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Transport Airplane Hydraulic Fuse Functional Reliability Study

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Final Report

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16. Abstract Hydraulic fuses can have latent failures. Certain latent failures of fuses coupled with another type of failure may result in an unsafe airplane condition. The goal of the Transport Airplane Hydraulic Fuse Functional Reliability Study was to determine whether critical latent failures exist on removed hydraulic fuses and, if so, determine the failure rate. There are two types of hydraulic fuses used in transport category airplanes: those that trigger on flow rate and those that trigger on a specific fluid loss volume. For this study, rate fuses (2-7680 and 2-7681) and volume fuses (2-8020 and 2-8041) were tested. Sandia National Laboratories (SNL), working with the FAA, partnered with Delta Air Lines to test fuse functionality after in-service removal. Delta Air Lines performed the component maintenance testing. SNL determined the failure mechanisms, analyzed the data, and assessed the failure mechanisms and rates. The safety impact assessment was supported by the FAA Transport Airplane Directorate in line with standards Title 14 Code of Federal Regulations (CFR) Part 25 25.903(d)(1), 14 CFR 25.631, and 14 CFR 25.1309. SNL characterized the fuses in the study by examining time from fuse and plane manufacture, time from the previous fuse inspection, and reported previous fuse repairs. The following failure frequencies associated with two outcomes were calculated: whether the fuse failed any of the acceptance tests and whether the fuse failed to set. An estimated 25% of rate fuses and 68% of volume fuses failed at least one step in the maintenance routine inspection process. The rates of latent failures were lower, with an estimated 11% of rate fuses and 6% of volume fuses failing to cut off hydraulic flow.					
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LIST OF ACRONYMS

CFR	Code of Federal Regulations
CI	Confidence interval
MRB	Maintenance Review Board
NPRD	Nonelectronic Parts Reliability Data
SNL	Sandia National Laboratories

EXECUTIVE SUMMARY

Transport category airplanes have a number of mechanical systems that receive periodic inspections of critical components. The FAA is concerned about components installed on airplanes that fail without detection (latent) and leave the airplane one failure away from a catastrophic event. The FAA and other regulatory agencies require periodic inspections to limit latency on flight-critical components. These limitations ensure that the catastrophic event is extremely improbable ($<10^{-9}$). Hydraulic fuses can fail latently and leave the airplane vulnerable. Hydraulic fuses are designed to close when they sense a sudden increase in hydraulic fluid flow (rate fuses) or when a certain volume of fluid has passed through (volume fuses), thereby preserving hydraulic power to all services upstream of the fuse, including other flight-critical systems. Hydraulic fuses are typically used in brake systems, high-lift systems, nose landing gear up and down lines, and the thrust reverser pressure and return lines. Volume fuses are also used to limit the amount of hydraulic fluid that can feed a fire (e.g., in airplane braking systems).

The goal of the Transport Airplane Hydraulic Fuse Functional Reliability Study was to determine the functionality at inspection of hydraulic fuse components on transport category airplanes and determine failure rates. Sandia National Laboratories (SNL) staff studied the functional reliability of hydraulic fuses at different flight hours/flight cycles for each model of hydraulic fuse. For this study, SNL and Delta Air Lines tested four models of hydraulic fuses for functionality after removal from service. To complete the goal of this study, SNL determined the fuse failure mechanisms and analyzed the data to determine the reliability values for each category of hydraulic fuse.

SNL tested 151 fuses: 44 flow rate and 107 volume-type hydraulic fuses. By part number, 60 2-8020 volumetric fuses, 30 2-7680 flow rate fuses, 14 2-7681 flow rate fuses, and 47 2-8041 volumetric fuses were tested. The authors characterized the population of tested fuses by examining properties of the fuses and their history (i.e., recording the airplanes they came from, time from manufacture, and time from the previous inspection). Most fuses tested were at least 12-years old and previously inspected within the last 5–8 years. A review of maintenance planning documents found that hydraulic fuses are typically scheduled for removal after approximately 25,000 flight hours.

The failure frequencies associated with two primary outcomes were assessed: whether the fuse failed any of the maintenance tests and, specifically, whether the fuse failed to set. Failure to set is a latent failure in which the hydraulic fuse never fuses, leaving the airplane one failure away from catastrophe. This study focused on the frequency of failure rather than the time to fuse failure or the failure rate. The authors were not able to accurately characterize the expected times or rates at which fuses would fail in this study because of the data collection methodology. Specifically, some fuses were removed for cause, whereas some were removed because of scheduled maintenance. In addition, the authors do not have an exact measure of the time in which all of the fuses have been in use (e.g., flight hours, cycles, calendar years, etc.). However, examining fuse aging patterns may not be a critical question because fuses are mechanical parts that are used infrequently and, therefore, may not wear out or age substantially over time. Fuse failures associated with, for example, fluid cleanliness, purity, tolerances, and hysteresis may be more likely, but were beyond the scope of this study.

This study found that 68% of volume fuses and 25% rate fuses failed at least one test step of the routine inspection; however, rates of latent failures were lower, with an estimated 6% of volume fuses and 11% of rate fuses experiencing latent failures. The failure frequency is highest for the 2-8041 (94% failing at least one test step); this is likely because only fuses that failed on-plane screenings were tested off-plane and included in this study.

1. BACKGROUND

This section is a review of the role of hydraulic fuses in transport airplane safety and a description of this study to characterize failure rates of these fuses.

1.1 AIRPLANE CERTIFICATION AND LATENT FAILURES

Design standards for transport airplanes are contained in Title 14 Code of Federal Regulations (CFR) Part 25. The standard that directly relates to reliability of hydraulic fuses is 14 CFR 25.1309, a requirement that multiple failures be considered during the airplane design process. Designers often incorporate fluid fuses to preserve a hydraulic system in the event that a downstream rupture occurs. Without the fluid fuse, a rupture could lead to catastrophe. Latent failures are undetected failures and, when found in a hydraulic system, may leave an airplane one failure away from catastrophe. Title 14 CFR 25.1309 addresses latent failures and requires that latency periods be limited such that catastrophes will not occur in the life of the model of an airplane. For multiple failures, this is usually a probability on the order of $1e-9$ [1]. Note that most fuse failures are detectable. For example, leakage is detected by loss of hydraulic fluid. If the fuse sets prematurely, there is usually a loss of some kind of system performance, such as loss of yaw damping. However, a latent failure that prevents the fuse from stopping hydraulic flow will be undetected without testing.

1.2 PURPOSE AND USES OF HYDRAULIC FUSES

Hydraulic power systems provide means for pilots to operate different aircraft components such as landing gears, flaps, flight control surfaces, and brakes [2]. To provide redundancy in the aircraft, there are multiple, independent hydraulic power systems for different aircraft components. The hydraulic power systems in transport aircraft are large and complex and are critical to the operation of most transport airplanes [2]. Though transport airplanes usually have multiple hydraulic systems to provide redundancy, hydraulic fuses are a critical component to prevent several catastrophic events.

On August 12, 1985 at Gunma Prefecture, a Boeing 747 (Japan Airlines Flight 123) experienced a catastrophic event when an explosive decompression severed all four hydraulic lines resulting in a complete hydraulic pressure loss that severely degraded the pilot's ability to control the airplane [3]. The decompression was caused by a local fatigue crack in the aft pressure bulkhead, which initiated from a faulty repair completed several years prior to the accident [3]. With the complete loss of all hydraulic power systems, Flight 123 flew for approximately 30 minutes before crashing in the mountainous terrain of Gunma Prefecture, Japan. Of the 524 passengers and crew on board, only four survived.

There have been other catastrophic accidents involving the loss of hydraulic system functions. For example, in 1989, United Airlines Flight 232, in Sioux City, Iowa, had an uncontained engine fan disk sever three of the hydraulic systems that powered the aircraft's flight controls. The pilot's only means of control was differential thrust. There were 111 people fatally injured [4]. Though hydraulic fuses would not prevent the aft pressure bulkhead from cracking in the Japan Airlines Flight 123 accident or the fan disk from breaking in the United Airlines Flight 232 accident, hydraulic fuses could have preserved one or more of the hydraulic systems, thereby

allowing the pilot to maintain the necessary control to land the airplane safely. The use of hydraulic fuses in airplanes has supported airplane designs to maintain flight control capability after particular risks such as bird strikes or uncontained engine failure. Hydraulic fuses are also used to reduce the amount of hydraulic fluids spilled onto hot brake components, which could lead to a catastrophic fire. In both cases, failure of the hydraulic fuse to set at the appropriate time could result in catastrophic consequences.

The purpose of this study was to determine, through testing, the reliability of fuses used onboard transport airplanes. It is hoped that airlines and transport airplane manufacturers can use this information to validate/revise the maintenance intervals they use to test these components.

1.3 HYDRAULIC FUSE DESIGN

Hydraulic fuses commonly used today in transport airplane systems are mechanical components. They typically consist of a cartridge, sliding components, springs, seals, and connecting elements that allow them to be directly inserted into hydraulic lines. The internal components, such as slides, contain hydraulic flow passages that meter flow rate or volume and cause the fuse to set appropriately such that no further fluid may pass through the fuse. The springs typically provide reset capability such that when pressure is removed from the system, the slide will translate back to the unfused state. Like their electrical counterparts, hydraulic fuses normally allow fluid to flow through them until it reaches a predetermined point, at which time the fuses cut off all flow. As such, these mechanical devices rarely trip.

1.4 HYDRAULIC FUSE FAILURE CHARACTERISTICS

Because hydraulic fuses are purely mechanical devices with hydraulic fluid flowing through them, and because they do not experience much activity, failure characteristics may be reserved to fractures, friction/hysteresis, clogging, and jamming. With little activity, fuses do not see much wear. However, it is possible that fluid flowing through passages might cause erosion. In addition, because of the potential for hysteresis, clogs, and jams, some failures might occur only intermittently. These types of failure modes are difficult to characterize in a preventive maintenance program, and testing of many fuses may be the only method by which reliability can be determined.

1.5 HISTORICAL HYDRAULIC FUSE FAILURE RATES

Nonelectronic Parts Reliability Data (NPRD) 95 identifies a blanket failure rate for hydraulic fuses at $1.61e-6$ failures per flight hour. This rate is based on a report published in 1962 [5]. There are no failure rates related directly to failure modes, such as a failure to set. The authors did not find much additional data on failure rates in the literature. This study provides a better understanding of hydraulic fluid fuse reliability.

1.6 STUDY PURPOSE

The purpose of this study was to:

- Collect hydraulic fuse data from in-service transport category airplanes.
- Determine failure frequencies for both evident and latent failures.
- Develop results that can be used by airlines and transport airplane manufacturers to validate/revise hydraulic fuse maintenance intervals or design.

1.7 STUDY DESIGN

This study examined 151 hydraulic fuses from 27 different transport planes. Of the 151 hydraulic fuses, five fuses came from salvage yards, and the rest came from Delta Air Lines. Initially, all of the hydraulic fuses were going to be purchased from salvage yards and then inspected at Delta Air Lines TechOps in Atlanta. Because of the difficulty in purchasing hydraulic fuses with the necessary part history information from salvage yards, Sandia National Laboratories (SNL) partnered with Delta Air Lines to inspect the majority of the hydraulic fuses already being serviced by Delta Air Lines TechOps in Atlanta. All fuses were manufactured by Dowty Aerospace in Yakima, Washington.

Most fuses included in the study were installed in Delta Air Lines' transport category aircrafts, though some were installed in non-Delta Air Lines airplanes. For each fuse taken from a Delta Air Lines plane, additional information about the plane was also collected. This additional information included plane tail number, flight hours for the plane, flight cycles for the plane, date of manufacture of the plane, date of manufacture of the fuse, and last date of installation for the fuse. No additional information was available for the non-Delta Air Lines planes.

To obtain the last inspection date for the Delta Air Lines fuses, the authors assumed that the date of last inspection corresponded to the date of last installation, which is available in appendix A. This assumption could be made because this inspection was part of the Delta Air Lines maintenance program. Note that if a fuse failed at a previous inspection and was discarded and replaced, that fuse would not be included in the collected data. Therefore, the study population only consisted of fuses that survived the previous inspections.

1.7.1 Data Analysis Methods

To determine the functionality of hydraulic fuses in transportation category aircraft, two analyses were conducted:

- Characterization of fuse failures
- Estimation of time to fuse failure

Fuses can fail in different ways, and some failure mechanisms lead to catastrophic events. Specifically, fuses can fail by fusing immediately, fusing too early, fusing too late, never fusing, and inconsistent fuse failure timing across tests (e.g., early on one test and late on another). Based on the failure mechanisms, this study distinguishes between evident failures and latent failures. Evident failures are defined as failures that flight crews might detect in service. A latent

failure is defined as a failure that would not be detected by the flight crew until the fuse was needed. For the tests conducted in this study, a latent failure is identified when the hydraulic fuse never sets/closes.

First, failure frequencies were estimated based on data collected from testing for each part number. Estimates are presented for evident failures and latent failures. Confidence intervals (CIs) are calculated to characterize uncertainty in failure frequencies using the binomial distribution for binary outcomes. Because fuse failure is a binary outcome, the binomial distribution (for independent binary outcomes) is used to draw inferences about the fuse failure frequencies. CIs are interpreted as follows: considering the fuses in this study are a random sample of fuses receiving routine screening, there is 95% confidence that the true fuse failure frequency on routine screening is within the CI. Next, the number of failures and failure mechanisms are tabulated by part number among fuses that failed any test to determine the most prevalent failure mechanisms. An assessment was completed to find whether there was evidence of an association between failure mechanism and part number/type using Fisher's exact test.

Failure time modeling was used to estimate the time to failure for fuse part numbers with sufficient failures. Failure time analysis modeling is a tool for understanding when a fuse is expected to fail. Failure time modeling provides the most information when failure times of all the test articles are known (e.g., the exact date or flight hours at which the fuse became defective). In this study, exact failure times are unknown; only the failure status at the time the fuse was tested is known. Because of the lack of precision in failure times and the small number of failures, the failure time analysis does not provide much additional information for this study but was included for the sake of completeness. To estimate the time at which a certain percentage of fuses will fail, the number of flight hours was used as the time scale and it was assumed that fuse failure times follow a Weibull distribution. The Weibull distribution is a two-parameter distribution that is frequently used to characterize failure distributions. This study uses "any failure" as the outcome and does not include latent failures as an outcome for this analysis because the number of latent failures is too small. More details of the failure time modeling are available in appendix B.

An approximate fuse failure rate was calculated by dividing the number of fuse failures by the total number of fuse flight hours ($\# \text{ failures} / [\# \text{ fuses} \times \text{flight hours per fuse}]$). All fuses have approximately 25,000 flight hours until their required inspection. This maintenance interval is conservative as a latent failure rate could occur at any point during the maintenance interval. More details regarding difficulties defining flight hours in use are provided in appendix B. The rate estimates are compared to the fuse failure rate estimates in NPRD 95 to examine whether the failure rates in this report are consistent with the estimates that are currently in use.

When interpreting this study's results, it is important to note how the data were collected. Certain concepts should be noted regarding the selection of the fuses. Ideally, the fuses should be from random planes due for routine screening, such that the test data can be considered a random sample (i.e., all fuses in the population have an equal probability of being selected) and the results of this study can be generalized to fuses that were not included in the sample population. Routine screening is defined as the inspections required in the Maintenance Review Board (MRB) reports. If fuses were screened earlier/later than the routine screening procedure dictates,

then the failure probability would be lower/higher than fuses receiving routine inspection. Furthermore, if the fuses are a non-random sample, then the failure frequency rate could be too high or too low, depending on how sampling occurred.

2. VOLUME HYDRAULIC FUSE

2.1 VOLUME FUSE TEST ARTICLES AND EQUIPMENT

The testing and inspection of each hydraulic fuse was performed at the Delta Air Lines TechOps in Atlanta. Volume fuses were inspected, tested, and repaired (if necessary) in accordance with the component maintenance manual. All hydraulic fuses were manufactured by Dowty Aerospace, in Yakima, Washington. The volume hydraulic fuses (2-8020 and 2-8041) were tested with different equipment than the rate hydraulic fuses (2-7680 and 2-7681). The 2-8020 hydraulic fuses are the purple fuses on the bottom row of figure 1. The 2-8041 hydraulic fuses are shown on the top row of figure 1. The 2-8020 and 2-8041 hydraulic fuses were tested using the equipment shown in figure 2.



Figure 1. Volume and rate hydraulic fuses

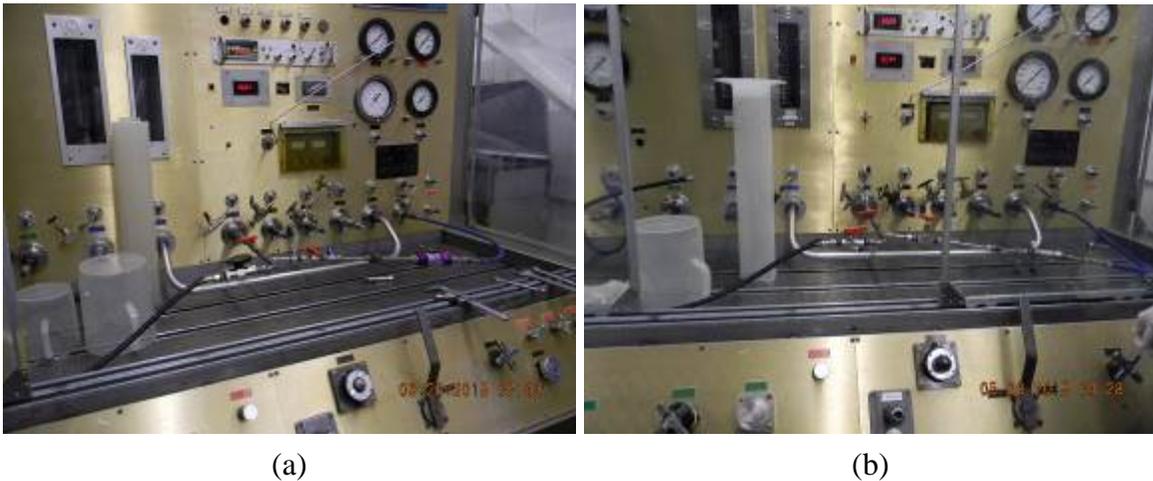


Figure 2. Volume Fuse Seaton-Wilson Systron-Donner test equipment for (a) 2-8020 and (b) 2-8041 hydraulic fuses

The equipment shown in figure 2 relies on the operator's readings of the pressure gages, stop watch, and hydraulic fluid measurements from the measuring containers to determine whether the hydraulic fuses pass or fail inspection. No digital data were recorded.

2.2 VOLUME FUSE FUNCTIONAL TESTING PROCEDURE

The hydraulic fuses studied came from several Boeing airplanes. MRB reports indicated that failure of the fuse to set is hidden safety or latent. Therefore, each fuse must be tested after a certain number of flight hours/cycles. For the volumetric fuses, these intervals were all approximately 25,000 flight hours. Actual removal hours were used in the calculations.

Brake fuses (often 2-8041s) can be tested on-plane rather than in-shop. If a defect is detected on-plane, the fuse gets tested in-shop. Because all of the fuses in this study were tested in-shop, it may be the case that all of the brake fuses in the study were included because a failure was detected on-plane. The component maintenance testing procedure in table 1 was used to identify the latent failure in the volume fuses.

Table 1. Volume fuse routine testing procedure steps

List Number	Test Step Title	Test Step Description	Test Step Pictures for 2-8020 and 2-8041 Hydraulic Fuses
1	Visual Inspection	Check for good workmanship, no corrosion, correct markings, and proper installation of all parts	
2	Proof Pressure Test	Ensures there is no external leakage, failure, distortion, or permanent set	
3	Pressure Drop Test	Check that the pressure differential does not drop more than 100 psid from the initial applied pressure	
4	Internal Leakage Test	Ensures that the hydraulic fuse is not leaking inside after the fuse is set closed	
5	Fault Isolation	If the hydraulic fuse fails any of these previous steps, the test operator will determine why the fuse failed	—
6	Volumetric Capacity Test	Ensures that fluid will flow through the fuse within the designated range of volumes at the designated fluid flow rate	
7	Reverse Flow Test	Ensures that the minimum required amount of fluid flow to pass through the fuse	
8	Manual Fusing and Reset Test	Test performed by the operator opening the valve to increase fluid flow	
9	Closing Time Test	Ensures the fuse will set closed within the designated time	
10	Bypass Test	Ensures the bypass lever is functional and fuses completely	

Though the testing steps are the same for every hydraulic-fuse category in this study, there are specific requirements (e.g., flow rates, pressures, fuse time, etc.) that change according to each specific type of fuse. The specific requirements for each hydraulic fuse are available in their respective component maintenance manuals.

2.2.1 Testing Procedure for 2-8020 Hydraulic Fuse

The 2-8020 hydraulic fuses are volume- or quantity-measuring fuse assemblies. Quantity-measuring hydraulic fuses allow the quantity of hydraulic fluid necessary for one complete actuation of the fuse component [6]. Therefore, when the hydraulic fluid demand is greater than the above necessary amount because of a leak, rupture, or total failure downstream

of the fuse, the fuse will close and prevent any further loss of hydraulic fluid [6]. The testing procedure for 2-8020-1, -2, -3, and -5 hydraulic fuses includes list step numbers 1–6 and 9 from table 1. The testing procedure for 2-8020-6 hydraulic fuses includes list step numbers 1–6, 7, and 9 from table 1.

2.2.2 Testing Procedure for 2-8041 Hydraulic Fuse

The 2-8041 hydraulic fuses are volumetric fuse assemblies. Volumetric fuses contain bypass levers that use pressure to help maintain a constant pressure and volume of hydraulic fluid flowing through the hydraulic system [7]. When the pressure changes outside of the prescribed range, the bypass lever closes, thereby closing the fuse and preventing further hydraulic fluid loss in the system [7]. The testing procedure for 2-8041 hydraulic fuses includes list step numbers 1–6, 7, 8, and 10 from table 1.

2.3 VOLUME FUSE FINDINGS

2.3.1 Volume Fuse Test Results

SNL tested 107 volume fuses: 60 2-8020 volumetric fuses and 47 2-8041 volumetric fuses. The 2-8020-6 fuses are distinguished from the 2-8020-1, -2, -3, and -5 fuses in the analysis, given that the testing for the 2-8020-6 included an additional test step, list step number 7 in table 1. Most fuses had complete test data; one 2-8020-1 fuse, failing visual inspection, did not receive any additional tests. There were also 30 2-8041s with missing reverse flow test outcomes. Table A-3 in appendix A contains the amount of each type of volume hydraulic fuse that failed each test shown in table 1. The test result summary statistics about the population of volume fuses included in the study are provided in table 2. The majority of volume fuses on Delta Air Lines planes were inspected 5–8 years since last inspection and 12–18 years from the date of manufacture.

Table 2. Number of volume fuses tested by flight hours, years since last inspection, and years since manufactured

	%	N
Customer		
Delta	68.2	73
Non-Delta	31.8	34
Flight hours		
1–20K	4.7	5
20–30K	65.4	70
30–32K	0.0	0
Hours unknown	29.9	32
Years since last inspection		
1-5	2.8	3
5-8	60.7	65
8-13	0.9	1
Date Unknown	35.5	38
Years since manufactured		
5–12	2.8	3
12–18	59.8	64
18–27	0.0	0
Date unknown	37.4	40
Total	100.0	107

Most fuses were manufactured in the late 1990s and early 2000s (figure 3(a)), with approximately 8–12 years between the fuse manufacture date and present inspection. The range of years between last inspection and manufacture date is 2–15 years. If all fuses were inspected in 5–8 year intervals and all fuses were receiving their second inspection, all points would be expected to fall within the 5–8 year box (figure 3(b)) that represents the expected first and second inspection times. Most volume fuses appeared to be on their second inspection, some appeared to be on their third inspection, and other fuses may be inspected earlier than expected.

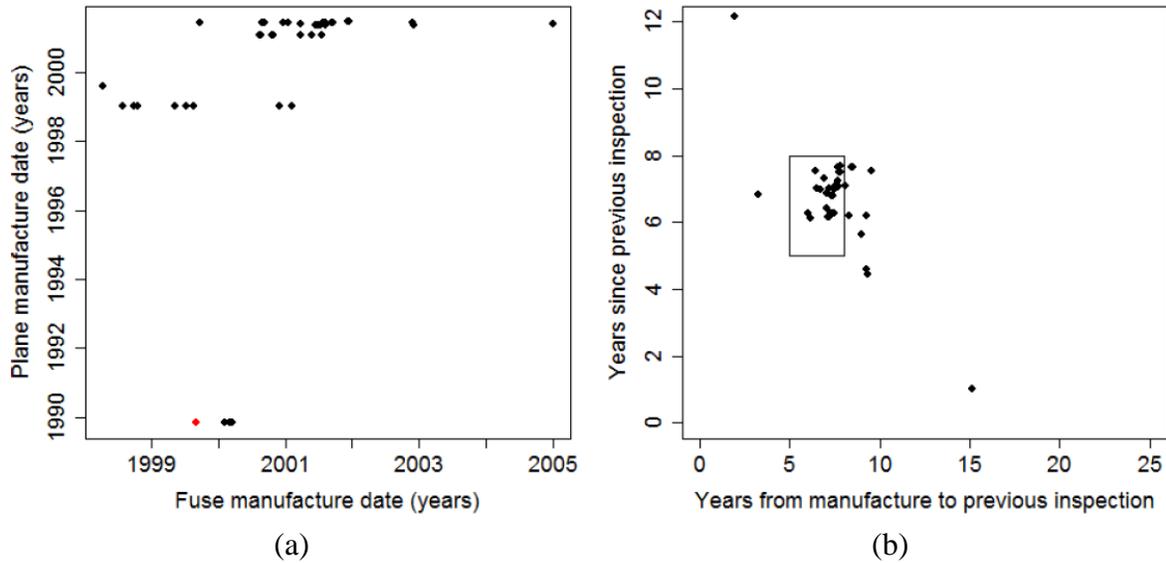


Figure 3. Volume fuse (a) date of plane manufacture as a function of fuse manufacture date for volume fuses with non-missing dates of plane and fuse manufacture (the red dot is a fuse with previous repairs) and (b) years since previous inspection as a function of years from manufacture to previous inspection for volume fuse (the box encompasses the 5–8 year window period which corresponds to the expected inspection time interval)

Detailed results from the previous inspections are not available. However, previous repair information for 75 volume fuses was available. Previous repairs were reported for three 2-8020-5 fuses at the last inspection time. In the most recent inspection conducted for this study, all three of the volume fuses with previous repairs failed the volumetric capacity test: one by fusing early, one by fusing late, and one by never fusing at all.

2.3.2 Volume Fuse Failure Frequency

Latent failures in volume fuses are defined as failures due to never fusing. The estimated failure frequencies for any failure and latent failures are presented by part number in table 3. The CIs are wide for the 2-8020s because of the limited sample size, but failure rates are non-negligible. It is estimated that 68% of volume fuses failed at least one test step of the routine inspection; however, rates of latent failures were much lower, with an estimated 6% of volume fuses experiencing latent failures. The failure frequency is highest for the 2-8041 (94% failing at least one test step), likely because only fuses that failed on-plane screenings were tested off-plane and included in this study. Therefore, this high failure rate in the 8041s should be interpreted with an understanding of that mitigating dynamic.

Table 3. Volume fuse failure frequency (failed at least one test) for routinely screened planes (X is the number of volume hydraulic fuses that failed and N is the total number of hydraulic fuses in each specific fuse category; the frequency estimate [Freq] and 95% confidence interval [lower and upper] are also shown)

Part	N	X	Any failure			X	Latent failure		
			Freq	Lower	Upper		Freq	Lower	Upper
8020	53	28	0.53	0.39	0.67	4	0.08	0.02	0.18
8020-6	7	1	0.14	0.00	0.58	0	0.00	0.00	0.41
8041	47	44	0.94	0.82	0.99	2	0.04	0.01	0.15
Volume	107	73	0.68	0.59	0.77	6	0.06	0.02	0.12

Assuming all fuses were in use for 25,000 flight hours, the estimated fuse failure rate is $2.7e-5$, with 95% CI ($2.3e-5$, $3.1e-5$), whereas the estimated latent failure rate is $2.2e-6$ failures per flight hour, with 95% CI ($8.3e-7$, $4.7e-6$). Though these rate estimates are likely biased because of the inaccurate flight hours, obtaining a “ballpark” estimate of the rate facilitates comparison with the failure rates specified in NPRD 95.

Of the 53 2-8020 fuses shown in table 3, 27 failed test procedure step 6 in table 1. Only one of seven 2-8020-6 fuses failed additional steps (steps 3 and 9). Of the 47 2-8041 fuses shown in table 3, 44 failed test procedure step 6 in table 1. The majority of the fuses failed only one test step from their respective testing procedure, as shown in table 4. Only one of the 2-8020 volume fuses failed three test steps.

Table 4. Number of failed test steps, by part number, out of the total volume of fuses tested (N)

Part	Number of failed tests								N
	0	1	2	3	4	5	6	7	
2-8020	25	27	0	1	0	0			53
2-8020-6	6	1	0	0	0	0	0	0	7
2-8041	3	44	0	0	0	0	0	0	47

The failure mechanisms for the different part numbers are shown in table 5. A Fisher’s exact test was used to test for an association between part number and failure mechanism. There is evidence that failure mechanisms differ by part number ($p < .001$), with 2-8041 fuses more likely to fail early and 2-8020 fuses more likely to fail late.

Table 5. Volume fuse failure mechanisms

	X	Immediate	Early	Late	Never	Inconsistent	Other type
2-8020	28	0	6	15	4	1	2
2-8020-6	1	0	1	0	0	0	0
2-8041	44	3	38	0	2	1	0
Total	73	3	45	15	6	2	2

2.3.3 Volume Fuse Failure Time Analysis

Results from failure time modeling of the volume fuses are provided in this section. However, the authors recommend concentrating on the failure frequency in the previous section because of the substantial limitations of failure time modeling for these data described in appendix B.

Because the failure time analysis relies on known dates of last repair and dates of fuse manufacture, the fuses with missing information on these covariates must be excluded from the analysis. Fifty-four hydraulic fuses are included in this portion of the analysis: 18 2-8020 fuses, of which 10 failed, and 36 2-8041 fuses, of which 35 failed.

Figure 4 shows the probability of the fuse working properly as a function of time. CIs are wide for 2-8020 fuses because of the limited number of failures. Estimated failure time quantiles are shown in table 6. The failure quantiles are interpreted as the number of calendar years from the date of installation of the healthy fuse, after which $100*Q\%$ of fuses are expected to fail. The CIs are again wide for the 2-8020 fuse failure quantiles because of the limited number of observed failures and interval-censored nature of the data. Therefore, the authors cannot do a good job of characterizing failure times for the 2-8020 fuses with the collected data. Because most of the 2-8041 fuses failed, the CIs are relatively narrow, and the failure times for the 2-8041 fuses can be characterized more precisely (assuming the modeling assumptions are correct). However, the 2-8041 fuses were likely a biased sample of fuses that failed an on-plane test, thereby compromising the interpretability of these results. In summary, the failure time analyses for the fuses are not very informative because of the limited number of fuse failures for all part numbers aside from the 2-8041, for which defective fuses were over-tested.

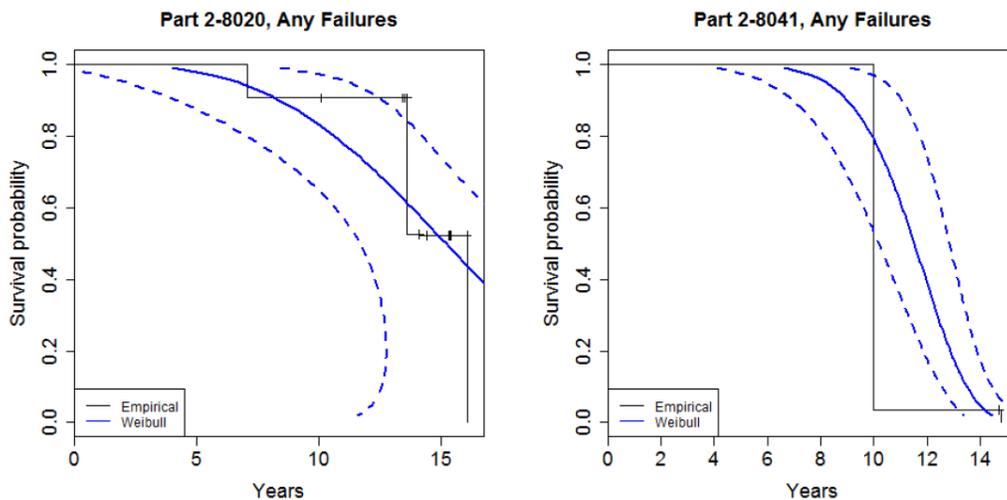


Figure 4. Empirical and parametric survival curves as a function of years since installation of healthy volume hydraulic fuses

Table 6. Volume fuse Weibull distribution: estimated times at which 100*Q% of fuses have failed with 95% CI for the outcome that any failure for years since healthy fuse is installed

Part	Q	Large-sample			Bootstrap		
		Estimate	Lower	Upper	Estimate	Lower	Upper
2-	0.10	8.40	5.13	13.76	6.27	5.08	8.41
2-	0.50	15.21	12.12	19.08	15.42	12.95	17.21
2-	0.90	22.20	14.52	33.95	27.43	19.99	31.63
2-	0.10	9.01	7.20	11.27	7.63	6.18	8.76
2-	0.50	11.53	10.30	12.91	10.92	10.01	11.38
2-	0.90	13.50	12.59	14.47	13.41	12.83	15.36

2.4 VOLUME FUSE FINDINGS

Below are the findings for the volume fuses:

- Estimated 6% had latent failures
- Estimated 68% failed at least one test
- Estimated latent failure rate of 2.2e-6 failures per flight hour
- 94% fail at least one test

2.5 VOLUME FUSE CONCLUSION AND RECOMMENDATIONS

The goal of the Transport Airplane Hydraulic Fuse Functional Reliability Study was to determine the functionality at inspection of hydraulic fuses on transport category airplanes. An estimated 68% of volume fuses failed at least one test step of the routine inspection; however, rates of latent failures were much lower, with an estimated 6% of volume fuses experiencing latent failures. The failure frequency is highest for the 2-8041 (94% failing at least one test step), which is possibly due to biased sampling in these fuses. The following recommendations are based on the results of this study:

1. Transport airplane manufacturers review these data to ensure that the failure rates seen in testing support their fault tree analyses to limit latency.
2. Manufacturers review these data to support reliability and maintainability programs.
3. Test internal hydraulic fuse components using automated digital equipment, as shown in figure 5, to determine whether the lifetime of the internal components aligns with the maintenance inspection requirements.



Figure 5. Rate fuse Avtron testing equipment for 2-7680 and 2-7681 hydraulic fuses

3. RATE HYDRAULIC FUSE

3.1 RATE FUSE TEST ARTICLES AND EQUIPMENT

The testing and inspection of each hydraulic fuse was performed at the Delta Air Lines TechOps in Atlanta. Volume fuses were inspected, tested, and repaired (if necessary) in accordance with the component maintenance manual. The volume hydraulic fuses (2-8020 and 2-8041) were tested with different equipment than the rate hydraulic fuses (2-7680 and 2-7681). All fuses were manufactured by Dowty Aerospace, in Yakima, Washington. The three smaller hydraulic fuses (2-7680 and 2-7681) are shown on the left of the bottom row of figure 1. The 2-7680 and 2-7681 hydraulic fuses are tested using equipment shown in figure 5.

Figure 5(a) shows the equipment setup where the hydraulic fuse is attached and figure 5(b) shows where the information is collected at the computer system. The testing setup shown in figure 5 was almost completely automated (it automated and measured hydraulic fluid pressures, measured time, instructed the technician to follow testing procedures, and recorded results) and was able to record and print a report of the inspection results when testing was complete. Because of this automation of the system, the testing setup in figure 5 is preferred over the testing equipment setup shown in figure 2.

3.2 RATE FUSE FUNCTIONAL TESTING PROCEDURE

The hydraulic fuses studied came from several Boeing airplanes. MRB reports indicated that failure of the fuse to set is hidden safety or latent. Therefore, each fuse must be tested after a certain number of flight hours/cycles. For the rate fuses, according to the MRB reports, these intervals were all approximately 25,000 flight hours or 72 months, whichever comes first. Actual removal hours were used in the calculations. A latent failure is identified when the hydraulic fuse never sets/closes. The list of all rate hydraulic fuse testing steps, used to determine the latent failures, is shown in table 7.

Table 7. Rate fuse routine testing procedure steps

List Number	Test Step Title	Test Step Description	Test Step Pictures for 2-7680 and 2-7681 Hydraulic Fuses
1	Visual Inspection	Check for good workmanship, no corrosion, correct markings, and proper installation of all parts	
2	Proof Pressure Test	Ensures there is no external leakage, failure, distortion, or permanent set	
3	Pressure Drop Test	Check that the pressure differential does not drop more than 100 psid from the initial applied pressure	
4	Internal Leakage Test	Ensures that the hydraulic fuse is not leaking inside after the fuse is set closed	
5	Fault Isolation	If the hydraulic fuse fails any of these previous steps, the test operator will determine why the fuse failed	—
6	Manual Fusing and Reset Test	Test performed by the operator opening the valve to increase fluid flow	
7	Automatic Fusing and Reset Test	Test performed by the testing stand computer which increases the fluid flow	
8	Closing Time Test	Ensures that the fuse will set closed within the designated time	

Though every category of hydraulic fuse in this study has testing steps that are the same, there are specific requirements (e.g., flow rates, pressures, fuse time) that change for each specific type of fuse. The specific requirement for each hydraulic fuse are found in their respective component maintenance manuals.

3.2.1 Testing Procedure for 2-7680 and 2-7681

The 2-7680 and 2-7681 hydraulic fuses are hydraulic flow rate fuse assemblies. Hydraulic flow rate fuses are self-resetting fuses that sense the flow rate of the hydraulic fluid and allow the flow rate to only be within the specific range [6]. If there is a leak or rupture, the change in flow rate outside of the specified range will cause the hydraulic fuse to close, preventing further loss of hydraulic fluid [7]. The testing procedure for the 2-7680 and 2-7681 hydraulic fuses includes test steps 1–8 in table 7.

3.3 RATE FUSE FINDINGS

3.3.1 Rate Fuse Test Results

SNL examined 44 rate fuses for this study: 30 2-7680 flow rate fuses and 14 2-7681 flow rate fuses. Table A-6 in appendix A contains the amount of each type of volume hydraulic fuse that failed each test shown in table 7. Summary statistics about the population of rate fuses included in the study are shown in table 8. The majority of rate fuses on Delta Air Lines planes were inspected within 8 years of the last inspection and 12–18 years from the date of manufacture.

Table 8. Number of rate fuses tested by flight hours, years since last inspection, and years since manufactured

	%	N
Customer		
Delta	68.2	73
Non-Delta	31.8	34
Flight hours		
1–20K	4.7	5
20–30K	65.4	70
30–32K	0.0	0
Hours unknown	29.9	32
Years since last inspection		
1–5	2.8	3
5–8	60.7	65
8–13	0.9	1
Date Unknown	35.5	38
Years since manufactured		
5–12	2.8	3
12–18	59.8	64
18–27	0.0	0
Date unknown	37.4	40
Total	100.0	107

Most fuses were manufactured in the late 1990s and early 2000s (figure 6(a)). For most fuses, approximately 8–16 years have passed between the fuse manufacture date and present inspection, suggesting that most fuses are receiving their second (but possibly third) inspection (figure 6(b)). The range of years between last inspection and manufacture date was 7–25 years.

If all fuses were inspected in 5–8 year intervals and were receiving their second inspection, all points would be expected to fall within the 5–8 year box in figure 6(b) that represents the expected first and second inspection times. Some fuses may be on their third inspection and some may be inspected earlier than expected.

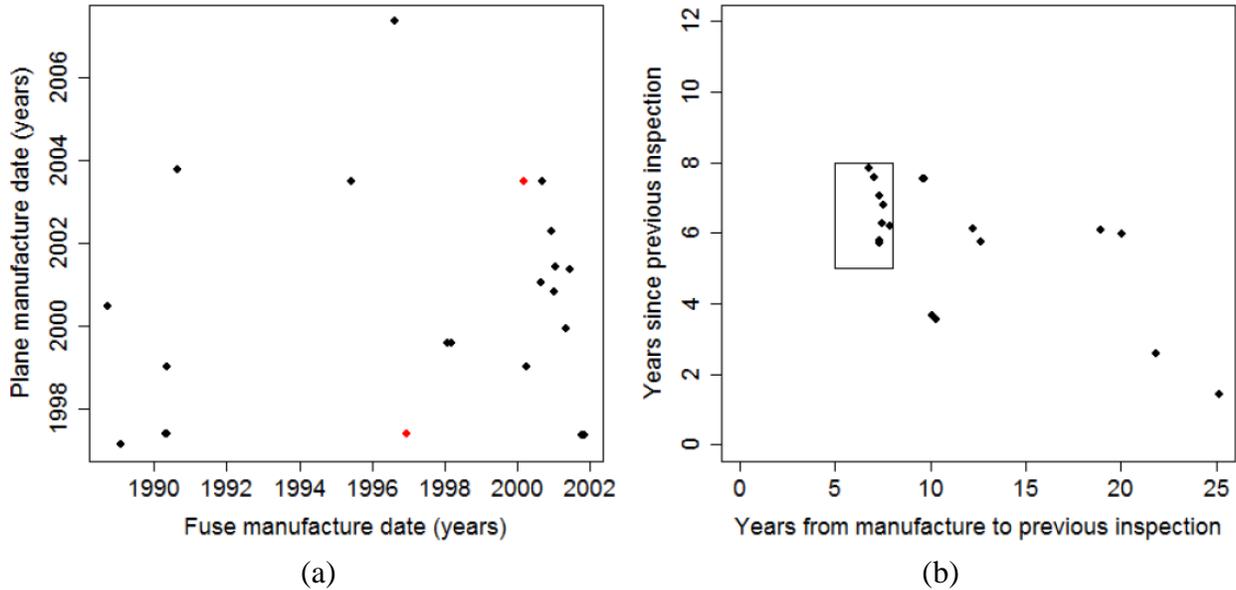


Figure 6. Rate fuse (a) date of plane manufacture as a function of fuse manufacture date for rate fuses with non-missing dates of plane and fuse manufacture (the red dot is a fuse with previous repairs) and (b) years since previous inspection as a function of years from manufacture to previous inspection for rate fuse (the box encompasses the 5–8 year window which corresponds to the expected inspection time interval)

Results from the previous inspections are not available, though previous repair information is available for 33 of the rate fuses. Previous repairs were reported for one 2-7680 and one 2-7681. The previously repaired 2-7681 fuse was repaired in 2002, 4 years prior to the most recent inspection in 2006. The repair date for the previously repaired 2-7680 fuse is unknown. The 2-7680 fuse with previous repairs passed the most recent inspection. The previously repaired 2-7681 fuse failed by never fusing, which is a latent failure.

3.3.2 Rate Fuse Failure Frequency

The estimated failure frequencies for any failure and latent failures are presented by part number and rate fuse in table 9. The CIs are wide because of the limited sample size, but failure rates are non-negligible. Specifically, an estimated 25% of rate fuses failed at least one test step of the routine inspection; however, rates of latent failures were much lower, with an estimated 11% of rate fuses experiencing latent failures.

Table 9. Rate fuse failure frequency (failed at least one test) for routinely screened planes (X is the number of rate hydraulic fuses that failed and N is the total number of hydraulic fuses for each specific fuse category; the frequency estimate (Freq) and 95% confidence interval [lower and upper] are also shown)

Part	N	X	Any failure			X	Latent failure		
			Freq	Lower	Upper		Freq	Lower	Up
7680	3	9	0.30	0.15	0.49	4	0.13	0.04	0.31
7681	1	2	0.14	0.02	0.43	1	0.07	0.00	0.34
Rate	4	1	0.25	0.13	0.40	5	0.11	0.04	0.25

Assuming all fuses were in use for 25,000 flight hours, the estimated fuse failure rate is 1.0e-5 with 95% CI (5.3e-6, 1.6e-5). The estimated latent failure rate is 4.5e-6 failures per flight hour, with 95% CI (1.5e-6, 9.8e-6). Though these rate estimates are likely biased because of the inaccurate flight hours, obtaining a “ballpark” estimate of the rate facilitates comparison with the failure rates specified in NPRD 95.

The majority of the rate fuses did not fail any test steps, as shown in table 10. As shown in table 9, of the nine 2-7680 rate fuses that did fail, two failed all except the visual inspection. Of the other seven 7680 fuses that failed, a few of them failed multiple test steps from table 7. From table 7, test step 4 had two failures, test step 6 had four rate fuse failures, test step 7 had two failures, and test step 8 had one failure. The two 2-7681 rate fuses both failed test steps 6 and 7 from table 7. The number of rate fuses that failed an amount of test steps is shown in table 10.

Table 10. Number of failed test steps, by part number, out of the total rate fuses tested (N)

Part	0	Number of failed tests							N
		1	2	3	4	5	6	7	
2-7680	21	5	2	0	0	0	2	0	30
2-7681	12	0	2	0	0	0			14

The failure mechanisms for the different part numbers are shown in table 11. A Fisher’s exact test was used to test for an association between part number and failure mechanism. There is no evidence of a difference in failure mechanisms by part number ($p = 1.0$), though little data is available to detect such a difference.

Table 11. Rate fuses failure mechanisms

	X	Immediate	Early	Late	Never	Inconsistent	Other type
2-7680	9	0	3	1	4	0	1
2-7681	2	0	1	0	1	0	0
Total	11	0	4	1	5	0	1

3.3.3 Rate Fuse Failure Time Analysis

Failure time analyses were not conducted for the rate fuses because there were not enough data. For a failure time analysis, only fuses with known dates of last repair and manufacture can be used. There are 20 rate fuses with this information available: 7 2-7681 fuses, of which one failed, and 13 2-7680 fuses, of which four failed. The amount of information in a failure time analysis is driven by the number of failures observed and was too small to provide meaningful information for rate fuses.

3.3.4 Rate Fuse Failure Rates

Below are the findings for the rate fuses:

- Estimated 11% had latent failures
- Estimated 25% failed at least one test
- Estimated latent failure rate of $4.5e-6$ failures per flight hour

3.4 RATE FUSE CONCLUSION AND RECOMMENDATIONS

The goal of the Transport Airplane Hydraulic Fuse Functional Reliability Study was to determine the functionality at inspection of hydraulic fuses on transport category airplanes. It is estimated that 25% of rate fuses failed at least one test step of the routine inspection; however, rates of latent failures were much lower, with an estimated 11% of rate fuses experiencing latent failures. Based on the results of this study, the authors recommend testing most commonly failed internal hydraulic fuse components and encourage the testing of all types of hydraulic fuses. The authors recommend that this be done on more automated digital equipment, as shown in figure 5. Additional recommendations include:

- Transport airplane manufacturers review these data to ensure that the failure rates seen in testing support their fault tree analyses to limit latency.
- Manufacturers review these data to support reliability and maintainability programs.
- Testing most commonly failed internal hydraulic fuse components and encourage testing all types of hydraulic fuses; to be done using automated digital equipment, as shown in figure 5, to test the rate hydraulic fuses.

4. OVERALL FINDINGS AND RECOMMENDATIONS

Note that NPRD 95 indicated that the failure rate for hydraulic fuses is approximately $1.61e-6$ failures per flight hour. This estimate is consistent with the estimated latent failure rate in this study—specifically, $4.5e-6$ failures per flight hour. It is estimated that 68% of volume fuses and 25% of rate fuses failed at least one test step of the routine inspection; however, rates of latent failures were much lower, with an estimated 6% of volume fuses and 11% of rate fuses experiencing latent failures.

The failure frequency is highest for the 2-8041 fuses (94% failing at least one test step), likely because only fuses that failed on-plane screening were tested off-plane and included in this study. If all failure modes are considered, than the NPRD 95 data are not conservative. Each

manufacturer should use these data when they review the architecture of their system and the role of hydraulic fuses in their systems to determine whether they meet federal standards and their own internal safety and reliability requirements.

The design of this study is not conducive to estimating the expected fuse failure times, as discussed in appendix B. However, this study provides enveloping failure information that can be used to limit latency when showing compliance with 14 CFR 25.1309 and to set intervals in MRB analysis. In addition, the information gained in this study could be used to inform future studies aimed at estimating fuse failure times. Specifically, this study can help inform future sample sizes, sampling intervals, and sampling mechanisms.

Based on the results of this study, the following activities are recommended when conducting fuse testing:

1. Conduct analyses and testing to determine the life expectancy of fuse internal components. Investigate the lifetime of internal components within the hydraulic fuses (e.g., springs, seals, spring washers); determining the lifetime of internal components may provide more insight into determining the failure time of the hydraulic fuse. For example, the most common component to fail, which caused the 2-8041 hydraulic fuse to fail, was the spring washer shown in figure 7. Further testing of that spring washer may provide better information to estimate the lifetime of the 2-8041 hydraulic fuses.
2. Examine the role of fluid cleanliness in fuse failures. The cleanliness (or lack thereof) of the hydraulic fluid might also be a factor contributing to the failure of components inside the hydraulic fuse. Future studies can investigate the effect of hydraulic fluid cleanliness on the mechanical performance and lifetime of components inside the hydraulic fuse.
3. Use digital equipment similar to that shown in figure 5 to test all hydraulic fuses and for the digital recording of data. The equipment in figure 5 reduces some of the human error that can occur as a result of the misreading of pressure gauges, incorrectly measuring the volume of hydraulic fluid after volumetric capacity testing, incorrectly measuring the fusing/closing time of the hydraulic fuse, and/or setting the flow rates inaccurately.
4. Increase the frequency of functional testing to account for fuses that have gone through functional testing more than once. For example, some hydraulic fuses pass their first functional test, but they might fail sooner than a fuse that failed the first functional test and was repaired. This recommendation ties closely to the first recommendation in that it facilitates a better understanding of the lifetime of components inside of the hydraulic fuse.

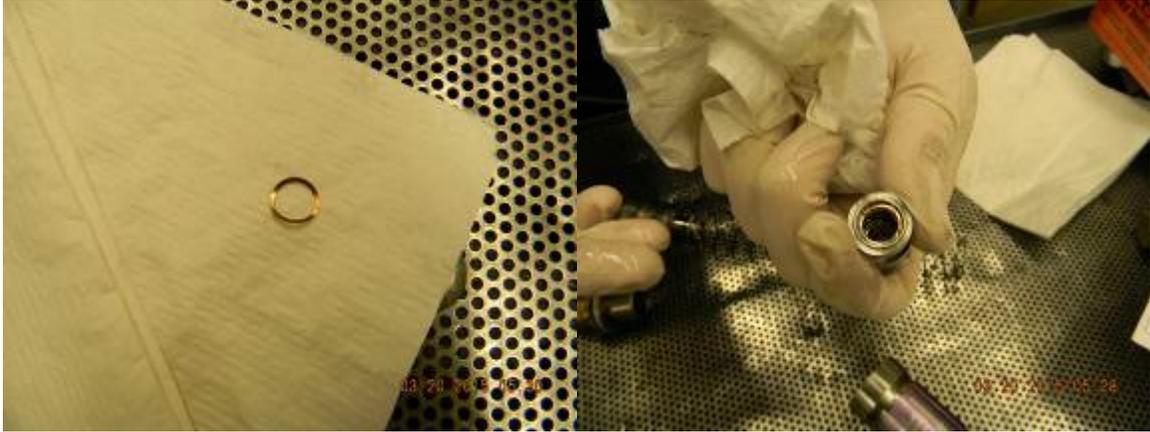


Figure 7. Volume fuse spring washer (left) and broken spring washer in a 2-8041 hydraulic fuse (right)

5. REFERENCES

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APPENDIX A—FULL DATASET DESCRIPTION

In data tables A-1, A-2, A-4, and A-5 for the volume and rate hydraulic fuses, the red wording indicates that the fuse failed at least one testing procedure step. Tables A-3 and A-6 indicate the failure frequency for individual test steps for the volume and rate fuses.

A.1 VOLUME FUSE FULL DATASET

Table A-1. Volume fuse 2-8020 full dataset

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8020-3	1097	11/3/2014	NO	23160	8751	Passed the 2 gpm test Failed the 1 gpm test by flowing too much (exceeded the max. limit)	10/2/2007	10/28/2014	3704	Boeing 737	3/7/2000
2-8020-5	2901	11/3/2014	NO	23160	8751	Passed the 11 gpm and 4 gpm tests failed the 0.6 gpm test by exceeding the max. limit	10/2/2007	11/4/2014	3704	Boeing 737	3/14/2000
2-8020-5	2332	11/3/2014	YES- REPAIRED PREVIOUSLY in 2007	23160	8751	Passed the 1 gpm test. Failed the 4 gpm and 0.6 gpm tests by closing too fast measuring fluid below the min. limit	10/2/2007	11/4/2014	3704	Boeing 737	8/31/1999
2-8020-5	2894	11/3/2014	NO	23160	8751		10/2/2007	11/4/2014	3704	Boeing 737	
2-8020-5	3698	11/3/2014	YES- REPAIRED PREVIOUSLY in 2007	23160	8751	Passed the 11 gpm and 4 gpm tests failed the 0.6 gpm test by exceeding the max. limit	10/2/2007	11/4/2014	3704	Boeing 737	
2-8020-2	1632	11/4/2014	NO	23160	8751		10/2/2007	11/4/2014	3704	Boeing 737	
2-8020-2	1655	11/4/2014	NO	23160	8751		10/2/2007	11/4/2014	3704	Boeing 737	
2-8020-6	1077	11/4/2014	NO	23160	8751		10/2/2007	11/4/2014	3704	Boeing 737	
2-8020-1	1070	11/4/2014	NO	23160	8751	Passed the 4 gpm test but failed the 10 gpm test by exceeding the max limit and Failed the 0.6 gpm test by closing too fast measuring the fluid below min. limit	10/2/2007	11/4/2014	3704	Boeing 737	2/3/2000
2-8020-3	0726	11/14/2014	NO	25706	9774		3/14/2007	11/11/2014	3706	Boeing 737	10/17/1998
2-8020-5	2126	11/14/2014	NO	25271	9610		3/14/2007	11/10/2014	3706	Boeing 737	7/8/1/999
2-8020-5	2092	11/17/2014	NO	25271	9610		4/27/2007	11/1/2014	3706	Boeing 737	7/8/1999

A-2

Table A-1. Volume fuse 2-8020 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8020-5	1412	11/17/2014	NO	3713	1325		11/1/2013	11/10/2014	3706	Boeing 737	9/25/1998
2-8020-6	0914	11/17/2014	NO	25146	9558		5/16/2007	11/14/2014	3706	Boeing 737	8/19/1999
2-8020-1	0711	11/18/2014	NO	25646	9754	Failed ,6 GPM test. Fused early.	3/19/2007	11/11/2014	3706	Boeing 737	9/26/1998
2-8020-5	9567	1/28/2015	NO DATA	NO DATA	NO DATA	Fuse too late on 11gpm test. Fuse too early on 0.6gpm test.	NO DATA	NO DATA	CUSTOMER		10/27/2006
2-8020-5	9507	1/28/2015	NO DATA	NO DATA	NO DATA	Fuse too early on 0.6gpm test.	NO DATA	NO DATA	CUSTOMER		10/25/2006
2-8020-5	9506	1/28/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		10/25/2006
2-8020-5	9532	1/28/2015	NO DATA	NO DATA	NO DATA	Fuse too late on 0.6gpm test. Over flowed by about 342 cc	NO DATA	NO DATA	CUSTOMER		10/27/2006
2-8020-6	1458	1/28/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		6/20/2001
2-8020-3	1537	1/28/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		9/11/2001
2-8020-2	2299	1/28/2015	NO DATA	NO DATA	NO DATA	Fuse to late. Over flowed by about 100cc	NO DATA	NO DATA	CUSTOMER		5/23/2001
2-8020-5	3580	1/29/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		10/31/2000
2-8020-3	1325	1/29/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		1/1/2008
2-8020-1	1441	1/29/2015	NO	23497	8947		1/15/2008	1/22/2015	3742	Boeing 737	7/19/2001
2-8020-6	1243	2/4/2015	NO	24663	9342		10/4/2007	1/22/2015	3742	Boeing 737	10/25/2000
2-8020-5	3830	2/23/2015	NO	24504	8186		4/8/2008	2/10/2015	3744	Boeing 737	1/2/2005
2-8020-5	4571	3/5/2015	NO	22556	7633		9/23/2008	2/21/2015	3746	Boeing 737	9/18/2001
2-8020-2	2168	3/5/2015	NO	21642	7367		12/17/2002	2/21/2015	3746	Boeing 737	1/18/2001
2-8020-1	1206	3/5/2015	NO	21642	7367		12/17/2008	2/21/2015	3746	Boeing 737	9/22/1999
2-8020-6	1224	3/5/2015	NO	21642	7367		12/17/2008	2/21/2015	3746	Boeing 737	8/30/2000
2-8020-3	1270	3/5/2015	NO	21642	7367		12/17/2008	2/21/2015	3746	Boeing 737	9/13/2000

A-3

Table A-1. Volume fuse 2-8020 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8020-2	2122	3/17/2015	NO	21642	7367	Fuse sticks. Won't fuse	2/17/2008	2/21/2015	3746	Boeing 737	12/22/2000
2-8020-6	1461	3/19/2015	NO DATA	21842	7494		12/5/2008	3/13/2015	3747	Boeing 737	6/20/2001
2-8020-3	1494	3/19/2015	NO DATA	21842	7494		12/5/2008	3/13/2015	3746	Boeing 737	7/25/2001
2-8020-5	4427	3/19/2015	NO DATA	21842	7494	FAILED 11GPM TEST BY 0.6 SECONDS. Fuse too late	12/5/2008	3/13/2015	3746	Boeing 737	8/8/2001
2-8020-5	3898	3/19/2015	NO DATA	21306	7321		1/29/2009	3/13/2015	3746	Boeing 737	12/1/2002
2-8020-5	7350	3/19/2015	NO DATA	21388	7342	FAILED 11GPM TEST BY 0.6 SECONDS. Fuse too late	1/22/2009	3/13/2015			1/7/2005
2-8020-5	4540	3/19/2015	NO DATA	21842	7494	FAILED 0.6GPM TEST WILL NOT FUSE. ALSO FAIL 11GPM TEST BY 0.3SECONDS.	12/5/2008	3/13/2015	3746	Boeing 737	9/11/2001
2-8020-2	2420	3/19/2015	NO DATA	21842	7494		12/5/2008	3/13/2015	3747	Boeing 737	8/7/2001
2-8020-1	1452	3/20/2015	NO	21842	7494	FAILED 0.6GPM TEST. WON'T FUSE	12/5/2008	3/13/2015	3747	Boeing 737	7/14/2001
2-8020-2	2417	3/20/2015	NO	21842	7494		12/5/2008	3/13/2015	3747	Boeing 737	8/7/2001
2-8020-5	0946	5/7/2015	NO DATA	NO DATA	NO DATA	FAILED 0.6 LOW FLOW TEST BY FUSING TOO LATE BY ABOUT 100CC.	NO DATA	NO DATA	CUSTOMER		4/9/1998
2-8020-5	4977	5/7/2015	NO DATA	NO DATA	NO DATA	FAILED 0.6 LOW FLOW TEST BY FUSING TOO LATE BY ABOUT 300CC.	NO DATA	NO DATA	CUSTOMER		2/4/2002
2-8020-5	10444	5/7/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		5/2/2007
2-8020-5	0936	5/7/2015	NO DATA	NO DATA	NO DATA	FAIL 0.6GPM AND 4GPM FLOW TESTS. 4 GPM TEST FUSED TOO EARLY BY ABOUT 200CC. 0.6 GPM TEST FUSED TOO EARLY BY ABOUT 500CC.	NO DATA	NO DATA	CUSTOMER		4/9/1998

Table A-1. Volume fuse 2-8020 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8020-5	0945	5/7/2015	NO DATA	NO DATA	NO DATA	FAILED 0.6 LOW FLOW TEST BY FUSING TOO LATE BY ABOUT 250CC.	NO DATA	NO DATA	CUSTOMER		4/9/1998
2-8020-2	0727	5/7/2015	NO	17990	7018						5/8/1998
2-8020-2	0724	5/7/2015	NO DATA	NO DATA	NO DATA	FAIL 1GPM TEST BYT FUSING EARLY BY ABOUT 400CC.	NO DATA	NO DATA	CUSTOMER		5/8/1998
2-8020-1	2562	5/7/2015	NO	21642	7367	THREADS AND TOP OF BODY CONTAIN DAMAGE. Therefore no test					8/19/2013
2-8020-1	0821	5/7/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		7/30/2009
2-8020-6	2503	5/20/2015	NO	NO DATA	NO DATA	FAIL 0.6GPM TEST BY FUSING TOO EARLY (ABOUT 300CC SHORT OF MIN.)	NO DATA	NO DATA	CUSTOMER		2/28/2006
2-8020-2	5359	5/20/2015	NO DATA	NO DATA	NO DATA	FAIL 2GPM TEST BY FUSING LATE BY ABOUT 200CC OVER THE MAX.	NO DATA	NO DATA	CUSTOMER		
2-8020-2	5360	5/20/2015	NO	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		5/7/2007
2-8020-3	1250	5/20/2015	NO	NO DATA	NO DATA	FAILED ALL TESTS EXCEPT 2GPM TEST. 1GPM AND LOWER TESTS FAILED BY FUSING LATE BY ABOUT 250CC OVER MAX.	NO DATA	NO DATA	CUSTOMER		9/13/2000
2-8020-1	2177	5/20/2015	NO	NO DATA	NO DATA	FAILED 0.6GPM TEST ONLY BY FUSING LATE BY ABOUT 100C OVER MAX.	NO DATA	NO DATA	CUSTOMER		1/19/2005
2-8020-5	3156	5/20/2015	NO	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		6/7/2000
2-8020-5	1018	5/20/2015	CORROSION ON BODY LAST TIME IN SHOP 12OCT2007	NO DATA	NO DATA	FAILED 0.6GPM TEST ONLY WON'T FUSE (PROBABLY DUE TO LOW SPRING TENSION)	NO DATA	NO DATA	CUSTOMER		

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Table A-1. Volume fuse 2-8020 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8020-5	2046	5/20/2015	NO	NO DATA	NO DATA	FAILED 0.6GPM TEST ONLY FUSE EARLY BY ABOUT 100CC BELOW MIN.	NO DATA	NO DATA	CUSTOMER		5/3/1999
2-8020-1	1268	5/20/2015	NO	NO DATA	NO DATA	FAILED 0.6GPM TEST ONLY BY FUSING LATE BY ABOUT 400C OVER MAX.	NO DATA	NO DATA	CUSTOMER		11/28/2000

Table A-2. Volume fuse 2-8041 full dataset

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8041-1	03009	11/19/2014	NO	NO DATA	NO DATA	Failed 1.5 and .1 GPM TEST. FUSED EARLY	NO DATA	11/11/2014	3706	Boeing 737	7/29/1998
2-8041-1	03007	11/19/2014	NO	NO DATA	NO DATA	Failed 1.5 and .1 GPM TEST. FUSED EARLY	NO DATA	11/11/2014	3706	Boeing 737	7/29/1998
2-8041-1	05948	11/19/2014	NO	15219	5748	Failed 1.5 and .1 GPM TEST. FUSED EARLY	6/1/2010	11/11/2014	3706	Boeing 737	2/7/2001
2-8041-1	07120	11/19/2014	NO	25275	9611	Failed 1.5 and .1 GPM TEST. FUSED EARLY	4/27/2007	11/11/2014	3706	Boeing 737	11/29/2000
2-8041-1	05797	11/20/2014	NO	23260	8788		10/2/2007	10/28/2014	3704	Boeing 737	2/7/2000
2-8041-1	04323	11/20/2014	NO	25765	9798	FAILED 1.5 and .1 GPM TEST. FUSED EARLY	3/8/2007	11/10/2014	3706	Boeing 737	5/7/1999
2-8041-1	07127	11/20/2014	NO	25271	9610	FAILED 1.5 and .1 GPM TEST. FUSED EARLY	4/27/2007	11/10/2014	3706	Boeing 737	11/29/2000
2-8041-1	061606	11/20/2014	NO	18853	7152	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/10/2009	10/28/2014	3704	Boeing 737	3/15/2000
2-8041-1	05876	11/20/2014	NO	23260	8788	FAILED 1.5 and .1 GPM TEST. FUSED EARLY	10/2/2007	10/28/2014	3704	Boeing 737	2/7/2000
2-8041-1	05877	11/20/2014	NO	23260	8788	FAILED 1.5 and .1 GPM TEST. FUSED EARLY	10/2/2007	10/28/2014	3704	Boeing 737	2/7/2000

Table A-2. Volume fuse 2-8041 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8041-1	05971	12/15/2014	NO	23260	8788	Failed 1.5 and .1 GPM TEST. FUSED EARLY	10/2/2007	12/28/2014	3704	Boeing 737	2/7/2000
2-8041-1	06977	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/23/2000
2-8041-1	06974	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/23/2000
2-8041-1	06992	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/26/2000
2-8041-1	06963	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/23/2000
2-8041-1	06959	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/23/2000
2-8041-1	06964	1/7/2015	NO	22590	8560	Failed 1.5 and .1 GPM TEST. FUSED EARLY	3/4/2008	12/15/2014	3741	Boeing 737	10/23/2000
2-8041-1	08732	1/20/2015	NO	NO DATA	NO DATA	Failed 1.5 and .1 GPM TEST. FUSED EARLY	NO DATA	1/20/2015	CUSTOMER		10/1/2009
2-8041-1	08675	1/28/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		9/24/2001
2-8041-1	08670	1/28/2015	NO DATA	NO DATA	NO DATA	Fused immediately at 6gpm test. Cracked spring.	NO DATA	NO DATA	CUSTOMER		9/19/2001
2-8041-1	06685	2/5/2015	NO	23442	8298	FAILED 6 GPM FLOW TEST	1/29/2008	1/22/2015	3742	Boeing 737	8/21/2000
2-8041-1	06630	2/5/2015	NO	23448	8931	FAILED 6 GPM FLOW TEST	1/28/2008	1/22/2015	3742	Boeing 737	8/14/2000
2-8041-1	07650	2/5/2015	NO	15793	5946	FAILED .1 GPM FLOW TEST	6/25/2010	1/22/2015	3742	Boeing 737	3/27/2001
2-8041-1	08022	2/5/2015	NO	23442	8928	FAILED .1 GPM FLOW TEST	1/29/2008	1/22/2015	3742	Boeing 737	5/29/2001
2-8041-1	07666	2/24/2015	NO	24287	8139	FAILED 6 GPM FLOW TEST	4/8/2008	2/19/2015	3744	Boeing 737	3/27/2001
2-8041-1	07663	2/24/2015	NO	24287	8139	FAILED .1 GPM FLOW TEST	4/8/2008	2/19/2015	3744	Boeing 737	3/27/2001
2-8041-1	10340	3/20/2015	NO	21858	7497	FAILED 0.1 GPM TEST BY 383CC, FUSE TOO EARLY. REPLACE CRACKED COPPER SPRING	12/4/2008	3/13/2015	3747	Boeing 737	12/6/2002

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Table A-2. Volume fuse 2-8041 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8041-1	08195	3/20/2015	NO	21842	7494	FAILED 1.5 GPM TEST BY 383CC,FUSE TOO EARLY. FAILED 0.1GPM TEST FUSE IMMEDIATELY. REPLACE CRACKED COPPER SPRING AND PASSED ALL TESTS THAT WERE RE-DONE.	12/5/2008	3/13/2015	3747	Boeing 737	7/2/2001
2-8041-1	08152	3/20/2015	NO	21858	7497	FAILED 0.1 GPM TEST WILL NOT FUSE. REPLACE CRACKED COPPER SPRING	12/4/2008	3/13/2015	3747	Boeing 737	6/19/2001
2-8041-1	08197	3/20/2015	NO	21842	7494	FAILED 1.5 GPM TEST FUSE IMMEDIATELY. FAILED 0.1GPM TEST FUSE IMMEDIATELY. REPLACE CRACKED COPPER SPRING.	12/5/2008	3/13/2015	3747	Boeing 737	7/2/2001
2-8041-1	08202	3/20/2015	NO	21842	7494	FAILED 1.5 GPM TEST FUSE IMMEDIATELY. FAILED 0.1GPM TEST FUSE IMMEDIATELY. REPLACE CRACKED COPPER SPRING.	12/4/2008	3/13/2015	3747	Boeing 737	7/2/2001
2-8041-1	08211	3/26/2015	NO	21842	7494	Failed due to a broken spring	12/5/2008	3/13/2015	3747	Boeing 737	7/2/2001
2-8041-1	09065	4/2/2015	NO	21603	7273	FAILED 6 GPM FLOW TEST	2/4/2009	3/31/2015	3748	Boeing 737	12/14/2001
2-8041-1	09049	4/2/2015	NO	21603	7273	FAILED .1 GPM FLOW TEST	2/4/2009	3/31/2015	3748	Boeing 737	12/14/2001
2-8041-1	09018	4/2/2015	NO	21603	7273	FAILED .1 GPM FLOW TEST	2/4/2009	3/31/2015	3748	Boeing 737	12/6/2001
2-8041-1	02362	5/7/2015	NO	25217	9592	FAILED ALL TESTS FIAL BY FUSEING TOO EARLY. 6GPM AS 200CC BELOW MINIMUM LIMIT.	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998
2-8041-1	02361	5/7/2015	NO	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998
2-8041-1	02342	5/8/2015	NO	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998

Table A-2. Volume fuse 2-8041 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-8041-1	02340	5/8/2015	NO	25217	9592	FAILED ONLY 0.1 TESTS BY NOT FUSING.	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998
2-8041-1	02369	5/8/2015	NO	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998
2-8041-1	02359	5/8/2015	NO	25217	9592	FAILED ONLY 0.1 TEST BY FUSEING TOO EARLY	10/12/2007	5/3/2015	3708	Boeing 737	4/11/1998
2-8041-1	07776	5/13/2015	No Data	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	NO DATA	NO DATA	CUSTOMER		4/23/2001
2-8041-1	07778	5/13/2015	No Data	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	NO DATA	NO DATA	CUSTOMER		4/24/2001
2-8041-1	07779	5/13/2015	No Data	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	NO DATA	NO DATA	CUSTOMER		4/25/2001
2-8041-1	07780	5/13/2015	No Data	25217	9592	FAILED ALL TESTS BY FUSEING TOO EARLY.	NO DATA	NO DATA	CUSTOMER		4/26/2001
2-8041-1	17210	1/28/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		1/18/2007
2-8041-1	08369	5/13/2015	NO DATA	NO DATA	NO DATA	FAILED 0.1GPM TEST BY FUSING EARLY BY ABOUT 500CC BELOW MIN.	NO DATA	NO DATA	CUSTOMER		8/8/2001

Table A-3. Volume fuse failure frequencies for the individual tests by part number

Table	Test	X	N	Freq.
8020	VI	2	53	0.04
8020	PP	0	52	0.00
8020	MFR	0	0	
8020	AFR	0	0	
8020	PD	1	52	0.02
8020	IL	1	52	0.02
8020	CT	0	0	
8020	VC	26	52	0.50
8020	RF	0	0	
8020	Fail Any	28	53	0.53
8020-6	VI	0	7	0.00
8020-6	PP	0	7	0.00
8020-6	MFR	0	0	
8020-6	AFR	0	0	
8020-6	PD	0	7	0.00
8020-6	IL	0	7	0.00
8020-6	CT	0	0	
8020-6	VC	1	7	0.14
8020-6	RF	0	7	0.00
8020-6	Fail Any	1	7	0.14
8041	VI	0	47	0.00
8041	PP	0	47	0.00
8041	MFR	0	0	
8041	AFR	0	0	
8041	PD	0	47	0.00
8041	IL	0	47	0.00
8041	CT	0	0	
8041	VC	44	47	0.94
8041	RF	0	0	
8041	Fail Any	44	47	0.94

Table A-3 contains test-specific failure frequencies for the fuses. The abbreviations used in the table include:

- VI–Visual inspection
- PP–Pressure proof
- MFR–Manual fuse reset
- AFR–Automatic fuse reset
- PD–Pressure drop
- IL–Internal leakage
- CT–Closing time
- RF–Reverse flow

A.2 RATE FUSE FULL DATASET

Table A-4. Rate fuse 2-7680 full dataset

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-7680-2	7494	11/3/2014	NO	23160	8751	Manual Fuse and Reset Test Failed by 0.01gpm	10/2/2007	11/4/2014	3704	Boeing 737	
2-7680-2	1292	11/3/2014	NO	NO DATA	NO DATA		NO DATA	11/11/2014	3706	Boeing 737	5/4/1990
2-7680-2	8811	12/2/2014	NO	2403	4591	Fused Manual fusing too early	2/20/2009	11/7/2014	6808	Boeing 757	11/1/2001
2-7680-2	8736	12/4/2014	NO	24300	4640		1/26/2009	11/7/2014	6808	Boeing 757	10/11/2001
2-7680-2	8752	12/8/2014	NO	12135	4495		4/8/2011	10/20/2014	3737	Boeing 737	1/1/2001
2-7680-2	7887	1/8/2015	NO	22962	7979		3/5/2008	12/22/2014	6805	Boeing 757	9/12/2000
2-7680-2	4710	1/8/2015	NO	23723	4606		3/26/2009	12/22/2014	6806	Boeing 757	8/13/1996
2-7680-2	9361	1/8/2015	NO	NO DATA	NO DATA	Fuse stuck. Lap assy bad.	NO DATA	11/29/2014	5812	Boeing 757	9/12/2000
2-7680-2	4297	1/8/2015	NO	NO DATA	NO DATA		NO DATA	11/29/2014	5812	Boeing 757	6/7/1995
2-7680-2	7404	1/10/2015	NO	15132	1489		6/23/2011	1/1/2015	7007		
2-7680-2	1230	1/10/2015	NO	14941	1472		7/6/2011	1/2/2015	7007		
2-7680-2	0304	1/16/2015	NO	20163	7072	FUSE STUCK. Lap assy bad.	1/5/2009	12/22/2014	6805	Boeing 757	11/17/1998
2-7680-2	8369	1/29/2015	NO	15665	1568		5/25/2011	1/26/2015	7005	Boeing 777	4/26/2001
2-7680-2	0497	2/26/2015	NO	24883	4803	Excessive internal leakage	2/24/2009	2/9/2015	6805	Boeing 757	1/30/1989
2-7680-1	0190	3/3/2015	NO DATA	NO DATA	NO DATA						9/22/1988
2-7680-2	1328	3/3/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		5/24/1990
2-7680-2	1746	3/19/2015	NO DATA	8664	3152		6/25/2012	1/26/2015	5816	Boeing 757	8/21/1990
2-7680-2	9487	3/19/2015	NO DATA	NO DATA			NO DATA	NO DATA	CUSTOMER		3/26/2003
2-7680-2	2908	3/19/2015	NO DATA	21842	7494	Excessive internal leakage AP 100psi test. Passed Internal Leak test at 3000psi test. Failed due to wear on shaft.	12/5/2008	3/13/2015	3747	Boeing 737	6/8/2001
2-7680-2	1316	5/7/2015	NO	25108	4818	CLOSE TOO FAST. PROBABLY DUE TO LOW SPRING TENSION	3/31/2009	4/27/2015	6807	Boeing 757	5/4/1990
2-7680-2	4872	5/7/2015	Replaced Worn Seal	24976	4800		3/9/2009	4/27/2015	6807	Boeing 757	12/7/1996
2-7680-1	0213	5/7/2015	NO	1451	518		11/20/2013	4/23/2015	3723	Boeing 737	9/22/1988
2-7680-2	5947	5/7/2015	NO	25217	9592		10/12/2007	5/3/2015	3708	Boeing 737	3/2/1998
2-7680-2	13291	5/7/2015	No Data	No Data	No Data		NO DATA	NO DATA	CUSTOMER		6/29/2009
2-7680-2	3853	5/14/2015	NO	16904	1697		4/1/2011	4/29/2015	7004	Boeing 777	NO DATA
2-7680-2	7556	5/14/2015	NO	16904	1697		4/1/2011	4/29/2015	7004	Boeing 777	NO DATA

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Table A-4. Rate fuse 2-7680 full dataset (continued)

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-7680-2	1238	5/14/2015	NO	16904	1697	STICKS- NO FUSE	4/1/2011	4/29/2015	7004	Boeing 777	NO DATA
2-7680-2	8455	5/14/2015	NO	16904	1697	STICKS-NO FUSE	4/1/2011	4/29/2015	7004	Boeing 777	NO DATA
2-7680-2	8459	5/20/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		6/7/2001
2-7680-2	8053	5/20/2015	NO	31659	3875		4/21/2008	5/8/2015	1821	Boeing 767	12/12/2000

Table A-5. Rate fuse 2-7681 full dataset

Part Number	Serial Number	Date Tested	Previous Repairs? Yes/No & any details about repair if available	Flight Hours on As Removed Fuse	Number of Cycles on As Removed Fuses	Details about why Fuse Failed	Date Installed on Airplane	Date Removed from Airplane	Tail #	Airplane Make Model	Date of Manuf.
2-7681-2	2297	11/3/2014	NO	23160	8751		10/2/2007	11/4/2014	3704	Boeing 737	
2-7681-2	5807	11/12/2014	Yes- REPAIRED PREVIOUSLY in 2002	28140	9508	Unit would not fuse completely. Fluid flow would not stop.	12/14/2006	10/14/2014	5811	Boeing 757	2/28/2000
2-7681-2	2355	11/12/2014	NO	18853	7152		3/10/2009	10/28/2014	3704	Boeing 737	
2-7681-2	2369	11/13/2014	NO	25378	9653		4/17/2007	11/11/2014	3706	Boeing 737	3/31/2000
2-7681-2	2510	1/8/2015	NO	22577	8557		3/5/2008	12/15/2014	3741	Boeing 737	8/22/2000
2-7681-2	2982	1/8/2015	NO	20464	7171		11/25/2008	12/18/2014	685		8/17/2001
2-7681-2	2980	1/29/2015	NO DATA	NO DATA	NO DATA	FUSE TOO SOON. Manual fuse too early by about .33 seconds. Automatic fuse too early by about 4 seconds.	NO DATA	NO DATA	CUSTOMER		6/17/2001
2-7681-2	4813	1/29/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		10/6/2011
2-7681-2	2704	3/3/2015	NO	21642	7367		12/17/2008	2/21/2015	3746	Boeing 737	1/23/2001
2-7681-2	3526	3/19/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		4/10/2003
2-7681-2	2280	5/7/2015	NO	27331	9128		8/21/2007	5/3/2015	3750	Boeing 737	12/23/99
2-7681-2	0164	5/7/2015	NO	25103	4818		3/31/2009	4/27/2015	6807	Boeing 757	4/25/1990
2-7681-2	1406	5/7/2015	NO	25217	9592		10/12/2007	5/3/2015	3708	Boeing 737	2/3/1998
2-7681-2	1914	5/20/2015	NO DATA	NO DATA	NO DATA		NO DATA	NO DATA	CUSTOMER		1/29/1999

Table A-6. Rate fuse failure frequencies, by part number, for the individual tests

Part	Test	X	N	Freq.
7680	VI	0	30	0.00
7680	PP	2	30	0.07
7680	MFR	6	30	0.20
7680	AFR	4	30	0.13
7680	PD	2	30	0.07
7680	IL	4	30	0.13
7680	CT	3	30	0.10
7680	VC	0	0	
7680	RF	0	0	
7680	Fail Any	9	30	0.30
7681	VI	0	14	0.00
7681	PP	0	14	0.00
7681	MFR	2	14	0.14
7681	AFR	2	14	0.14
7681	PD	0	14	0.00
7681	IL	0	14	0.00
7681	CT	0	14	0.00
7681	VC	0	0	
7681	RF	0	0	
7681	Fail Any	2	14	0.14

Table A-6 contains test-specific failure frequencies for the fuses. The abbreviations used in the table are:

- VI–Visual inspection
- PP–Pressure proof
- MFR–Manual fuse reset
- AFR–Automatic fuse reset
- PD–Pressure drop
- IL–Internal leakage
- CT–Closing time
- RF–Reverse flow

APPENDIX B—STATISTICAL METHODS FOR FAILURE TIME ANALYSIS

Failure time analyses are used to characterize failure probabilities over time. For the time to failure to be well-defined, the time scale and time origin must be specified. For this study, a healthy fuse is defined as either a new fuse or a fuse that has been repaired, and then the time to failure for a healthy fuse is considered. The time origin is defined as either the date of fuse manufacture, if no previous repairs occurred, or the date of last installation, if previous repairs did occur. This definition of the time origin is made under the assumption that repaired fuses are no different from new fuses in terms of failure probability. Furthermore, the date of manufacture likely does not directly relate to the date of first use of the fuse, resulting in some error in the time origin. The most natural time scale for this application is time that the healthy fuse is in use. Though it would be ideal to conduct the analysis using time in fuse flight hours since first operation of the healthy fuse, the collected data contain limited information about the life history of the fuse and do not include a measure of “healthy” fuse flight hours. Therefore, time is measured in calendar years.

Many failure time studies are prospective, in which units are followed over time and observed to see when the failure occurs. This study is “retrospective” in nature; that is, fuses are inspected by selecting planes due for inspection. Therefore, the sample is potentially left-truncated. That is, if a fuse failed at the previous inspection and was discarded and replaced, than the fuse would not show up in the dataset. It is assumed in this analysis that no left truncation occurred; fuse failure times were overestimated in the presence of left truncation. For example, in figure B-1, “Failure 1” would not be in the collected data if the failed fuse was discarded, whereas “Failure 2” would be included in the data. It was also assumed that the screening time is independent of the fuse failure time (that is, fuses are not being targeted for inspection based on a known malfunction).

The amount of “censoring” (i.e., how much is known about when the failure occurs) dictates the amount of uncertainty present in the failure time estimates (conditioning on the sample size). The collected data can be viewed as interval censored. With interval-censored data, it is known that an object failed during some time interval (e.g., after the most recent inspection or between the prior and most recent inspections). The amount of information contained in interval-censored data depends on the width of the interval relative to the failure time; in this case, the intervals are rather wide, 6–8 years, and, therefore, the data contain relatively little information relative to other types of failure time data. In addition, because many planes were presumably receiving “routine screening,” censoring times are rather homogeneous in the collected data, making it further difficult to identify exactly when fuses are failing.

Parametric failure time models were fit to estimate the years to fuse failure from installation of the healthy fuse, assuming that no fuses were discarded at the previous inspection (no left truncation) and that repaired fuses are as healthy as new fuses. Failure time estimates would be biased high in the presence of left truncation. First, nonparametric and parametric survival curves were estimated assuming that the failure times follow a Weibull distribution, as shown in figure 4 in the main report. Survival curves are defined as the survival probabilities for a fuse as a function of time. The survival probability for a fuse at a specific time is defined as the probability that a fuse still functions at that time; the survival time for a fuse is defined as the

time at which the fuse would fail (and is assumed to be a random variable). The point-wise large-sample 95% confidence intervals (CIs) for the parametric curves are wide for the 2-8020 hydraulic fuses because of the small number of observed failures.

The quantiles of the failure times are also estimated using the Weibull failure time model. The Q th quantile for a fuse failure time is defined as the time at which $100*Q\%$ of fuses would fail. For example, estimating the time at which 50% of fuses will fail may be of interest. Estimation of the failure quantiles with corresponding 95% CIs is completed by using large-sample maximum likelihood estimates and parametric bootstrap resampling because maximum likelihood estimates can be inaccurate with a small sample. Bootstrap estimates can also be unstable with high censoring rates, so both estimates are presented and it is advised that the conservative estimates be given more weight.

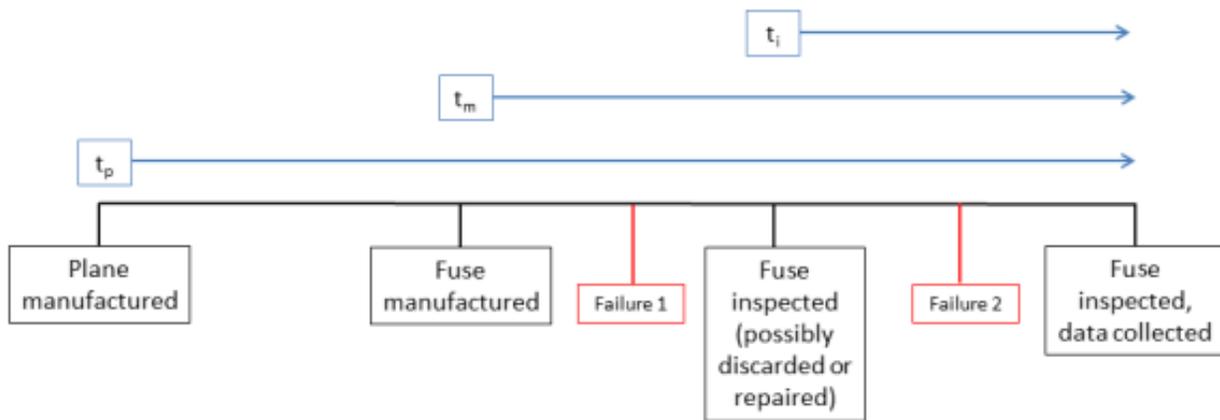


Figure B-1. Graphical depiction of various time scales