T-38 FUSELAGE STRUCTURAL LIFE ASSESSMENT

by

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Abstract

The T-38 "Talon" jet aircraft is a major component of the USAF Air Education and Training Command's (AETC) pilot training, and has been the advanced trainer since the early 1960s. The size of the AETC training fleet is several hundred aircraft, with other smaller T-38 fleets employed by the USAF and others. These fleets are used in various roles, such as undergraduate pilot and basic fighter skills training, the proficiency and test pilot training, and as chase aircraft.

Several structural modifications to the fuselage have been implemented to extend the T-38 structural service life. In order to determine the future structural life of the fuselage, a full-scale structural durability test, teardown, and structural life evaluation was needed. The effort outlined in this paper is geared to support that evaluation with the ultimate goal to help determine if the T-38 fuselage structure can be safely and economically used as an advanced trainer until calendar year 2025.

A representative fuselage was provided by the Air Force and tested to 8,500 hours of a severe usage. Data gathered during testing and teardown was analyzed to determine the locations and test hours-to-cracking for three different life-limiting structural components. All three components were modified or installed after initial production via fleet-wide time-compliance-technical-order modification, and all experienced cracking at different times during the test. Discovery of the cracks, combined with knowledge of the total time on the airframe and severity of usage, are primary inputs into the statistical analyses of the components' cracking.

Because of the long service time, the multiple roles and usages, and previous modifications made to the T-38 fuselage, it was necessary to consider aircraft individually. Each aircraft has had a different combination of usages for different lengths of time since their acceptance into the Air Force and different times modifications were made to the fuselage. Additionally, each of the usages has a different severity when compared to others, and that level of severity also varies by component.

The preferred method of comparing aircraft to each other is to baseline the hours of the different components against a particular usage. By combining the way each aircraft was

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Introduction

In July 2002, the Ogden Air Logistics Center (OO-ALC) initiated a program to evaluate the structural life of the T-38 fuselage. That assessment is based upon a full-scale fuselage durability test and destructive teardown inspection performed by Southwest Research Institute® (SwRI®), coupled with findings from fleet inspections, evaluation of fleet flying history, and future flying projections for the T-38.

Background

The primary purpose of the T-38 Fuselage Structural Fatigue Test and Life Evaluation was the determination of the long-term viability of primary structural components on the T-38 fuselage. This includes the first ever fuselage fatigue test for the T-38, including modifications that have been installed in the fleet. These modifications include the steel dorsal longerons (SDL - installed fleet-wide in the 1980s), the cockpit enclosure modification (CEM - installed in the 1990s), upper longeron splice (also installed in the 1990s), and new primary bulkheads (replaced for stress-corrosion cracking). Another benefit of this program was investigation of fatigue critical locations (FCLs) on the fuselage. This includes confirmation of FCLs assumed from original analyses (or past fleet findings) and determination of possible new locations that may be susceptible to fatigue cracking. Secondary benefits of the test include evaluation of repairs and collection of load, stress, and deformation data to support finite element modeling and analysis.

Approach

The overall approach for the fuselage life study is shown in the blocks of the cycle diagram in Figure 1. First the fuselage test is performed and the test article is torn down (blocks 1 and 2 of Figure 1). Fleet history is established under various usages and the severities of those usages are evaluated (blocks 3 and 4). The hours on each component in the fleet are determined and their time in different usages is converted to the baseline that was used during the fuselage test (block 5 and 6). The findings both during testing and teardown are considered for statistical analysis and the analysis is performed for key life limiting airframe components (block 7). Historical flying rates and relative severity for current usages are established to determine how many equivalent hours an aircraft will accumulate in a given usage per calendar time increment (block 8). Knowing each components equivalent hours relative to the test, predictions can be made using the results of the statistical evaluation (block 9).

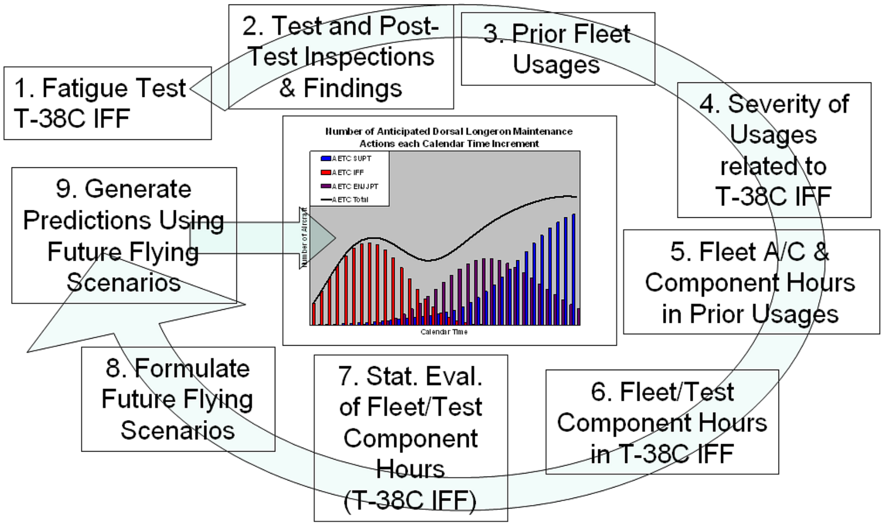


Figure 1 Process for the T-38 Fuselage Life Study

Review of Test and Fleet Inspections

Test Article and Test Set-up

The fuselage fatigue test was conducted at SwRI® in San Antonio, Texas during the period from December 2004 to October 2006. The test was conducted under IFF usage loading spectra collected by SwRI at Columbus AFB and Randolph AFB during the period 1996-1997 [Ref. 1].

The fuselage test article represented the most modern T-38 structural configuration, the T-38C. This includes structural modifications made by: (1) Pacer Classic I, (2) Pacer Classic II, and the Propulsion Modification Program (PMP).

The applied loads for the test article include the mass inertias from the AUP, PMP, and instructor and student ejection seat upgrades. The first T-38Cs with the PMP were delivered to training bases in November 2002. In this paper, T-38 aircraft flying with the AUP and PMP modifications noted above will be designated as T-38C.

The external loads applied to the fuselage test article are based upon flight data recorder programs conducted at Columbus AFB and Randolph AFB in the period 1995-1997 [Ref. 1] on aircraft flying the IFF usage. As discussed later in this paper, the IFF usage data collected in 1995-1997 differs somewhat from the IFF usage recently collected on T-38C aircraft at Moody AFB. Because of this difference, the IFF usage used for the fuselage fatigue test is designated as T-38C IFF (Test). The IFF usage for Moody AFB aircraft is designated as T-38C IFF (Moody). Figure 2 shows the position of actuators for load application to the test fuselage. More information regarding the test can be found in Ref. 2.

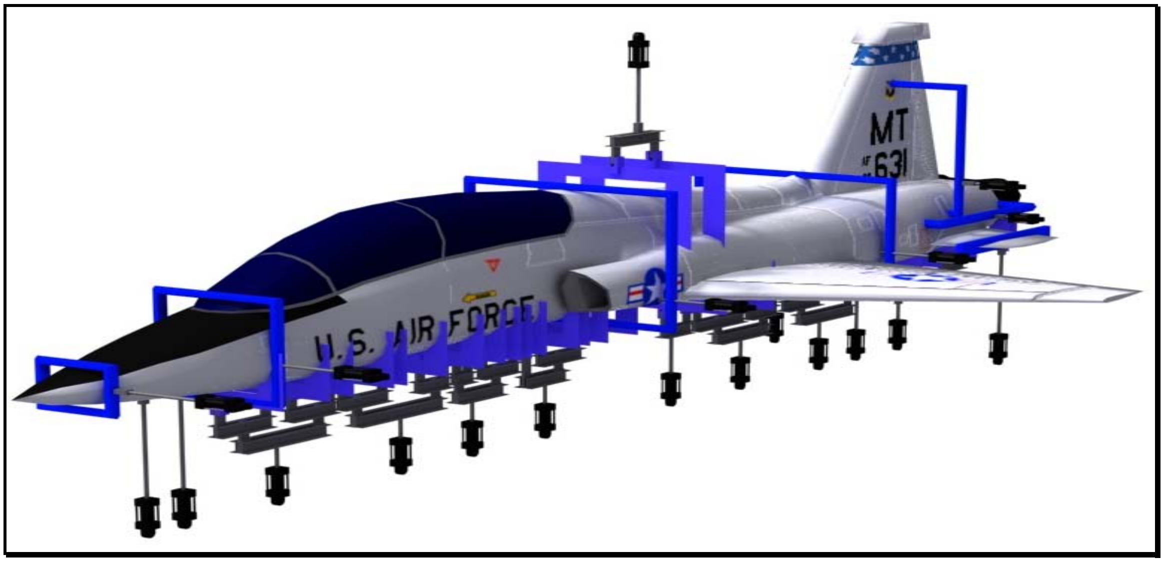


Figure 2 Load Application Arrangement

Major Cracking and NDI Indications Found During Testing

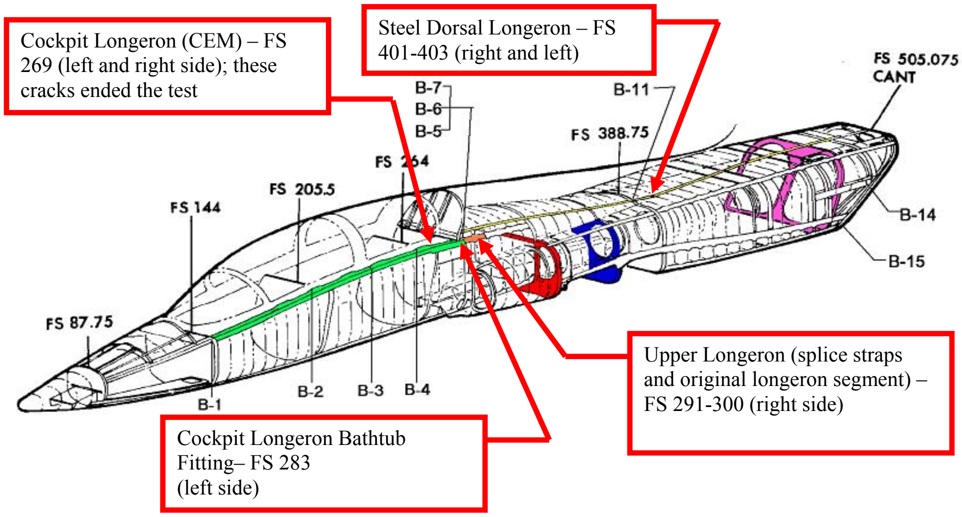
Around 4,500 simulated T-38C IFF (Test) flight hours, significant cracking started to appear on the fuselage. Table 1 below summarizes the significant cracking found during the test period, which was important in the life evaluation process.

Table 1 Observed Major Cracking Found During Test

Component	Fuselage Station/Side	First Observed (IFF Test Hours)	Disposition
Steel Dorsal Longeron	FS 403/Right	4500	Repaired with steel doubler
Steel Dorsal Longeron	FS 403/Left	5500	Repaired with steel doubler
Steel Dorsal Longeron	FS 401/Left	7500	Under repair area for FS 403 steel doubler
Test stopped at 8139 hours to remove the earlier repair steel doublers and install bonded boron doublers on both sides due to continuing accumulated damage of steel dorsal longerons			
Dorsal Deck	FS 397, Left & Right of Centerline	8139	Repaired with aluminum doublers
Upper Longeron	~FS 293/Right	8139	Splice Straps Replaced
Upper Longeron	~FS 297/Right	8139	Oversized 2 holes in upper longeron
Cockpit Longeron Bathtub Fitting	FS 283/Left	8500	Repair started
Cockpit Longeron	FS 269/Left FS269/Right	8500	Discovery of these cracks ended test

Figure 3 shows the general location of the cracking. Of the four components shown, three of them were candidates for this evaluation (Steel Dorsal Longeron, Upper Longeron, and the Cockpit Upper Longeron). The fourth item (dorsal deck) was repaired with a typical structural repair manual approach and was not included in the evaluation since it is not a fatigue critical structural item (it is not expected to be a critical driver of structural component life).

There were three observable cracks found on the left and right SDLs along with a small, non-visible crack found by non-destructive inspection (NDI) at 7,000 simulated flight hours. These three cracks were used in the statistical life evaluation of the SDL. The three cracks found on the RHS splice straps, that resulted in replacement of the straps, were considered 'one crack event' and the location was evaluated as such in the statistical life analysis of the 284 splice. This was considered a 'one crack event' since the primary cracks in the straps were at the same fuselage station and on the same side of the aircraft. Because of the cracking at FS 269 on both left and right longerons, along with the technical difficulty and financial/schedule impact of making repairs, the Air Force decided to stop the test. It was decided, for the statistical life evaluation, to consider the cracking on the cockpit longeron as a ‘two crack event,’ one on each side of the fuselage.



Cockpit Longeron (CEM) – FS 269 (left and right side); these cracks ended the test

Steel Dorsal Longeron – FS 401-403 (right and left)

Upper Longeron (splice straps and original longeron segment) – FS 291-300 (right side)

Cockpit Longeron Bathtub Fitting– FS 283 (left side)

Figure 3 Major Cracking Found During Fatigue Test

Post Test Teardown Cracking

Additional cracking was found during the destructive teardown of the T-38 test fuselage. A couple of these findings were on the components in the life evaluation but most were on secondary structure or primary structure which is not fatigue critical. The two cracks found on the SDL were in the region of the three cracks found during testing. Due to a lack of knowledge as to when they had formed were omitted from the analysis.

Inspection Information from TCTO 1T-38-809

After the cracks were found in the steel dorsal longerons of the test aircraft, the USAF issued Safety Time Compliance Technical Order (TCTO) 1T-38-809 [Ref. 3]. That TCTO called for inspections of dorsal longerons P/N 3-11413-1/-2, at F.S 400.5 to 424.5 on 116 T-38 training aircraft. Serial numbers of these aircraft are given in the TCTO. No indications of cracking were found on these 116 aircraft from the TCTO 1T-38-809 inspections.

Variations in Fleet Usages

Because of the variation in usage severity of an operational or fighter trainer aircraft, total flight hours is not a good indicator of how the aircraft has been flown. A better indicator is to put the aircraft on a common usage severity basis. For this evaluation the common usage basis will be that used in the full-scale fuselage test, which was designed to represent the T-38C flying IFF usage. This usage is designated as the T-38C IFF (Test).

A similar approach was done for the economic life evaluations for the -29 wing. For example in Refs. 4 and 5, the -29 wing economic lives were expressed in terms of equivalent flight hours for SUPT, IFF, ENJJPT, and SUPT/IFF (a mixture of SUPT and IFF) usages. Ref. 6, which updated the economic lives for the -29 wings flying IFF usage, expressed results in terms of equivalent IFF flight hours.

The categories given in the Reliability and Maintainability Information System (REMIS) are an indication of the usage assigned to a particular aircraft for a flight hour or time interval. USAF Technical Order (TO) 1T-38A-6 [Ref. 7], which sets the T-38 scheduled inspection requirements, defines which aircraft are assigned to the Category Levels 1-8 where category level is a usage specific code and not a measure of relative severity. A further distinction was made between usages depending on whether the aircraft configuration was that of a T-38A/AT-38B or the heavier T-38C configuration with PMP. Aircraft were considered to be modified once they had PMP complete and their new usage was noted as the Category plus the suffix “PMP”.

Severity of Usages Related to T-38C IFF (Test)

Usage Severity for SDL

Fatigue critical location (FCL) B-11V is the closest currently identified FCL to the 5/32-inch countersunk hole at FS 405.05. FCL B-11V is a crack from a nut plate hole in the vertical leg of the steel dorsal longeron at FS 352.5.

To determine usage severity factors for other past usages and usages anticipated in the future, damage tolerance crack growth analyses were conducted for the usages and aircraft configurations. Note that the T-38C includes all fuselage modifications, including the PMP upgrade. The usage categories also makes a distinction between the T-38C (Test) and T-38C (Moody) because the four aircraft instrumented at Moody AFB with flight data recorders indicate that those aircraft are being flown more severely than the fuselage test usage.

Normalized factors were developed by scaling each crack growth curve, on the basis of flight hours, so that the resulting curve matched the crack growth curve for the T-38C IFF (Test). Ref. 8 contains the most recent durability and damage tolerance evaluation of this FCL for SUPT and IFF usages. The fuselage inertias used in the Ref. 8 DADTA are representative of T-38A aircraft prior to the weight changes of the T-38C. Figure 4 shows example crack growth curves, indicating the method of collapsing other usages upon the baseline usage. In the given example the usage severity factor is 0.5, or one hour of this fictitious usage equals 0.5 hour of T-38C IFF (Test) usage.

The DTAs for FCL B-11V indicate that crack growth retardation is present at this location. The degree of retardation is determined by calibrating crack growth analyses with coupon testing conducted under variable loading representative of the usage spectrum. Since no coupon test has been conducted for T-38C IFF usage, retardation factors used in Ref. 8 were assumed.

To evaluate the effect of retardation, unretarded analyses were conducted for the T-38A ENJJPT and T-38C usages. Comparison of the retarded and unretarded results revealed that usage factors for the retarded analyses are greater than the unretarded. Therefore, the usage factors including retardation effects will be used for the SDL life evaluations.

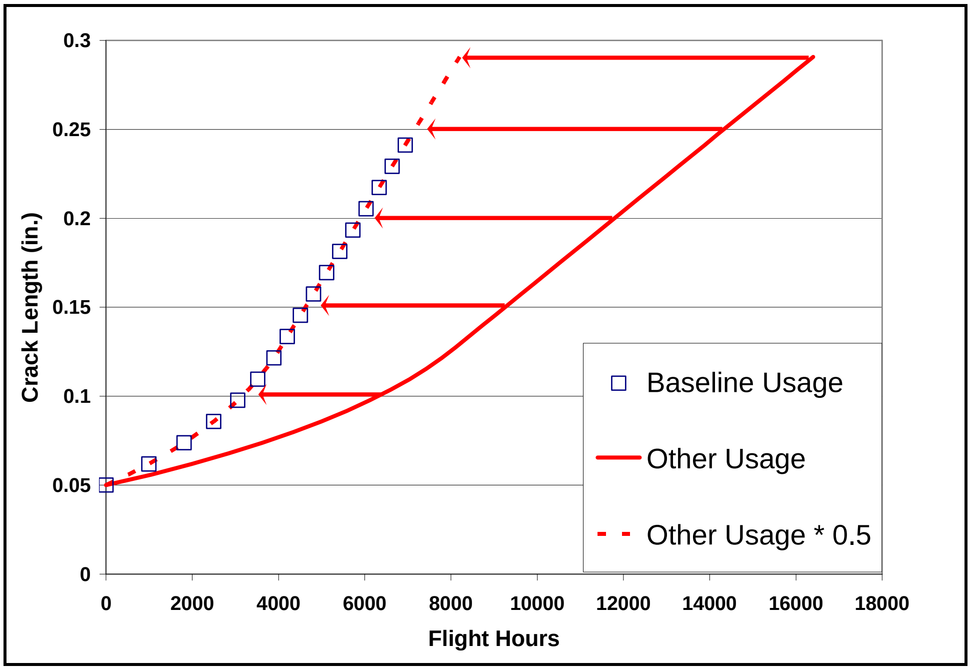


Figure 4 Example Crack Growth Curves and the Usage Severity Factor Represented

Usage Severity for CEM

Fatigue critical location (FCL) B-4CEM is the closest currently identified FCL to the cracks found on the upper cockpit Longeron at FS 269. FCL B-4 CEM is a crack from the corner of the CEM upper longeron hook slot at FS 267. Ref. 8 contains the most recent durability and damage tolerance evaluation of this FCL for SUPT and IFF usages.

The same process used for the SDL was employed to determine the usage severity factors for the CEM. The DTA for FCL B-4CEM indicate that no crack growth retardation is present at this location. Therefore, all analyses were conducted unretarded.

Fleet Aircraft and Component Usage Hours

Prior Usages

All T-38 aircraft have been flown in a variety of usages since they began service in the 1960s. Some usages were relatively benign to the aircraft structure, while other usages, such as the LIF and IFF, are more severe. Generally, the T-38 usage severity has increased over time, as evidenced by several generations of wing structural changes. As part of the T-38 ASIP, usage severity is monitored by flight data recorders installed on aircraft at the Air Force training bases.

To determine the equivalent IFF (Test) hours of each component analyzed on each aircraft, three different pieces of historical information were needed. The first of these items relate to each aircrafts historical usage, mainly: what usage categories did the aircraft fly, when did they fly them, how many hours were flown? Second, when was the component of interest installed on each aircraft? Finally, at what time were they inspected? Each item will be discussed in the order presented above.

A large text file containing monthly aircraft data, retrieved from REMIS, was obtained by SwRI in early 2002. This information included tail number, model, total hours, command, category, status, recorder and 'as of' date. It included 908 separate tail numbers and ranged from as early as 1975-1980 up to the 1995-2002 timeframe. The data provided a starting point to build the history of each individual aircraft. An Excel macro was written to discard all data that did not represent a change in usage category or command and separated out each aircraft. Added to this was current information, including all known changes in category and inclusion of TCTO 1T-38-792, which added the PMP modification to the aircraft. A T-38 A or B model officially becomes a C model with the installation of TCTO 1T-38-800, which is the AUP program. The additional weight of the PMP included in the fuselage fatigue test loads more closely represents aircraft after the PMP modification. This large dataset provided the necessary background information needed to determine each aircraft's usage history.

Prior Usage of Components

The next step was to determine the time at which each modification was performed in order to ‘zero time’ the item. The aluminum dorsal longerons for the entire T-38 fleet were replaced by steel dorsal longerons in the years 1982-1992. Over 800 aircraft were modified by two different TCTOs.

A similar process was used to determine the prior usage for the CEM for each aircraft. It too was installed by TCTO over a 9 year period during the 1990s.

Equivalent T-38C IFF (Test) Hours

By using the usage factors previously developed, the equivalent number of T-38C IFF (Test) hours was developed for the SDL and CEM for each individual aircraft in the T-38 fleet. For the example, the test aircraft had 1045 and 265 equivalent T-38C IFF (Test) hours on the SDL and CEM/284 Splice, respectively, prior to test.

Figure 5 shows the equivalent number of T-38C IFF (Test) hours on the SDL and CEM/284 Splice for all 116 aircraft inspected per TCTO 1T-38-809. In this figure, when an equivalent flight hour number is selected from the horizontal axis, the curves will define the number of aircraft that have that number or fewer equivalent flight hours on the component for which the curve is plotted. Table 2 summarizes the prior usage calculations and results from the fatigue test. Figure 5 includes the data from Table 2 for the total equivalent T-38C IFF (Test) hours (test + prior usage) when cracks were found or estimated on the SDL, CEM and 284 Splice. The data shown in Figure 5 was used to establish the statistical life distribution for the SDL, CEM, and 284 Splice.

Table 2 Summary of Prior Usage and Test Hours on SDL, CEM and 284 Splice

Component	Prior Usage Hours (1)	Test Hours (2)	Prior Usage & Test Hours (3)
SDL	1045	4500 5500 7500	5545 6545 8545
CEM	265	7200 8500	7465 8765
284 Splice	265	7200	7465

(1) Equivalent T-38C IFF (Test) Hours
(2) Times Cracks were Found or Estimated from Fuselage Test
(3) Total Hours Used for Statistical Life Evaluation

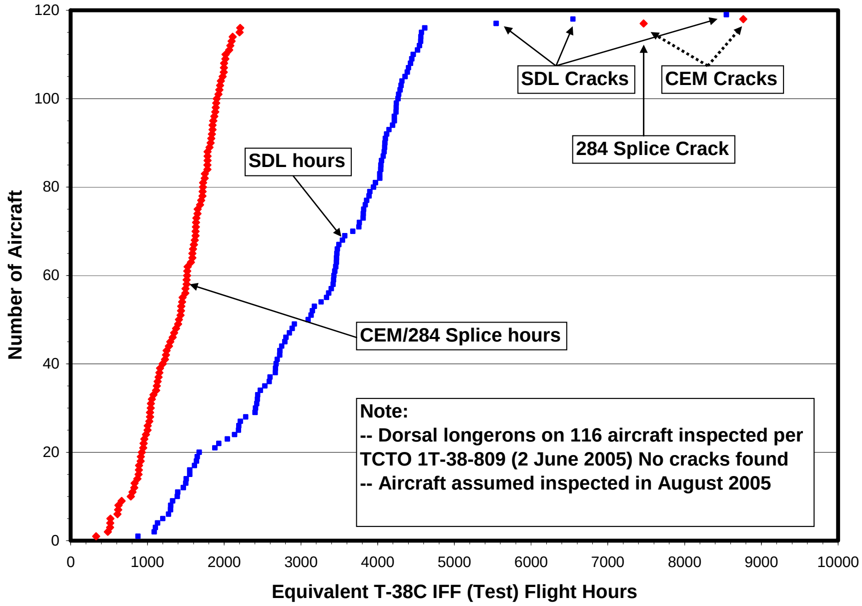


Figure 5 Equivalent Hours on 116 TCTO 809 Aircraft Relative to Cracking Found on Test Aircraft

Statistical Life Evaluation

Introduction

This section discusses and presents the results of the statistical life analyses for components that experienced cracking found in the fuselage full-scale fatigue test. Because of the cracking found in the SDL during the test, the Air Force issued TCTO 1T-38-809 that required inspection of 116 fleet aircraft. No cracking was found in the SDLs of these 116 aircraft.

Background for Statistical Life Analyses

Statistical life analysis is often associated with the Weibull distribution, which was named after its inventor Waloddi Weibull, a Swedish engineer. His landmark paper [Ref. 9] was published by the American Society of Mechanical Engineers (ASME) in 1951. The Weibull distribution is the most widely used statistical model for life data.

The New Weibull Handbook [Ref. 10] by Dr. Robert B. Abernethy contains an excellent historical discussion of Waloddi Weibull and the use of Weibull analysis of life data. Earlier work by Abernathy and others was published by the USAF Wright Aeronautical Laboratories in 1983 [Ref. 11]. These references provide detailed examples of Weibull analysis. Other respected work on life analysis and the Weibull distribution are by Wayne Nelson [Ref. 12, 13]. These books were first published in 1982 and 1990 and reprinted in 2004.

Other distributions are also used in life analyses. These include, for example, the normal, lognormal, Gumbel, exponential, and Rayleigh distributions. The mathematical expressions for these distributions can be found in standard references on statistics and probability.

Several commercial computer codes are available for conducting statistical life analyses. Two codes that SwRI has used are *WinSMITH Weibull* [Ref. 14] and *Weibull ++* [Ref. 15]. Each code has somewhat different analysis capabilities. For test cases using both codes, SwRI found that the results compare very favorably, certainly with the range of expected engineering accuracy.

Statistical Life Analyses for the SDL and CEM/284 Splice

For the life analysis of the SDL, the population will include the three cracks found on the left and right longerons of the test article, and the 232 (116 x 2) longerons inspected in the 116 aircraft fleet per TCTO 1T-38-809. The 232 SDLs, for which no cracks were found during the TCTO inspections, are called “suspended” or “censored” units. The analysis assumes that if cracks existed on the inspected SDLs, they would have been found. The detectable crack should be in the order of 0.05 inch.

The three SDL cracks found on the fuselage during the test are not failures in the sense that the SDLs are broken. However, if found in service, maintenance action would have to occur, either repair of the crack or replacement of the SDL, before the aircraft would be permitted to fly. The subsequent flight time to failure of the SDL for cracks that have been found in the range ~0.2 inches is on the order of several hundred flight hours. It is not known if complete failure of the SDL would lead to loss of aircraft. Prudent engineering dictates that loss of aircraft from an unrestricted allowance of an aircraft to fly with a crack should never be permitted to occur.

Figure 5 shows the entire population of 232 SDLs inspected on 116 aircraft plus the three cracks found on the test article in terms of the equivalent T-38C IFF (Test) hours. As indicated on the figure, the three dorsal cracks are “lead the fleet.” The test aircraft accumulated 1045 equivalent T-38C IFF (Test) hours before the start of the test, and first crack occurred at 5545 (4500 + 1045) equivalent test hours.

An analysis was conducted using the WinSMITH Weibull program [Ref. 14] with the SDL data shown on Figure 5. WinSMITH Weibull determined that the lognormal distribution best fits the data. Two standard methods for computing the lognormal parameters are Rank Regression (RR) and Maximum Likelihood Estimate (MLE). In the RR method, the median ranks of the failure point are computed and plotted on a lognormal probability scale. The lognormal parameters are computed using a least-squares regression analysis. Ref. 14 recommends that the regression analysis be conducted considering the time to failure as the dependent variable and the median rank as the independent variable since the time to failure has more scatter.

For the data given in Figure 5, which includes the three failure points and the 232 suspensions, the median ranks are not affected by the inspection times on the 232 inspected longerons since the failures all occurred later (to the right) than all inspections. For the Maximum Likelihood Estimate method, a computer program such as WinSMITH Weibull or Weibull ++ is required to numerically iterate to obtain the values of the statistical model parameters that best fit the observed data. As such, the failure times, as well as the suspensions are used in the analyses.

The RR and MLE methods are discussed in detail in standard references such as Refs. 10, 12, and 13. The New Weibull Handbook [Ref. 10] indicates that in small sample size analyses the MLE method is biased, resulting in a slope that is too steep. The three SDL failures certainly constitute a small sample size. The WinSMITH Weibull program has a special computational method to reduce the bias called the Reduced Bias Adjustment (RBA). See Section 5.5 of Ref. 10.

For the life analysis of the CEM, the population will include the two cracks found on the fuselage test article. Although the CEMs were not inspected as a part of TCTO 1T-38-809, this analysis will assume that no cracks exist in the left and right hand CEMs of the 116 aircraft fleet. As in the case for the SDLs, these are called “suspended” or “censored” units.

Figure 5 shows the entire population of 234 CEMs in terms of the equivalent T-38C IFF (Test) hours. As indicated on the figure, the two CEM cracks are “lead the fleet.” An analysis was conducted using the WinSMITH Weibull program and the CEM data shown on Figure 5. WinSMITH Weibull determined that the Weibull distribution best fits the CEM data. The above discussion of the Rank Regression, Maximum Likelihood Estimate, and Reduced Bias Adjustment methods also applies to the Weibull distribution.

Figure 6 shows the WinSMITH Weibull program graphical output for the SDL and CEM using the RBA method. The three SDL and two CEM cracks are highlighted on the plots, which for the SDL and CEM use lognormal and Weibull scales, respectively. For that reason, the lognormal and Weibull CDF lines are linear in Figure 6.

For the life analysis of the 284 Splice, the population will include the one crack found on the fuselage test article. Although the 284 Splice was not inspected as a part of TCTO 1T-38-809, this analysis will assume that no cracks exist in the left and right hand 284 Splices of the 116 aircraft fleet. Like the SDL and CEM, these are called “suspended” or “censored” units.

Because of the proximity of the 284 Splice to the observed cracks in the CEM, this analysis will assume that the usage severity factors for the 284 Splice are the same as for the CEM. In addition, the 284 splice repair was required to be installed by TCTO at the same time as the CEM. Therefore, the distribution of 284 Splice flight hours in the 116 aircraft fleet is the same as the CEM (see Figure 5). Since only one crack was observed in the 284 splice, the distribution parameters cannot be determined like the parameters for the SDL (lognormal, λ and ξ) and CEM (Weibull, η and β). The life analysis will assume that the 284 Splice follows a Weibull distribution with a slope β equal to the Weibull slope of the CEM. Using this assumption, the Weibull characteristic life, η, is calculated by the WinSMITH Weibull program. This is called a Weibayes analysis.

Figure 7 shows the probability of repair or replacement curves, plotted on a linear scale, for the SDL, CEM, and 284 Splice using the cumulative distributions from the statistical life analysis. The observed cracking found during the full-sale test is also noted on this figure.

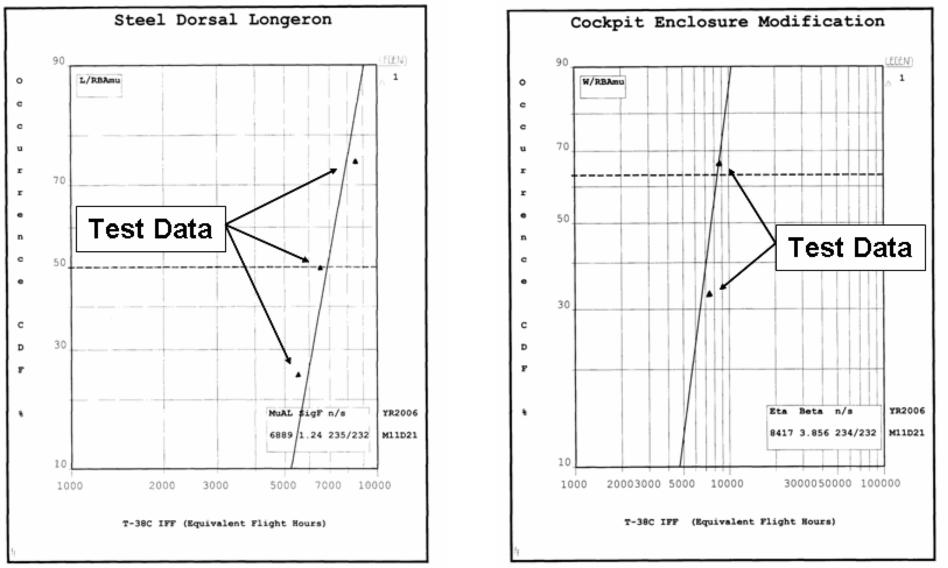


Figure 6 Graphical Output from WinSMITH Weibull -- Best fit for SDL is Lognormal (left) and for CEM is Weibull (right)

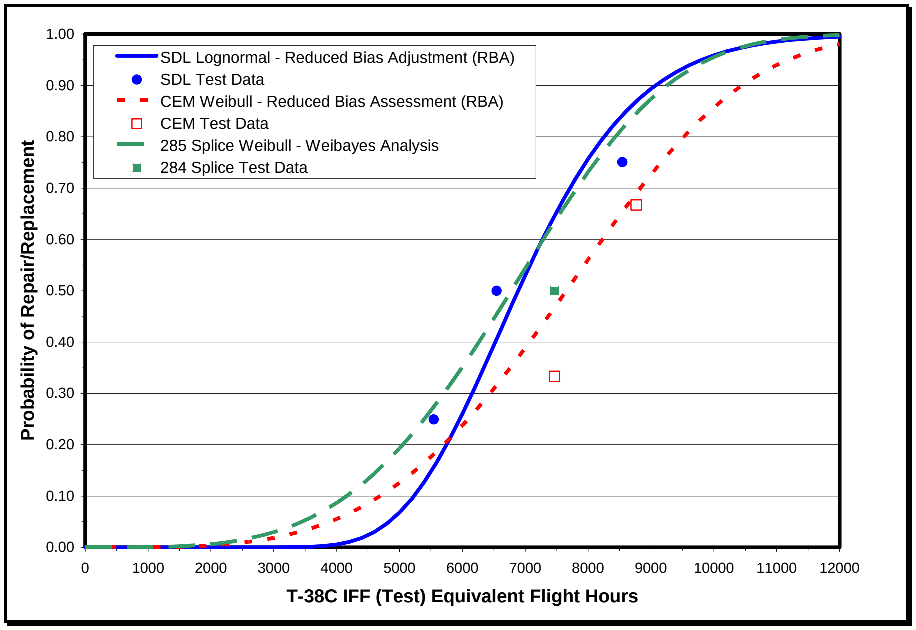


Figure 7 CDF Functions for SDL, CEM, and 284 Splice with Cracking Found During Full-Scale Test

The WinSMITH Weibull program also calculates what is called the Now Risk for the Reduced Bias Adjustment (NowRiskRBA). In mathematical terms

$$\text{NowRiskRBA} = \sum_{i=1}^{r} 2F(t_i) + \sum_{j=1}^{s} F(t_j)$$

where F(t) is the cumulative distribution function for failure, i is summed over the number of failures, and j is summed over the number of suspensions (2 x 116) in the fleet of 116 inspected aircraft.

The above equation gives extra weight (the factor of 2 in the first term) to the number of failures because the Reduced Bias Adjustment is biased on the low side when the number of failure is small. This is the case for the present analyses.

Table 3 summarizes the calculated distribution parameters and the NowRiskRBA for the SDL, CEM and 284 Splice. Note that calculated NowRiskRBA values are reasonably close to the number of observed cracks in the test article.

The Now Risk can also be calculated for the aircraft in the active T-38 fleet. Since no failures have been observed in the fleet, the first term disappears leaving only the summation of all $F(t_j)$. The failures in the test article are not included.

Table 3 Statistical Life Results Calculated by WinSMITH Weibull for the SDL, CEM and 284 Splice

	SDL	**CEM**	**284 Splice**
		Weibull Fit for CEM	*Weibull Fit for CEM* [1]
Characteristic Life T-38C IFF (Test) hours (η)	--	8417	7455
Weibull Slope (β)	--	3.856	3.856
	Lognormal Fit for SDL		
λ = mean of ln(t)	8.8378	--	--
exp[mean of ln(t)] (T-38C IFF Test hours)	6890	--	--
ξ = Std of ln(t)	0.2151	--	--
exp[Std of ln(t)]	1.24	--	--
NowRiskRBA (116 aircraft fleet + test aircraft)	3.9	2.7	1.9
Number of Observed Cracks (116 aircraft fleet + test aircraft)	3	2	1
Note 1 – FS 284 Splice used a Weibayes analysis having same Weibull slope as CEM			

Table 4 shows the Now Risk by Command/Usage for the SDL, CEM, and 284 Splice. As expected, the Now Risk is greatest for the AETC IFF fleet, followed by the AETC SUPT fleet. The numerical calculation of Now Risk produces results expressed in "fractions" of longerons, although "fractions" have no physical meaning. Rounding the totals for the AF fleet, the analysis predicts that there is approximately one each SDL, CEM, and 284 Splice crack in the fleet. Note that this is an indication of when the problems may occur and not an indication of fleet safety. Structural safety is ensured by NDI via TOs and depot economy repair program (DERP) tasks.

Table 4 Predicted Now Risk in the Active T-38 Fleet

Command/Usage	Relative Number of Aircraft	SDL	CEM	284 Splice
AETC SUPT	Large	0.112	0.117	0.187
AETC IFF	Medium	0.984	0.365	0.582
AETC ENJJPT	Medium	0.000	0.160	0.255
ACC	Small	0.000	0.023	0.037
AFMC	Small	0.008	0.018	0.028
Total	**AF Fleet**	**1.104**	**0.683**	**1.089**

Economic Life and Mean Time to Failure

The economic life predictions of the T-38 -29 wing conducted by SwRI in the 1990s involved combining results of the full-scale -29 wing durability test with cracking experienced in the fleet. Results are documented in Refs. 4-6. The economic life definition, (i.e., 50 % probability of replacement) for the -29 wing was selected with the concurrence of the USAF.

It should be emphasized that the definition of economic life for the -29 wing did not affect the predicted number of replacement wings. The number of replacements was only dependent on the cumulative distribution functions, the future flying usage severity, the fleet size, and expected number of flight hours. The economic life was given solely to provide a qualitative estimate of when wing replacement should be expected. This is also the case of the SDL, CEM and 284 Splice.

Using the statistical parameters for the distributions given in Table 3, the economic lives for the three components can be calculated from the expression

$F(t_{\text{economic life}}) = 0.5$

where F(t) is the CDFs for the SDL, CEM, and 284 Splice. Results are given in Table 5.

Another term that is more commonly used in life evaluations is the Mean Time to Failure (MTTF) or the expected life. The MTTF for the SCL, CEM, and 284 Splice are also given in Table 5. For the Weibull distributions that characterize the CEM and 284 Splice, the Economic Life (50% Probability) and MTTF values are virtually the same. For the SDL, the values differ by only 2.3 percent. Practically speaking for this analysis, it makes no difference whether the Economic Life (50% Probability) or the MTTF values are used.

Table 5 Statistical Life Results for SDL, CEM and 284 Splice

	SDL	**CEM**	**284 Splice**
		Weibull Fit for CEM	*Weibull Fit for CEM* [1]
Economic Life (using 50% Prob. definition) (T-38C IFF Test hours)	6890	7653	6780
Mean Time to Failure (MTTF) (T-38C IFF Test hours)	7050	7613	6743
Largest Absolute % Difference in Economic Life and MTTF	2.3%	0.5%	0.5%
Note 1 – FS 284 Splice used a Weibayes analysis having same Weibull slope as CEM			

Since a given fuselage would probably not be removed from service by individual cracking in the SDL, CEM, or 284 Splice, it appears that it is more appropriate to use the term MTTF rather than Economic Life. Economic Life was used for the -29 wing, but, as indicated, wings were condemned and removed from service because of cracking in any of the three replacement modes noted above.

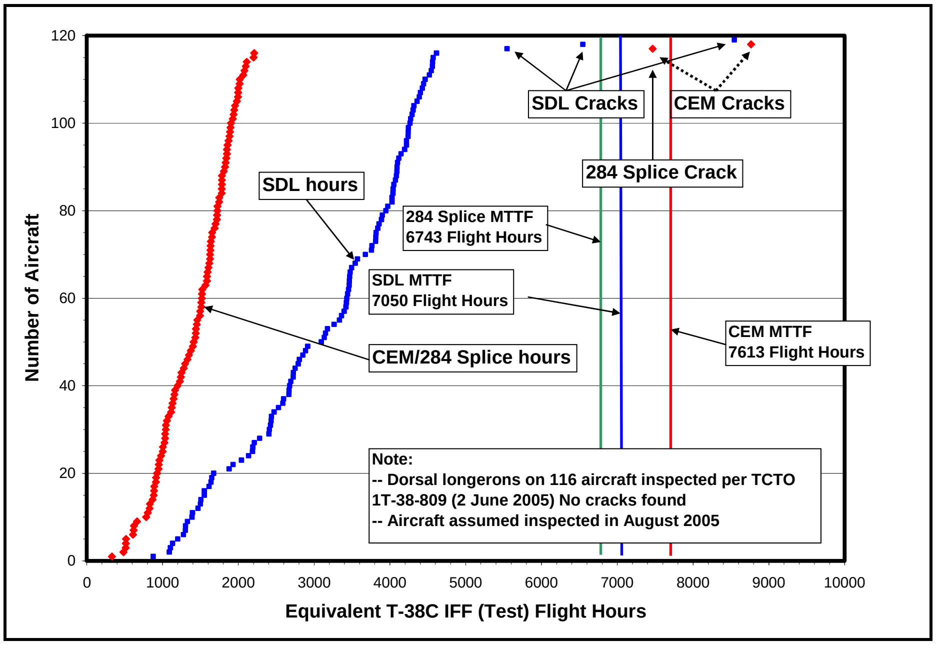
Figure 8 shows the calculated MTTFs relative to the cracking found in the test aircraft and the 116 aircraft inspected under TCTO-1T-809. Note that flight hours are expressed on the common T-38C IFF (Test) basis. The test data and the aircraft inspection data shown in this figure form the basis for the statistical life evaluation discussed in this section. The baseline time is August 2005, the time assumed for the 116 aircraft inspections for the SDL.

Future Flying Scenarios

The basic assumptions about the different Air Force fleets and the usage severity are as follows:

- AETC SUPT – All flying hours are determined with PMP installed.
- AETC ENJJPT – All flying hours are determined with PMP installed.
- AETC IFF – All flying hours are determined with PMP installed at the T-38C IFF (Moody) severity factor. This includes a number of aircraft stationed at Sheppard that fly IFF and ENJJPT.
- ACC – All flying hours are determined without PMP installed and their severity is assumed be category 5.

- AFMC – Since some of the aircraft received PMP, it is assumed all will fly with the PMP. Also, AFMC flies a mix of categories 3 and 5, but future predictions will conservatively assume all aircraft fly category 3.



Note:
-- Dorsal longerons on 116 aircraft inspected per TCTO 1T-38-809 (2 June 2005) No cracks found
-- Aircraft assumed inspected in August 2005

Figure 8 MTTF Relative to Test Article Cracking and Aircraft Inspected per TCTO-1T-809

In August 2005 when TCTO 1T-38-809 was performed a given number of aircraft were noted as active (not including AMARC) within the Air Force. As of March 2007, the total number has diminished due to a number of factors, including scheduled induction into AMARC, attrition, salvage in place, and retiring to museum. Population as of March 2007 was assumed to be the fleet size through 2040 for predictions purposes.

The final step to determine the future baseline flying rate is to multiply the calculated flying rates by the proper severity factor, based on the above assumptions and the part under consideration. The last assumption is that each aircraft assigned to the five Air Force fleets will fly the same amount each year regardless of its individual flying rate.

Development of Predictions

Study of the Fleets vs. MTTF

Now that the 2005 baseline has been accomplished, the statistical analysis has been performed and the future flying rates have been defined, it is possible to make predictions about expected replacements. Mean Time To Failure (MTTF), is a common expression of the expected reliability of the component.

Figure 9 shows each of the five fleets in different colors and their baseline hours in 2005, their baseline hours with 10 additional years of flying added (2015), and the baseline hours with 20 additional years of flying added (2025). Note that the flying rate includes an assumed 20% increase in severity discussed in the section Predicted Replacements. The MTTF is indicated by the solid black vertical line. For example, take the series of three red curves, each comprise the aircraft in the IFF fleet. The left-most curve is the baseline year in 2005. The middle curve is the predicted hours in 2015. Note that some of the aircraft will have longerons whose age exceeds the MTTF. By 2025, shown by the right-most red curve, all of the IFF fleet will have longerons that exceed the MTTF if they are not replaced.

Recall that the IFF fleet, flying the Moody IFF severity, is assumed to incur more equivalent IFF (Test) hours per calendar time. SUPT, on the other hand, incurs fewer equivalent IFF (Test) hours per calendar time, even though its actual flying hours are greater (250 vs. 220). If we examine the SUPT fleet (blue curves), we can see that its relative separation is less than that of the IFF fleet. This is the effect of the reduced equivalent IFF (Test) flying hour rate. However, just because SDLs do not exceed the MTTF in 2025 does not mean that some components will not need to be replaced. Rather, how close SDL hours are to the MTTF is synonymous with the likelihood that they will need to be replaced. Conversely, some SDLs that exceed the MTTF may not be cracked at all; however, they are more likely to be cracked than ones with fewer hours than the MTTF.

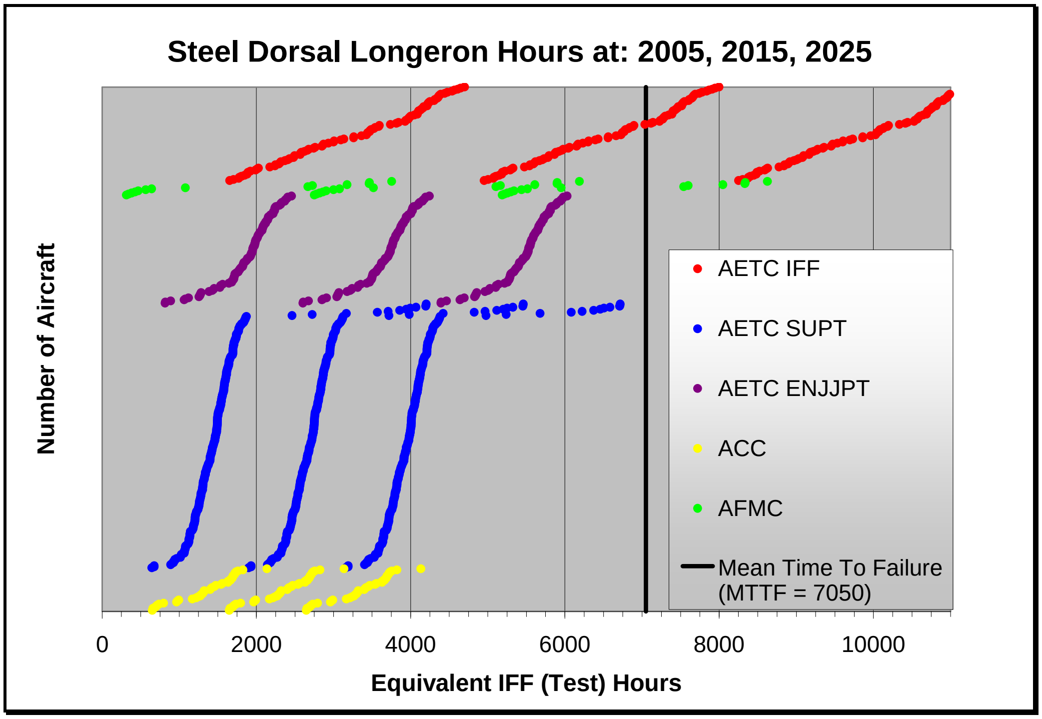


Figure 9 Distribution of the Individual Aircraft Equivalent IFF (Test) Hours of the SDL for Each of the Five Air Force Fleets

Prediction Methodology

The result of the statistical life evaluation is a mathematical representation of the risk of a crack for each individual longeron. This is given as a function F(t), either Weibull or Lognormal. F(t) varies between 0 and 1, where 0 is 0% chance for a crack and 1 is 100% chance of a crack occurring. This, however, is not the overall risk for a single T-38 since each aircraft has two SDLs, two CEMs and two 284 Splices. The data can be presented on a per longeron basis or a per aircraft basis. The most useful is to give the results on a per aircraft need for a maintenance action. The maintenance action can be repair, some form of replacement, or even condemnation of the aircraft.

For prediction purposes, the likelihood that a component, not cracked at the present time t, will have a crack at some future time increment u, can be expressed as:

Future Risk = $\dfrac{F(t+u)-F(t)}{1-F(t)}$ or Failure Forecast [Ref 10]

where F(t) is the present risk at time t, and F(t+u) is the risk at time t + time increment u.

The Future Risk for the fleet is the summation of the Future Risk over all aircraft.

If the aircraft is repaired or replaced such that a crack on one side would not necessarily result in maintenance on the other, then the risk for each aircraft needing a repair on any one side would be summation of the risk of each longeron installed on the aircraft. Since both SDLs were installed at the same time, the risk of each side is equal. The aircraft's risk for each component set would be 2 x 'the risk of each side'. Note that as the aircraft hours get relatively large, each individual component net risk would approach 2 since there is one component per side.

However, for the following predictions, it is assumed that the maintenance action will be, for reasons of economy, modification or repair of both sides at the same time. Unlike the scenario in the previous paragraph, the risk of a set of components (2 SDLs, 2 CEMs, 2 284 Splices) is the result any one of two independent events occurring. Should either the right or left side experience a positive indication of cracking, both sides will be replaced. This is the characteristic of a series system; that is, a system that fails whenever any one of its components fails. In the case of the left and right sides of the component sets (SDLs, CEMs, or 284 Splices), both sides will be replaced if a crack is found in any one side.

The reliability of a series system is the product of the reliabilities of its individual components. Since the risk, or unreliability, is the one minus of reliability, the risk can due to a component set is

$$Risk_{T-38} = (1 - R_{T-38}) = (1 - (1 - Risk_{Left}) * (1 - Risk_{Right}))$$

Since both sides of the aircraft were modified at the same time, the $Risk_{Left} = Risk_{Right}$ = Risk, and the combined risk is

$$Risk_{T-38} = 1-(1-Risk)^2$$

This is the basic equation used to calculate the per aircraft risk based on any of the three major components being examined. Note also that each of these components is examined individually since each has different function parameters, different baseline, and different T-38 IFF (Test) equivalent flying hours rate.

It is important that the risk of each aircraft be calculated independently prior to summing to represent the entire fleet risk since no two aircraft will have the same relative time on either the SDL or the 284 Splice.

Now let us assume that the depot modification task will replace the SDL, CEM and the 284 Splice, where the total reliability is the product of each component, each side. The risk can be defined as

$$Risk_{T-38} = 1-\left(1-Risk_{SDL}\right)^2 \bullet \left(1-Risk_{CEM}\right)^2 \bullet \left(1-Risk_{284\,Splice}\right)^2$$

The future risk for the T-38 at time t and u can be calculated using the expression at the beginning of this section.

Predicted Replacements

The predicted number of maintenance actions can no be determined by fleet and calendar time. This is simply the summation of the individual aircraft future risks, at each given calendar time increment, per fleet per individual component. Five different categories were analyzed: (1) SDL alone, (2) CEM alone, (3) 284 Splice alone, (4) SDL and 284 Splice together (center fuselage) and (5) SDL, CEM and 284 Splice together (full modification). Within each category, the total maintenance actions needed by a particular calendar time as well as the number of new maintenance actions needed each calendar increment were determined. The new maintenance actions is simply the total needed currently, minus the total needed the during the prior calendar time. Thus the total number of kits and the rate at which they must be supplied can be determined. This information was presented to ASIP and AETC headquarters for planning purposes.

To account for any uncertainty in the predictions and to ensure that funding estimates for repair and replacements were sufficient and did not underestimate the actual situation, an additional margin was added. As a historical precedent, the original -29 replacement predictions were increased an additional 10% to account for ‘unknowns’ and it was deemed prudent to do the same for the assumptions and calculations involving the fuselage. At the request of the T-38 ASIP manager, the margin of 20% is used.

Recall that the equivalent IFF (Test) flying rate accounts for both flying hours and severity. As such the 20% increase can accommodate a 20% increase in severity, a 20% increase in flying hours, or some combination of both up to a combined increased effect of 20%

All calculations are the same, other than the increase in the flying severity. Note that this increase only affects the uncertainty associated with the future and not the past, thus the baseline remains unchanged.

Figure 10 present the overall number of SDL maintenance actions needed by a particular calendar time. Figure 11 presents the number of SDL maintenance actions needed for each calendar time increment. Figure 12 and Figure 13 present similar results on the basis of a full modification where as all three components analyzed are replaced at the same maintenance action.

Summary

Crack findings on the SDL, CEM and 284 Splice from the fuselage full-scale fatigue test and inspections on the SDL of 116 aircraft were used to predict the number of future maintenance actions needed as a function of calendar time. The analysis accounted for the differences in IFF usage as documented in Ref. 8, as well as the Northrop Grumman FLDR program at Moody AFB. This information was used to develop severity factors for the different usages. These severity factors were combined with each aircraft's historical usage data to determine an equivalent T-38C IFF (Test) hours for the SDL, CEM, and 284 Splice. This baseline considered each component's installation time and was determined through the summer of 2005 when the TCTO 1T-38-809 was released. The baseline was used for both the statistical analysis of each of the three components as well as the maintenance predictions.

WinSMITH Weibull software [Ref. 10, 14] was used to perform the statistical analysis. The SDL failures were modeled with the lognormal distribution, while the CEM and 284 Splice were modeled with a Weibull distribution. From this, the MTTF was determined and the statistical distribution information was used for the maintenance predictions.

The maintenance predictions were developed using the summer 2005 baseline hours as a starting point and are presented from 2007 out to 2040 using the failure forecast method of Ref. 10. Each tail number had its individual results summed from the baseline adding an incremental amount of time equal to its usage categories for the 2003 T-38C IFF (Test) equivalent flying rates. The new 'hours' were entered into the results of the statistical evaluation to determine each fuselage's likelihood of having a crack with those hours. The fleet maintenance predictions are simply the summation of each aircraft's individual likelihood belonging to the fleet usage group.

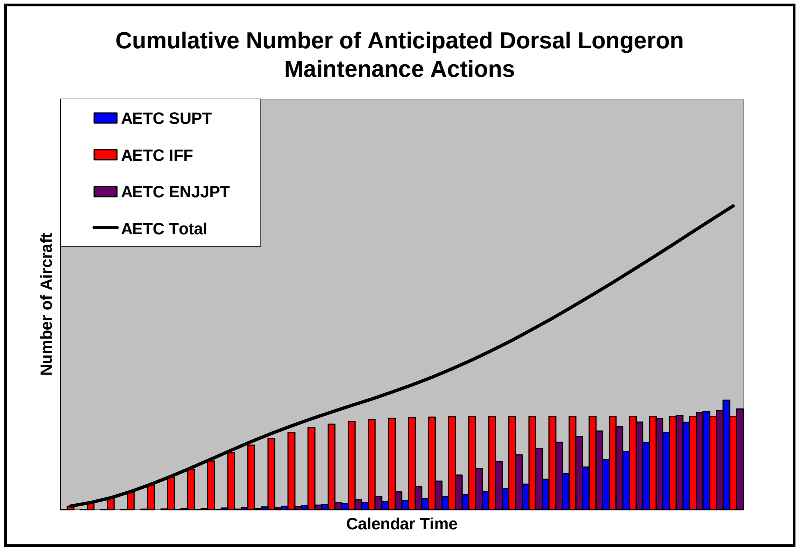


Figure 10 Anticipated SDL Maintenance Actions

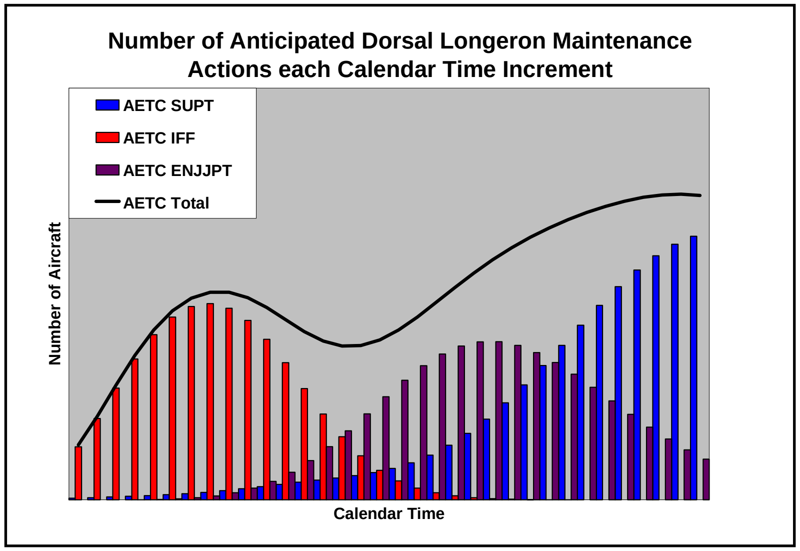


Figure 11 Anticipated SDL Maintenance Actions each Calendar Time Increment

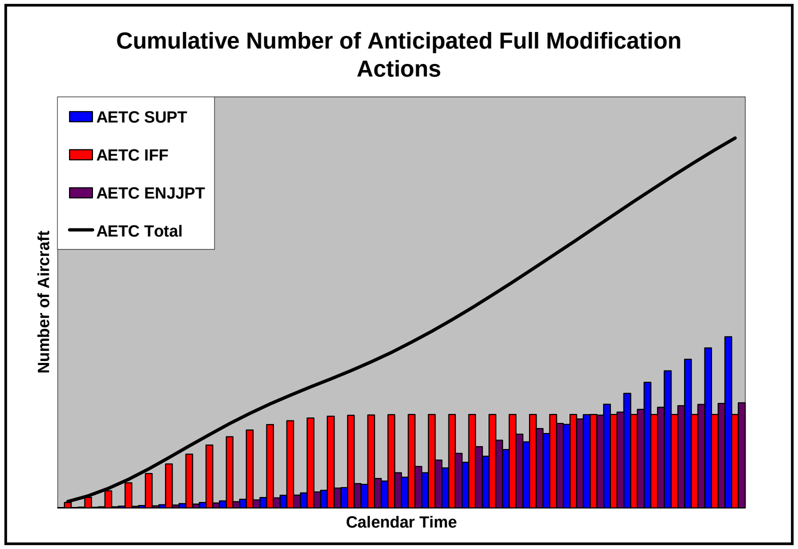


Figure 12 Anticipated Full Modification Actions

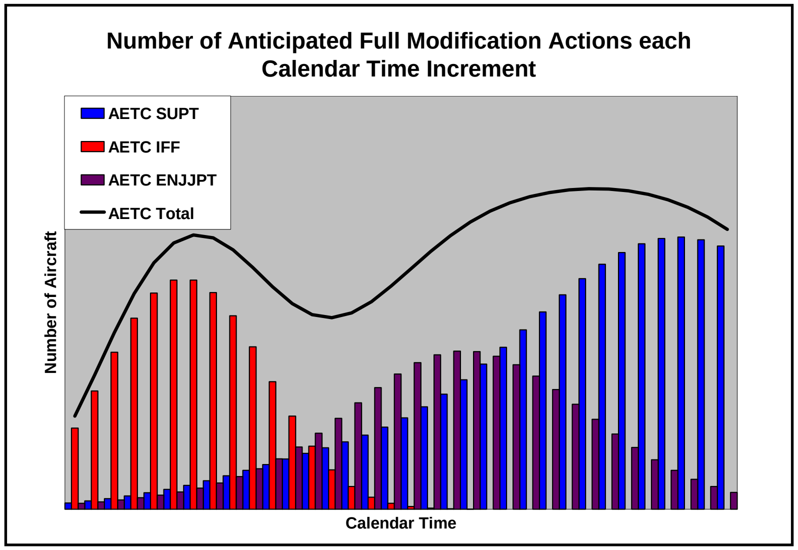


Figure 13 Anticipated Full Modification Actions each Calendar Time Increment

The predictions contain a 20% increase in the 2003 T-38C IFF (Test) equivalent flying rates to account for uncertainties in the input data and assumptions. Prediction with an increase in severity has historical precedent since it was used during the -29 wing replacement predictions. While the wing predictions use a 10% increase, 20% is warranted for the fuselage due to a lack of field failures for the analysis and the increase in severity measured in the T-38C IFF fleet at Moody AFB.

Certain benefits can be realized by performing multiple tasks at the same time. These benefits typically are manifested as a DERP task. The predictions consider two scenarios. The first is where the SDL and 284 splice are replaced during the same modification, and the second is where the SDL, CEM and 284 are all replaced during the same modification. Assuming all three of these components will need work at some point in the future, the first option would result in two different times that maintenance needs to be performed. One time would be when either one of the two SDLs needed replacement or when either of the 284 splices needed replacement. The other time would be when one of the two CEMs needs replacement. One shortfall in this approach is that the maximum life is not reached by the components, since one of the components (SDL or 284 Splice) will be replaced based on cracking in the other.

The second option would require only one maintenance induction to have all three modifications done, but would occur when a problem is discovered on the either of the SDLs, CEMs, or 284 splices. This option could potentially replace two un-damaged components based on the damage of a third. However, if each modification was done separately, aircraft availability would decrease because of multiple times that some aircraft would have to be transported to the repair facility and modified or repaired.

For example, at some future time there will be X aircraft that will require SDL maintenance, Y aircraft will require CEM maintenance, and Z will require 284 splice maintenance. This means there would be some number (X + Y + Z) of different maintenance actions required by 2020 if the three components were all serviced separately. By replacing all three major components at once it is possible to reduce the number of total maintenance actions. Even though each maintenance action involves replacing more structure there is the potential to reduce maintenance burden. It would also reduce the chance that the need for maintenance could outstrip the throughput of the repair facility. While replacing all three pieces of structure could theoretically reduce the number of maintenance actions by 67% compared to doing them separately, the greatest benefit is to seen over the range analyzed is just slightly over 50%. The decrease in maintenance actions for this scenario is shown in Figure 14.

It should also be noted that by replacing these components prior to discovering a problem helps mitigate the risk that a surge of crack findings in the fleet would result in a surge of aircraft needing modification. Such as surge could exceed the throughput at the modification facility, which would mean grounding aircraft waiting for their turn.

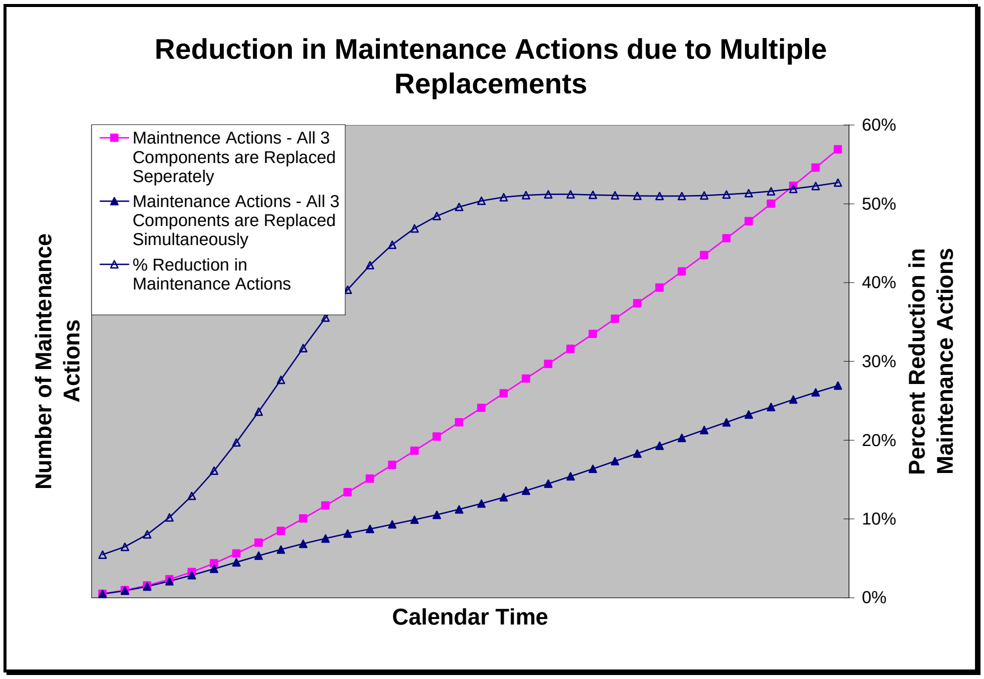


Figure 14 Reduction in Maintenance Actions due to Simultaneous Replacement

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