclusions are provided in this appendix under *Research*.

A-96-176 747 Handbook Changes for Center Tanks

Require that the Model 747 Flight Handbooks of TWA and other operators of Model 747s and other aircraft in which fuel tank temperature cannot be determined by flightcrews 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 limitations.

The Boeing flight and operations manuals do not contain information regarding temperature changes due to ground operation of the air-conditioning packs. Further, Boeing sent a message to all 747 operators to determine whether any other operators had a note similar to that found in the TWA manual. Responses from operators indicated two foreign operators with a similar note. One of the two operators (who had purchased their airplane from the second operator with the similar note) scrapped their only 747 and no longer operates 747 airplanes. TWA also no longer operates 747 airplanes. Boeing has requested the second operator to remove the note from their flight handbook.

A-96-177 Temperature Gauges for Heated Tanks

Require modification of the CWT of Model 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 the fuel tank temperatures.

In response to this recommendation, Boeing, as well as the FAA, has reviewed requirements for fuel temperature indication systems. The existing cockpit fuel temperature indication is for monitoring flight manual limits that ensure engine feed performance. Boeing has reviewed the procedures and the fuel temperature system indication and found them appropriate for this intended purpose. Boeing has evaluated potential operational changes to reduce fuel tank flammability (see A-96-175) and is continuing this effort. However, fuel tank flammable conditions currently exist to some extent on most flights. There are no practical procedures that the flight crew could take in-flight to change fuel tank temperature. Therefore, CWT temperature indication would not be beneficial to the flight crew. Boeing will continue to evaluate long-term changes to reduce flammability (see A-96-174) and will reconsider this recommendation if practical changes for flammability reduction are identified that would require flight crew action to control fuel temperature for the purposes of flammability reduction.

ARAC STUDY

Based on the comments on the NTSB 1996 Recommendations and the RFC, the FAA established an Aviation Rulemaking Advisory Committee (ARAC) working group called the Fuel Tank Harmonization Working Group (FTHWG).

The ARAC study concluded that the safety record of wing tanks was acceptable. ARAC also concluded that flammability levels of tanks without adjacent heat sources, or with directed ventilation, was similar to wing tanks. The conclusion of ARAC was that reducing flammability from the magnitude of heated tanks to that of unheated (and wing) tanks is a worthwhile goal.

ARAC evaluated “techniques to reduce or eliminate heat input to tanks from nearby heat sources” and concluded that “directed ventilation and relocation of significant heat sources reduce the exposure to an acceptable level.” While these changes were not found practical for in-service aircraft, the ARAC did “recommend that the FAA/JAA pursue a cost-effective approach to enhance aviation safety.” The ARAC proposed a new rule applicable to new designs that would limit flammability to “7% of the expected fleet operational time.” ARAC also evaluated other methods to reduce flammability of fuel tanks, including foam, suppression systems, inerting, and changes to jet fuel properties. None of these was found to be practical for incorporation in commercial aviation. ARAC also recommended further study of one form of nitrogen inerting, referred to as ground-based inerting (GBI). Information on the Boeing study of GBI is provided later in this appendix.

NPRM 99-18—PROPOSED FLAMMABILITY RULE AND INDUSTRY RESPONSE

This section provides a summary of the proposed FAR 25.981(c) rule change within NPRM 99-18 issued in October 1999 and the industry response. In this rule change, the FAA proposes that means be developed to minimize flammable vapors in fuel tanks or prevent catastrophic damage if ignition does occur.

In NPRM 99-18, the FAA proposes the following rule text:

> *§ 25.981 — Fuel Tank Ignition Prevention*
>
> *(c) The fuel tank installation must include—*
>
> *(1) Means to minimize the development of flammable vapors in the fuel tanks; or*
>
> *(2) Means to mitigate the effects of an ignition of fuel vapors within fuel tanks such that no damage caused by an ignition will prevent continued safe flight and landing.*

The industry agrees *in principle* with the FAA's overall intent to enhance the fuel system safety of future aircraft designs through measures to reduce fuel tank flammability exposure. The industry agrees that action should be taken, as identified by the ARAC FTHWG, "to address flammability mitigation as a new layer of protection to the fuel system." The industry further agrees that §25.981(c) should not be retroactively applied to existing type certifications, as that has not been shown to be practical.

The following discussion highlights concerns that the industry has with the proposed 25.981(c) regulation, and then presents several practical alternatives that should be considered.

Ongoing studies of fuel tank flammability have demonstrated that means to reliably quantify exposure to flammable fuel vapors do not currently exist. The FAA's Fuel Flammability Task Group, coordinated through the FAA Technical Center in Atlantic City, stated in its final report (DOT/FAA/AR-98/26):

> *Th[is] report cannot offer a single definitive answer to the question of when fuel tanks contain flammable vapor, but it does identify the research necessary for a better understanding of fuel flammability in aircraft fuel tanks.*

The FAA's proposed rule to require "means to minimize the development of flammable fuel vapors in fuel tanks" is problematic. The use of the term *minimize*, coupled with the uncertainty as to when fuel tanks contain flammable vapor, would result in a highly ambiguous rule. Findings of compliance with such a rule would be highly subjective, creating considerable uncertainty for the applicant. The FAA observes in the preamble of NPRM 99-18 that the "[d]evelopment of a definitive standard to address this recommendation will require a significant research effort that will likely take some time to complete."

Therefore, if the proposed rule is to be based upon the flammability of jet fuel, the industry believes that this rule should be postponed until a definitive, industry-recognized standard for assessing flammability is available.

The industry recommends that the FAA continue research to define practical standards by which to evaluate fuel tank flammability. This research should include evaluating the benefits of further flammability reduction as well as the potential costs of achieving such a reduction. This research could be performed in alliance with the industry through an ARAC committee. The desired outcome is the definition of standards for assessing flammability, which would in turn allow the development of practical, beneficial regulation.

In addition to recommending that a flammability rule not be implemented until the supporting studies are complete, we also recommend that the FAA harmonize this rule with non-U.S. regulatory authorities before it is implemented.

In the near term, a more meaningful rule could be proposed that would accomplish some degree of flammability reduction even though a definitive flammability standard does not exist. The industry suggests the current proposed rule be redefined to require *practical* measures to reduce heat transfer from adjacent heat sources into fuel tanks.

The industry's proposal avoids the current difficulties of assessing the level of fuel tank flammability and, at the same time, is responsive to the issue of fuel tank heating resulting from adjacent heat sources such as air-conditioning packs. The ARAC FTHWG evaluated various means of reducing fuel tank heating and concluded that concepts such as directed ventilation should be evaluated further as potential methods for meaningfully reducing the fleet average exposure to flammable fuel vapors.

GROUND INERTING

One of the concepts evaluated by the ARAC FTHWG was ground-based inerting (GBI). The concept is to purge the ullage of the CWT with nitrogen from a ground source to inert the tank. The study indicated that, providing the tank was less than 25 percent full at dispatch, the tank would remain inert until descent. While the ARAC estimates found the concept did not meet the FAA calculated benefit target, it was not grossly high (a factor of 10 or more) as were other concepts (such as onboard inerting systems). The ARAC FTHWG recommendations included that further study of GBI should be made. Since the ARAC report of July 1998, Boeing has continued to evaluate this concept.

Boeing's initial efforts were to determine what a conceptual system for a 747-size CWT would require in terms of line sizing and nitrogen volume. We have prepared a conceptual layout including studying where and how aircraft servicing would be done. We have done analysis to determine line sizing, a computational fluid dynamics analysis to determine if the proposed distribution system would purge the oxygen, and verified that noise requirements would not be exceeded. One of the concerns identified in the study (and during ARAC) has been whether the typical cross-vented system for a center tank would cause the inert nitrogen purge to be lost early in flight cycle. Unlike combat-type fighters, large commercial (and military) aircraft typically have the tanks "open" vented to atmosphere.

In response to the ARAC report, the FAA has also been studying the concept of GBI. One of the major questions that ARAC expressed about GBI was what the airport infrastructure would be to support GBI of aircraft. The FAA is studying this to determine the impacts.

As a part of its evaluation, the FAA has requested Boeing support of a ground and flight test to evaluate GBI of a CWT. Boeing is providing an airplane and test support to determine the effects of open cross-venting, the amount of nitrogen needed to reach an initial inert-tank level, and the effects of oxygen evolution from fuel loaded in the CWT. These factors are scheduled to be evaluated at Boeing within the next month in both ground and flight tests.

In summary, Boeing is working to evaluate whether GBI can be a practical method for reducing the flammability of commercial aircraft fuel tanks.

FUEL SYSTEM PROTECTION R&D

Boeing is working together with the FAA, NASA, and various DOD organizations to review, develop, and analyze potential technology opportunities to reduce flammable vapors in fuel tanks. Boeing has extensive experience in this area through past R&D activities and through current applications on military products such as the C-17, F/A-18, AV-8B, V-22, and AH-64 and RAH-66 helicopters. This includes a variety of protection technologies including foam, inerting, and detection/suppression systems. Boeing has also been involved in past studies of flammability reduction on commercial aircraft.

Through these various R&D activities, it has been recognized that there is no current fuel tank flammability reduction technique that is sufficiently robust to meet the high reliability and effectiveness standards that are required for high-volume commercial operations. Additional R&D is being conducted to identify and develop those technologies that may at some point be applied to commercial operations. Two examples of current cooperative government and Boeing R&D are the USAF TALON (total atmospheric liquefaction of oxygen and nitrogen) system and the NASA OBIGGS/OBOGS (onboard inert gas generating system/onboard oxygen generating system) study.

The TALON system is being developed under a joint program that includes Boeing and the USAF Research Laboratory. TALON would use an air-distillation process to separate engine bleed air into nitrogen and oxygen that may be used for multiple purposes including fuel tank inerting and passenger oxygen. The current R&D program plans to develop a test system for a flight test demonstration.

The NASA OBIGGS/OBOGS study is focused on commercial aircraft applications that include both fuel tank inerting and fire suppression using inert gas. This study has four major tasks, these being to define:

1. Aircraft requirements.
2. The state-of-the-art development in current systems.
3. OBIGGS/OBOGS system requirements.
4. Future research.

The first three tasks are expected to be complete in the first quarter of 2001. Future research will depend on findings from this and other related R&D activities.

CONCLUSION, ACTIONS, AND BOEING RECOMMENDATIONS

Boeing supports the concept of developing and implementing practical measures to reduce flammability to achieve an additional level of fuel tank protection. Boeing has expended considerable effort in pursuit of this potential enhancement.

The Boeing studies have led to the recommended use of ground conditioned air, as documented elsewhere in this submittal. Boeing is committed to further investigation of measures to incorporate practical flammability reduction.