DOT/FAA/TC-14/38

Federal Aviation Administration
William J. Hughes Technical Center
Aviation Research Division
Atlantic City International Airport
New Jersey 08405

Transport Airplane Fire Suppression System Field Survey Results

January 2015

Final Report

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Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
DOT/FAA/TC-14/38		

4. Title and Subtitle	5. Report Date
TRANSPORT AIRPLANE FIRE SUPPRESSION SYSTEM FIELD SURVEY RESULTS	January 2015
	6. Performing Organization Code
7. Author(s)	8. Performing Organization Report No.
Michel Bode and Michael Holle	
9. Performing Organization Name and Address	10. Work Unit No. (TRAIS)
Sandia National Laboratories Airworthiness Assurance Nondestructive Inspection Validation Center (AANC) 3260 Spirit Drive SE Albuquerque, NM 87106	11. Contract or Grant No. DE-AC04-94AL85000
12. Sponsoring Agency Name and Address	13. Type of Report and Period Covered
U.S. Department of Transportation Federal Aviation Administration Transport Airplane Directorate 1601 Lind Ave., SW Renton, WA 98057	Final Report
	14. Sponsoring Agency Code ANM-112

15. Supplementary Notes

The Federal Aviation Administration William J. Hughes Technical Center Aviation Research Division COR was Robert J. McGuire.

16. Abstract

Transport airplane fire suppression systems (FSS) located in cargo compartments are vulnerable to damage during heavy maintenance visits, as well as from cargo loading and unloading strikes. Injuries during maintenance activities can create impact or scuffing damage that is visually detectable, but might go undetected and lead to latent failures of the system, particularly the extinguishing media delivery tubing and dispensing nozzles. In 2011, Sandia National Laboratories Airworthiness Assurance Nondestructive Inspection Validation Center characterized the condition of the FSS tubing and nozzles in 35 transport airplanes using general visual inspection. These field surveys were performed during airplane heavy maintenance visits while the cargo compartments were opened for inspection and the FSS systems were completely exposed. Data from this survey support probabilistic inferences about the potential for an FSS failure during airplane operations. This study also highlights likely failure mechanisms through anecdotal data and, thus, aids maintenance engineers in determining what actions should be taken to prevent future damage.

17. Key Words	18. Distribution Statement
Fire suppression systems, Transport airplanes, Tubing, Nozzles	This document is available to the U.S. public through the National Technical Information Service (NTIS), Springfield, Virginia 22161. This document is also available from the Federal Aviation Administration William J. Hughes Technical Center at actlibrary.tc.faa.gov.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	21	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The authors want to thank American Airlines, Delta Air Lines, Southwest Airlines, Kalitta Air, FedEx® Express, United Airlines, and US Airways for hosting the field survey visits at their maintenance bases. Without air carrier participation, this work would not have been possible.

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LIST OF ACRONYMS

AANC	Airworthiness Assurance Nondestructive Inspection Validation Center
CFR	Code of Federal Regulations
ETOPS	Extended Range Twin Operations
FAA	Federal Aviation Administration
FSS	Fire Suppression System(s)
MRO	Maintenance, repair, and overhaul
NDI	Nondestructive Inspection

EXECUTIVE SUMMARY

This survey was conducted as the result of a concern that developed among Federal Aviation Administration engineers at the Transport Airplane Directorate about the integrity and, thus, the reliability of fire suppression systems (FSS) in cargo compartments of transport airplanes. The components in question are designed to defend against cascading failures, which could lead to catastrophic aircraft damage or loss in the event of an onboard fire in cargo compartments. Specific concerns include damage to dispensing nozzles during cargo loading and unloading operations, as well as workers accidentally stepping on the tubing during maintenance, which can cause pinching or kinking so that fire suppression media flow is restricted. Punctures in the tubing are also a concern. Additional damage, such as tubing connections pulling loose, can be caused by maintenance workers hanging extension cords, tools, or portable lights from the delivery tubing during work activities. U.S. domestic air carriers supported the survey by allowing Airworthiness Assurance Nondestructive Inspection Validation Center staff access to their airplanes during heavy maintenance visits. General visual inspections of the FSS in 35 transport airplanes were performed. The FSS components specifically inspected were tubing, connections, and nozzles. Inspection results were documented with findings of damage or no damage to each FSS, and digital photographs of the components were entered into a database. No significant damage or deficiencies were found in the FSS components of the 35 airplanes surveyed. A finding of no damage in the sample of 35 airplanes supports a statistical estimate of the probability of damage occurring in the U.S. domestic fleet based on the binomial probability distribution. From the results of this study (zero failures in 35 trials), it is inferred with 50% confidence that the probability of damage to tubes, connections, and nozzles in any FSS in the U.S. domestic transport airplane fleet is, at most, $p = 0.02$.

1. INTRODUCTION

1.1 PURPOSE

The Federal Aviation Administration (FAA) was concerned that the 20,000 flight hour inspection interval of fire suppression systems (FSS) could provide ample opportunities for system degradation, leading to failure in the event of a cargo compartment fire. This report describes a field survey of FSS installed in active transport airplanes in the U.S. air carrier fleet. The field survey was conducted by the Sandia National Laboratories Airworthiness Assurance Nondestructive Inspection (NDI) Validation Center (AANC) on transport airplanes that were undergoing heavy maintenance. Candidate airplanes for survey were those in which the interior panels and insulation blankets were removed to the extent that the FSS components were accessible for general visual inspection. A range of airplane models was selected based on availability at the time of survey visits, and operators participated on a voluntary basis. The specific components inspected during field surveys were extinguishing media delivery tubing, connections, and distribution nozzles. Thus, the purpose of this work was to gather data on the condition of the FSS components in the active U.S. air carrier fleet, specifically extinguishing media delivery tubing and nozzles. From this statistical sampling of the U.S. transport, airplane fleet probabilistic inferences about the potential for an FSS failure during airplane operations were made.

1.2 BACKGROUND

1.2.1 Accident History Caused by Onboard Cargo Compartment Fire

In the 1996 ValuJet Flight 592 incident, chemical oxygen generators improperly stored in a baggage compartment of a DC-9 airplane activated and caused an intense fire. The fire in the cargo compartment melted electrical wiring, flight control cables, and cabin floor panels, leading to the catastrophic loss of the airplane and killing all 110 people on board. As a result, the FAA issued revised rules in 1998 requiring the installation of cargo compartment smoke detection and fire suppression equipment on all passenger aircraft and installation of smoke detection equipment on all cargo aircraft. The “Revised Standards for Cargo or Baggage Compartments in Transport Category Airplanes, Final Rule,” amendments 25-07 and 121-269 effective March 19, 1998, eliminates Class D cargo compartments on newly certified aircraft under Title 14 of the Code of Federal Regulations (CFR) Part 25 and requires existing Class D compartments on 14 CFR Part 121 certified passenger aircraft to comply with the detection and suppression/extinguishing system aspects of Class C cargo compartment requirements by March 19, 2001 [1]. Cargo compartments previously certified as Class D have neither detection nor suppression systems and depend on limited oxygen availability in the cargo compartment to contain any fire that might occur by reducing it to a smoldering state [2]. These installations were given a 3-year compliance period so, by 2001, all U.S. transport airplanes were converted to meet either Class C or E standards. The Boeing Company began installing smoke-detection and fire-suppression systems into 737 production airplanes at line position 3078 for the 737-300/-400/-500 models and at line position 91 for 737-600/-700/-800 models as an example of implementing the FSS requirements. The production deliveries also included 195-minute Extended Range Twin Operations (ETOPS) configurations. The 195 minutes allow for

180-minute ETOPS diversion followed by 15 minutes for missed approach and emergency passenger evacuation.

1.2.2 The FSS Design and Maintenance

A Class C cargo compartment is one for which:

1. There is a separate approved smoke detector or fire detector system to give warning at the pilot or flight engineer station.

2. There is an approved built-in fire extinguishing or suppression system controllable from the cockpit. If a built-in fire extinguisher is provided:

    a. Each built-in fire extinguishing system must be installed so that:

        i. No extinguishing agent that will be hazardous to the occupants is likely to enter personnel compartments; and

        ii. No discharge of the extinguisher can cause structural damage.

    b. The capacity of each required built-in fire extinguishing system must be adequate for any fire likely to occur in the compartment where used, considering the volume of the compartment and the ventilation rate.

3. There are means to exclude hazardous quantities of smoke, flames, or extinguishing agent from any compartment occupied by the crew or passengers.

4. There are means to control ventilation and drafts within the compartment so that the extinguishing agent used can control any fire that may start within the compartment.

Therefore, Class C (passenger airplane standard) compartments have both detection and suppression equipment, and Class E (cargo airplane standard) certified cargo compartments have smoke/fire detection equipment only [1]. Figure 1 shows two typical FSS design concepts commonly used in single-aisle airplanes. It is important to note that all cargo compartments are fitted with a single FSS, although it may be assembled into two or more separate compartments (e.g., forward and mid/aft cargo compartments, depending on airplane model). Figure 2 shows examples of delivery tubing and connections, along with distribution nozzles. Tubing and connections are often protected from cargo by only the flexible cargo compartment liner. Nozzles are fully exposed to cargo at all times.

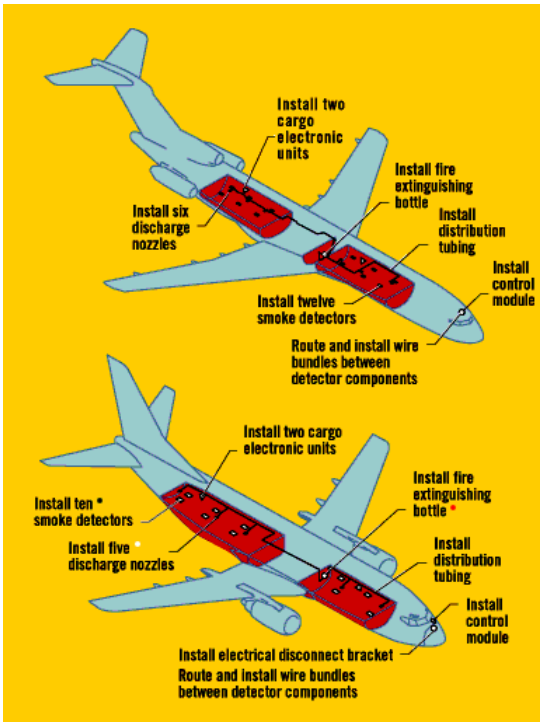

Figure 1. Typical Smoke Detector and FSS Components

(a) (b)

Figure 2. The (a) FSS Extinguishing Media Delivery Tubing and Connection, and (b) the Distribution Nozzle

To support operators in retrofitting their airplanes, Boeing developed modification kits, including revised documentation and the respective service bulletins. The Boeing portion of the kits included all hardware for installing the detection and suppression systems, including suppression media delivery tubes, control system wire bundles, support brackets, detector pans, suppression pans, extinguishing media delivery nozzles, and all standard-type hardware. An additional buyer-furnished equipment hardware kit was also required. Dillingham stated in his 1997 GAO report [3] that there were two FAA-approved Boeing suppliers of smoke detection and fire suppression retrofit kits and that two carriers had worked with other vendors to develop retrofit

kits for their airplanes. However, regardless of the manufacturer, all systems use essentially the same components and, therefore, are functionally equivalent. Additionally, the retrofit systems use the same components as the production systems installed in new airplanes. Therefore, no effort was made to distinguish between retrofitted and new production FSS during the field survey. The main assumption was that all FSS were operationally equivalent and used the same components, except for the extinguishing media bottles, which were not included in this survey. Another assumption is that all systems have been in place for up to 12 years, unless the airplane went into service after the 2001 compliance date, in which case systems were installed as part of the airplane original equipment and are the same age as the airplane. Therefore, all FSS inspected were in service for at least one heavy maintenance interval and were exposed to potential injury at least once.

Whereas FSS receive routine inspection and maintenance at intervals established by Industry Steering Committee Maintenance Review Boards, the cargo compartments in which they operate are an area of airplanes known to experience high rates of damage from loading and unloading activities, as well as cargo shifting. Additionally, certain components of FSS are exposed during heavy maintenance activities and could suffer unnoticed injury during other maintenance work. Therefore, the FAA was concerned damage could occur between inspections without being reported, leading to a cascading failure in the event of a cargo compartment fire. Additionally, since the implementation of the FSS requirements in 2001, no formal research has been conducted on the actual condition of these backup systems after a long period of continued airplane operation.

2. FIELD SURVEY OF IN-SERVICE AIRPLANES

2.1 STATISTICAL BASIS

One goal of the field survey was to gather enough quantitative data to make an estimate of expected frequency of damage to the FSS components of concern in the U.S. domestic transport airplane fleet. A binomial probability experiment [4] was designed and implemented to meet this goal. Binomial probability experiments are made up of repeated independent trials of a basic experimental act with only two possible outcomes—success or failure. The basic experimental act was performing a general visual inspection of the FSS components of interest in one airplane. The FSS components were defined as either undamaged (successful trial) or damaged (failed trial) and, therefore, met one requirement of a binomial probability experiment (only two possible outcomes). Performing independent general visual inspections of FSS components on separate airplanes met the other requirement (repeated independent trials). The appropriate sample size was determined by calculating the number of independent samples needed to obtain an upper bound for the probability of failure with a reasonable confidence level in the case for which no failures (damaged FSS components) were expected to be observed. This is known as a zero-failure sample plan. In practical terms, the sample size was the number of FSS to inspect during the field survey, assuming one FSS per transport airplane.

Table 1 lists sample sizes required at four confidence levels if there are no observed failures to obtain an upper bound for the failure rate of 2%. For example, if 114 independent FSS components were sampled and zero failures were observed, it could be concluded with 90%

confidence that the failure probability was, at most, $p = 0.02$. Based on the project resource constraints, a 0.5 confidence level was targeted for calculating sample size. Therefore, the initial sampling goal was set at 35 airplanes, meaning if no damage was found in the sample, with 50% confidence, the probability of damage occurring in any FSS in the population of U.S. transport airplanes would be, at most, $p = 0.02$. In cases for which damaged FSS components were found, larger sample sizes would be required to conclude the probability of damage was less than $p = 0.02$ with the same confidence level. Table 2 summarizes these sample sizes for up to five observed failures. For example, if one FSS was observed to be damaged, then a sample of 84 airplanes would be required to conclude with 50% confidence that the failure probability was, at most, $p = 0.02$.

Table 1. Number of Airplane Samples Required at Four Confidence Levels With Probability of Damage to Individual FSS Components Assumed at $p = 0.02$

Failure Probability to Demonstrate	Confidence Level (1-α)	Number of Failures Allowed	Sample Size (N)
0.02	0.99	0	228
0.02	0.95	0	149
0.02	0.90	0	114
0.02	0.50	0	35

Table 2. Sample Sizes Required at the 50% Confidence Level With $p = 0.02$ Assumed Probability and up to Five Occurrences of Damage to the FSS for a Given Airplane

Number Failed	Sample Size
0	35
1	84
2	134
3	184
4	234
5	284

Damage to the tubing, connections, and delivery nozzles would have a negative effect on the reliability of overall FSS. System components were defined as being undamaged and, therefore, expected to operate properly if no significant damage was observed and documented during general visual inspections. If damage to the extinguishing media delivery tubes, connections, or nozzles was found during visual inspections, the system was defined as damaged and not expected to operate properly. Whereas other system components could fail and compromise the system operability, the focus for this survey was on components that have an apparent propensity for damage during routine operations and regular maintenance activities. Other system components, such as pressurized bottles containing extinguishing media, system electronics, valves, and switches have been the subject of other reliability estimates made by the manufacturers during system certification applications, so they were not included in this survey.

Because no prior data existed on the proportion of FSS tubes, connections, and nozzles that actually fail in service, a target value of 2% was used as a conservative starting point for the purpose of sizing the sample.

Damage for tubes was defined as any crushing or pinching that caused a decrease in the cross-sectional area of 10% or more and any cracks or punctures of any size. Tube fittings at connections were deemed undamaged as long as they were not obviously disconnected or loose in a way that would cause leaking or loss of pressure. Nozzles were defined as operable if all openings were not obstructed and the main nozzle body was not cracked or otherwise damaged in a way that would prevent the proper spray pattern of the extinguishing media.

All transport airplane makes, models, and submodels operated by U.S. air carriers were treated as one population for sampling purposes. Whereas random samples are usually preferred in any statistical experiment, samples in this case, for practical reasons, were determined more by airplane availability than by any other factor. Accepting that the sample size would ideally be larger given more resources, it still appears that a reasonable cross section of operators and airplane models was obtained, as shown in table 3. Therefore, a probability statement for the condition of FSS components of interest for all the airplanes in the U.S. domestic fleet can be made. A total of 35 transport airplanes was sampled in the survey and was chosen by calculating the number of trials (airplane FSS inspections) required with no failures (defined as damage existing to the tubing, connections, or nozzles) to achieve at least an upper bound on the failure probability of 0.02 with 50% confidence. If one or more failures are observed, probabilities can then be calculated based on the number of observed failures (number of times damage was observed in the FSS components of an airplane) for a desired confidence level.

Table 3. The U.S. Air Carriers Participating in FSS Field Surveys

Operator	Aircraft Model	Number of Airplanes Surveyed
American Airlines	737-800	6
	757-200	3
	MD-80	6
Delta Airlines	757-200	2
	A319-100	1
FedEx	DC10-10	1
	MD10-10	4
Kalitta Air	747-200	1
Southwest Airlines	737-700	4
United Continental	757-200	3
	A320-200	3
US Airways	A330-300	1
	Total of All Models	35

2.2 AIR CARRIER SUPPORT

To obtain quantitative data on existing damage in the operational FSS components of interest, a field survey was conducted at several U.S. carrier maintenance bases. Airplanes receiving heavy maintenance typically have all interior panels and insulation blankets removed to facilitate inspection and repair activities. Full access to the FSS components of interest is readily available during such heavy maintenance visits, although the systems might not undergo inspection if between the 20,000 flight hour inspection intervals. Several major U.S. carriers were asked to participate in the field survey by allowing AANC staff to perform general visual inspection of the FSS components in their airplanes during heavy maintenance. Table 3 also lists the carriers who participated in this survey, as well as the airplane models and number of each model included in the survey. A total of seven carriers participated, two of which were exclusively cargo carriers; the other five were major passenger carriers. A reasonable cross section of common transport airplane makes and models was obtained, which included Boeing 737, 747, and 757 models; McDonnell Douglas MD-80 and MD-10 models; and Airbus A319/320 and A330 models. A total of 35 airplanes were inspected during the survey.

Whereas more samples from twin-aisle passenger airplanes would have been appropriate, it was not possible to find many. One difficulty with scheduling twin-aisle airplanes for field survey visits was that very few carriers still perform maintenance of wide-body aircraft domestically. The trend among U.S. carriers is moving heavy maintenance checks for twin-aisle airplanes to overseas maintenance facilities as a cost-cutting effort. Because narrow-body aircraft are restricted by ETOPS limits from most ocean crossing, they are still undergoing heavy maintenance checks domestically, often at third-party maintenance, repair, and overhaul (MRO) shops. However, maintenance work is being shifted to Central American countries into which narrow-body aircraft can fly without meeting ETOPS requirements. These circumstances increased the difficulty of scheduling visits to maintenance bases; however, at the end of the project, there was no indication of negative impacts due to not performing formal random sampling of airplanes.

Field survey trips were scheduled so that the number of aircraft inspected could be maximized on every trip and minimized on repeat trips to each operator. When possible, visits to different operators were scheduled on the same trip to reduce the total number of trips needed. A total of 12 trips were taken between December 2011 and April 2012. Whereas seven air carriers participated in the study, eight different maintenance bases were visited, two of which were third-party MROs to a major U.S. carrier.

2.3 THE FSS INSPECTION PROCESS

The process for completing a field survey of an aircraft was to perform a general visual inspection of all components of interest. Inspections were performed by NDI engineers from the AANC familiar with visual inspection processes. Flashlights and mirrors commonly used in visual inspection processes were used when required. The condition of each FSS component was documented with digital photos as much as possible. Limits on photographing some sections or components were occasionally encountered because of limited physical access in certain locations. All indications of damage were documented and assessed further to determine

whether each would have led to a failure of the system. The digital photographs were assembled into a database based on the date of field survey, location of maintenance base, and air carrier. Additional information on individual airplanes was stored in a Microsoft® Excel® spreadsheet with a link to the corresponding photographs. Because of the nature of heavy maintenance, photographs could not always be taken for every section of the FSS. If the FSS could be seen and examined, even without the photographs, the aircraft was counted toward the final count. Table 4 provides the total number of each make and model of transport airplane inspected during the field survey.

Table 4. Count of Airplane Make and Model Inspected During the FSS Field Survey

Make	Model	Count
Boeing	737	10
	747	1
	757	8
Airbus	A319	1
	A320	3
	A330	1
Douglas	DC10	1
McDonnell Douglas	MD-10	4
	MD-80	6
Total	DC10	35

3. FIELD SURVEY RESULTS

Figure 3 shows typical cargo compartments in both operational and heavy maintenance configurations. Note that the cargo liners shown in the picture on the left are relatively thin, flexible fiberglass panels that offer limited protection against puncture or crushing. During prior studies on visual inspection of airframes performed at the AANC, industry inspectors often noted that cargo compartment structural components suffer more damage than other portions of the airframe. The increased damage is a direct result of cargo handling and cargo shifting during flight. Another issue to note is the relative exposure of the FSS components to maintenance activities when cargo liners are removed, as shown in the picture on the right. It is not uncommon to see items such as extension cords, fastener bags, or temporary air ducting hanging from components of the FSS during heavy maintenance activities.

(a) (b)

Figure 3. Single-Aisle Cargo Compartments in (a) Operational Configuration and (b) Heavy Maintenance Configuration

Of the 35 airplanes FSS surveyed, no damage was found that could have led to inoperability of the system. Table 5 lists the inspection results for each airplane FSS inspected and also includes the specific carriers, airplane models, cargo compartment configurations, flight hours, and flight cycles for each airplane.

Table 5. The FSS Inspection Results for 35 Transport Airplanes

Airplane Number	Air Carrier	Airplane Model	Forward Cargo Bay	Mid Cargo Bay	Aft Cargo Bay	Damage Found	Total Hours	Total Cycles
1	American Airlines	737-800	Y	N	Y	N	35794	14863
2	American Airlines		Y	N	Y	N	35799	14840
3	American Airlines		Y	N	Y	N	34777	14767
4	American Airlines		Y	N	Y	N	35408	14764
5	American Airlines		Y	N	Y	N	X	X
6	American Airlines		Y	N	Y	N	34581	14360
7	American Airlines	757-200	Y	N	Y	N	66514	18656
8	American Airlines		Y	N	Y	N	40399	10390
9	American Airlines		Y	N	Y	N	67388	18876
10	American Airlines	MD-80	Y	Y	Y	N	68155	35849
11	American Airlines		Y	Y	Y	N	67847	35682
12	American Airlines		Y	Y	Y	N	56962	35360

Table 5. The FSS Inspection Results for 35 Transport Airplanes (Continued)

Airplane Number	Air Carrier	Airplane Model	Forward Cargo Bay	Mid Cargo Bay	Aft Cargo Bay	Damage Found	Total Hours	Total Cycles
13	American Airlines	MD-80	Y	Y	Y	N	34824	16841
14	American Airlines	MD80-82	Y	Y	Y	N	68191	35963
15	American Airlines	MD80-83	Y	Y	Y	N	55330	26716
16	Delta Airlines	757-200	Y	N	Y	N	X	X
17	Delta Airlines		Y	N	Y	N	X	X
18	Delta Airlines	A319-100	Y	N	Y	N	31741	16459
19	FedEx	DC10-10	Y	N	Y	N	78221	27490
20	FedEx	MD10-10	Y	Y	Y	N	79742	33003
21	FedEx		Y	Y	Y	N	74320	27169
22	FedEx		Y	N	Y	N	70295	31787
23	FedEx	MD10-30	Y	Y	Y	N	62131	19680
24	Kalitta Air	747-200	Y	N	Y	N	92249	14119
25	Southwest Airlines	737-700	Y	N	Y	N	21551	12775
26	Southwest Airlines		Y	N	Y	N	21133	12379
27	Southwest Airlines		Y	N	Y	N	21595	12725
28	Southwest Airlines		Y	N	Y	N	43516	25118
29	United Continental	757-200	Y	N	Y	N	72487	27214
30	United Continental		Y	N	Y	N	61124	21665
31	United Continental		Y	N	Y	N	74597	22932
32	United Continental	A320-200	Y	N	Y	N	60511	22731
33	United Continental		Y	N	Y	N	60300	22549
34	United Continental		Y	N	Y	N	54962	20532
35	US Airways	A330-300	Y	N	Y	N	50051	7093

On two occasions, small bends in the FSS tubes were noted. The reduction in diameter was measured for each and the associated reduction in cross-sectional area of the tube was calculated. The bends caused an internal reduction in cross-sectional areas of less than 10%. This level of deformation in the tubing did not meet the definition of damage that was established. Whereas the actual cause of bending was not identified, it is believed the bending could be the result of a misstep during maintenance when the floor boards were removed or from being impacted by a heavy dropped object. Figure 4 shows the extent of bending on one of the tubes.

Figure 4. Bend in FSS Extinguishing Media Delivery Tube

On another occasion, a small amount of blockage of the FSS nozzle was documented. The debris was not firmly attached to the nozzle and would have been expelled had the system been used. The debris was most likely a combination of rubber from the cargo power drive unit and dust. Figure 5 shows the blockage of the nozzle.

Figure 5. Partial Port Blockage of an FSS Nozzle

4. CONCLUSIONS

General visual inspections of the fire suppression system (FSS) in 35 in-service transport airplanes in the U.S. domestic fleet were performed. A variety of airplane makes and models being operated across several carriers were included. The FSS in all cargo compartments of a given airplane were inspected, and each airplane represented one trial in a binomial probability experiment. The FSS components specifically inspected were tubing, connections, and nozzles. Inspection results were documented with findings of damage or no damage to each FSS and digital photographs of the components were entered into a database. No significant damage or deficiencies were found in the FSS components of the 35 airplanes surveyed. Minor damage was identified in three instances, but after further investigation, it was determined not to have adverse

effects on the functioning of the overall system. Therefore, those instances were not deemed as damaged for the purpose of the binomial experiment and probabilistic statements on the potential for damage occurring in the U.S. fleet. A finding of no damage in the sample of 35 airplanes supports a statistical estimate of the probability of damage occurring in the U.S. domestic fleet based on the binomial probability distribution. From the results of this study (zero damage or failures in 35 trials), it is inferred with 50% confidence that the probability of damage to tubes, connections, and nozzles in any FSS in the U.S. domestic transport airplane fleet is, at most, $p = 0.02$.

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