

Transport Airplane Hydraulic Fuse Functional Reliability Study

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AA&S Conference 2017



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Goal of this study

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.

Airplane Certification

- 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.

Latent Failures

- 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].

Hydraulic Fuse Purpose and Uses

- Hydraulic power systems provide means for pilots to operate different aircraft components such as landing gears, flaps, flight control surfaces, and brakes [2].
- 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.

Importance of Hydraulic Fuses

- Japan Airlines Flight 123 at Gunma Prefecture on August 12, 1985 [3]



http://lessonslearned.faa.gov/ll_main.cfm?TabID=4&LLID=16&LLTypeID=2

- United Airlines Flight 232 in Sioux City, Iowa in 1989 [4]



http://lessonslearned.faa.gov/ll_main.cfm?TabID=3&LLID=17&LLTypeID=2

Hydraulic Fuse Design

- Hydraulic Fuses are mechanical components that 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.

Historical Hydraulic Fuse Failure Rates



- Nonelectronic Parts Reliability Data (NPRD) 95 identifies a blanket failure rate for hydraulic fuses at $1.61\text{e-}6$ 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.

Study Purpose

- 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.

Study Design

- Tested 151 hydraulic fuses from 27 different aircraft.
 - 5 hydraulic fuses came from salvage yards
 - 146 hydraulic fuses came from Delta Air Lines
- We partnered with Delta Air Lines to inspect the majority of the hydraulic fuses already being serviced by Delta Air Lines TechOps in Atlanta.
 - Difficult to purchase hydraulic fuses with the necessary part history information from salvage yards.
- All fuses were manufactured by Dowty Aerospace in Yakima, Washington.

Study Design Continued...

- 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.
 - Additional information collected from Delta Air Line airplanes include:
 - 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 airplanes.
- Had to assume that the last inspection date for the Delta Air Lines hydraulic fuses corresponded to the date of last installation.

Data Analysis Methods

- To determine the functionality of hydraulic fuses in transport category aircraft, two analyses were conducted:
 - Characterization of fuse failures
 - Estimation of time to fuse failure- Note that the failure time analysis were conducted but due to the small amount of fuses with the required data, we could not obtain useful information.
- Characterization of fuse failures by
 - Fusing immediately
 - Fusing too early
 - Fusing too late
 - Never Fusing
 - Inconsistent fuse failure across tests (e.g. early on one test and late on another test)
 - ❖ For the tests conducted for this study, a latent failure is identified when the hydraulic fuse never sets/closes.

Data Analysis Methods Continued...

- Estimation of time to fuse failures
 - Failure frequencies estimated based on data collected from testing for each part number
 - Confidence intervals (CI) are calculated to characterize uncertainty in failure frequencies using the binomial distribution
 - Assuming fuses in this study area a random sample of fuses receiving routine screening, we can calculate a 95% confidence interval for the true fuse failure frequency on routine screening.
 - The number of failures and failure mechanisms are tabulated by part number among fuses that failed any test to determine the most prevalent failure mechanism
 - Fisher's exact test was completed to assess whether there was evidence of an association between failure mechanisms and part numbers

▪ Fuse failure rate calculated by
$$\frac{\text{Number of failures}}{(\text{Number of fuses}) \times (\text{*Flight hours per fuse})}$$

*Assumed 25,000 flight hours per fuse

Volume Hydraulic Fuse Testing

- Tested at Delta Air Lines TechOps facility in Atlanta, GA.
- Volume fuses were manufactured by Dowty Aerospace, in Yakima, WA



2-8041

2-8020



Volume Hydraulic Fuse Testing Procedure

- For 2-8020-1, -2, -3, and -5 fuses
 - Steps 1-6, and 9
- For 2-8020-6 fuses
 - Steps 1-6, 7, and 9
- For 2-8041 fuses
 - Steps 1-8 and 10

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	

Volume Hydraulic Fuse Data Analysis

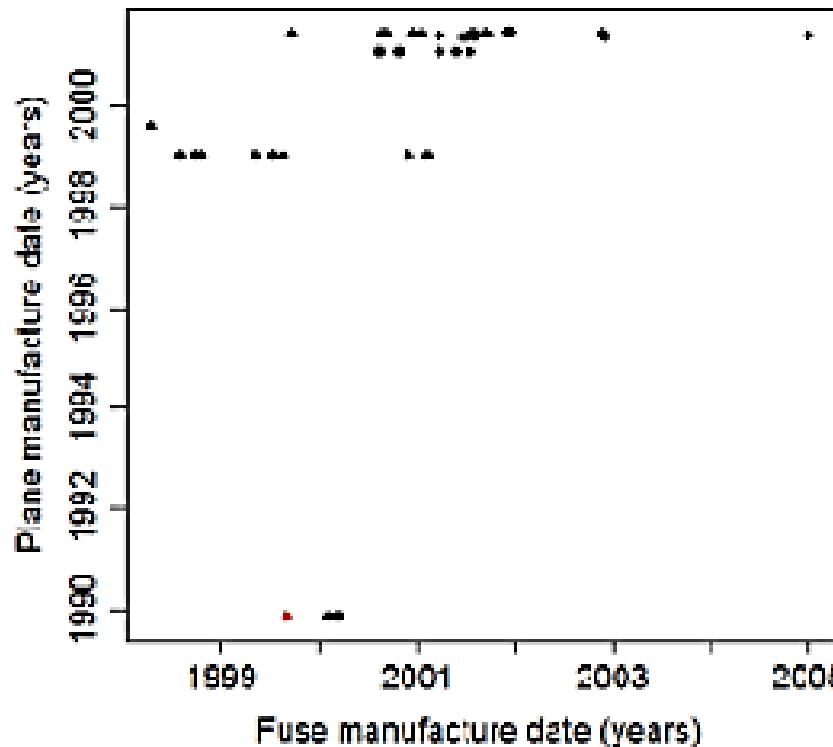
- Fuse Age and Inspection Intervals
 - Examined total of 107 volume hydraulic fuses
 - 60 of the 2-8020
 - 47 of the 2-8041
 - The majority of the Delta Air Lines planes were inspected:
 - every 5-8 years since last inspection
 - 12-18 years from date of manufacture

	%	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

Volume Hydraulic Fuse Data Analysis



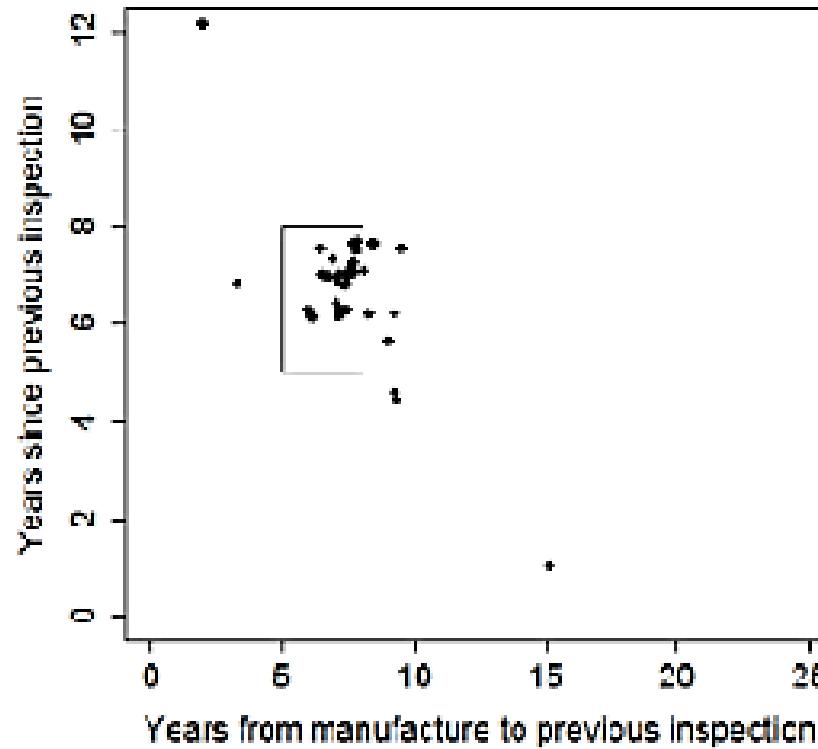
▪ Fuse Age and Inspection Intervals



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.

Volume Hydraulic Fuse Data Analysis

- Fuse Age and Inspection Intervals



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.

Volume Hydraulic Fuse Data Analysis

- Failure Frequency

Part	N	X	Any failure		Upper	X	Latent failure		Upper
			Freq	Lower			Freq	Lower	
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

Volume fuse failure frequency (failed at least one test) for routinely screened planes. N is the total number of hydraulic fuses each specific fuse category and X is the number of **volume** hydraulic fuses that failed. The frequency estimate (Freq) and 95% confidence interval (Lower and Upper) are also shown.

- Assuming all fuses were in use for 25,000 flight hours:
 - Estimated Fuse Failure rate is 2.7e-5 with 95%CI (2.3e-5, 3.1e-5)
 - Estimated Latent Failure rate is 2.2e-6 with 95%CI (8.3e-6, 4.7e-6)

Volume Hydraulic Fuse Data Analysis

- Failure Frequency

Part	Number of failed tests								
	0	1	2	3	4	5	6	7	N
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

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

- Of the fifty-three 2-8020 fuses, 27 failed step 6 in the test procedure and another fuse failed steps 3, 6, and 9.
- Of the seven 2-8020-6 fuses, 1 failed step 6
- Of the forty-seven fuses, 44 failed one step in the testing procedure

Volume Hydraulic Fuse Data Analysis

- Failure Frequency

	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

The failure mechanisms for the different part numbers are shown in this table. We tested for an association between part number and failure mechanism using a Fisher's exact test. There is evidence that failure mechanisms differ by part number ($p < .001$), with 2-8041s more likely to fail early and 2-8020s more likely to fail late.

Rate Hydraulic Fuse Data Analysis

■ Test Results

- Examined a total of 44 Rate Hydraulic Fuses
 - 30 of the 2-7680 Flow Rate Fuses
 - 14 of the 2-7681 Flow Rate Fuses

2-7680
&
2-7681



Rate Hydraulic Fuse Testing

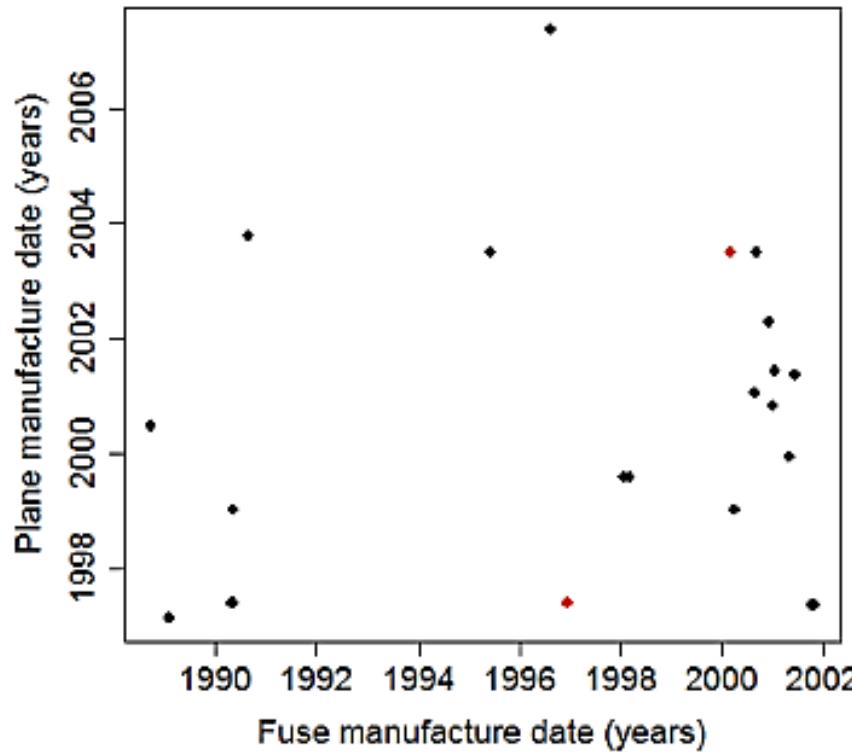
Procedure

- For 2-7680 and 2-7681
 - Steps 1-8

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	

Rate Hydraulic Fuse Data Analysis

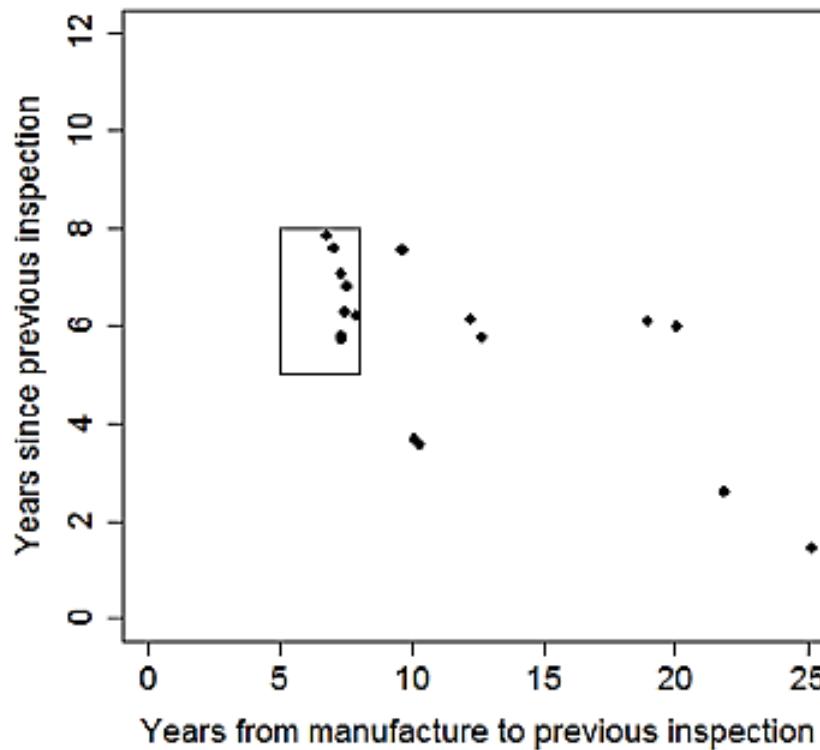
- Fuse Age and Inspection Intervals



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.

Rate Hydraulic Fuse Data Analysis

- Fuse Age and Inspection Intervals



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 period which corresponds to the expected inspection time interval.

Rate Hydraulic Fuse Data Analysis

- Failure Frequency

			Any failure						Latent failure	
Part	N	X	Freq	Lower	Upper	X	Freq	Lower	Up	
7680	30	9	0.30	0.15	0.49	4	0.13	0.04	0.31	
7681	14	2	0.14	0.02	0.43	1	0.07	0.00	0.34	
Rate	44	11	0.25	0.13	0.40	5	0.11	0.04	0.25	

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

Rate Hydraulic Fuse Data Analysis

- Failure Frequency

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

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

Rate Hydraulic Fuse Data Analysis

- Failure Frequency

	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

This table shows the failure mechanisms for the different part numbers.

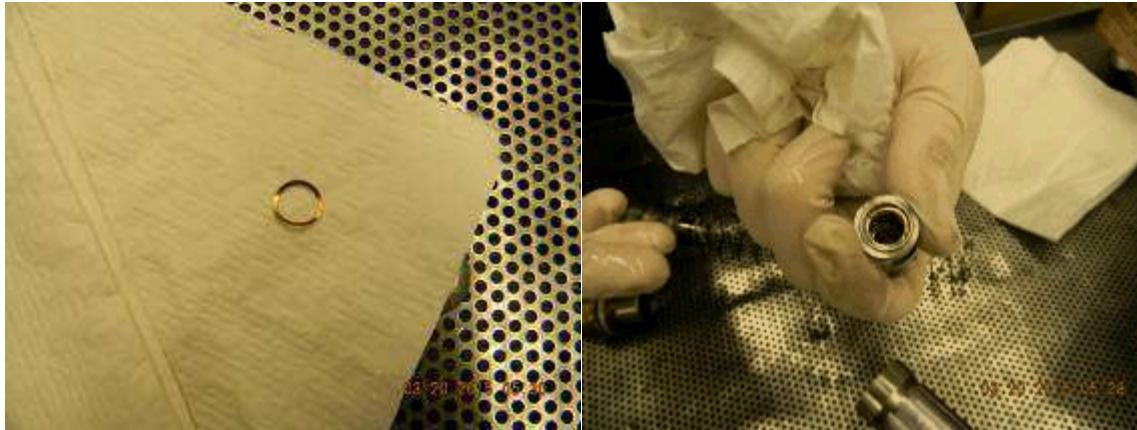
We tested for an association between part number and failure mechanism using a Fisher's exact test. There is no evidence of a difference in failure mechanisms by part number ($p = 1.0$), though we have very little data available to be able to detect such a difference.

Summary of Conclusions

- Note the NPPD 95 indicated that the failure rate for hydraulic fuses is about $1.61\text{e-}6$ failures per flight hour. This is consistent with the estimated latent failure rate in this study, $4.5\text{e-}6$ failures per flight hour for rate fuses and $2.2\text{e-}6$ failures per flight hour for volume fuses.
- We estimate that 68% of volume fuses and 25% rate fuses failed at least one test step of the routine inspection
- The rates of latent failures were much lower, with an estimated 6% of volume fuses and 11% of rate fuses experiencing latent failures.

Summary of Recommendations

- Conduct analyses and testing to determine life expectancy of fuse internal components.



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

- Examine the role of fluid cleanliness in fuse failures.
- Use digital equipment to test all hydraulic fuses.
- Increase the frequency of functional testing to account for fuses that have gone through functional testing more than once.

QUESTIONS?

References

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