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Critical Part Life Extension Efforts in a Military Engine

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Abstract

Three specific schemes aimed at increasing critical part lives of a military engine are described. Quantitative life extensions, as a result of implementing these schemes, are given when appropriate. Any of these schemes could be applicable to other engines when sufficient field usage data are available.

1.0 Introduction

A critical part is defined as a part whose failure will result in a catastrophic loss of the engine, the aircraft, and possibly human lives. Every gas turbine engine, with its inherent high pressure, high temperature, and high rotational speed operation, contains a number of such parts. When a new engine is first introduced for fleet use, various uncertainties ranging from material characteristics to the type of missions that will be flown prudently dictate that a rather conservative low cycle fatigue (LCF) life is released for each critical part. Life extension becomes possible as field experience and technological advancements are incorporated.

This turbofan engine was originally developed in the 1970s. It was upgraded for US Navy use and was fielded in 1993. Since then, as part of the component improvement effort, the lives of many critical parts have been re-evaluated and extended. For instance, the life of the high pressure turbine (HPT) disc was originally released at 8,900 LCF cycles. The performance of several spin tests, guided by refined 3-D finite element analyses, allowed the life to be increased first to 10,300 then to 15,400 cycles.

In addition to spin tests and state-of-the-art analyses, a variety of other schemes have been employed to specifically improve the lives of the critical parts in this engine. Three of these schemes are summarized in this paper. They are (1) Statistics Based Fill-in Exchange Rates, (2) Mission Specific Exchange Rates, and (3) High Resolution Airborne Data Recorder.

2.0 Statistics Based Fill-in Exchange Rates

The Navy aircraft under discussion is equipped with an Airborne Data Recorder (ADR). It records among other airframe and engine parameters, engine operating hours and LCF cycles consumed in each flight. A critical part in the engine is retired before its LCF damage accumulation exceeds the established limits. For various reasons from subsystem malfunction to memory overflow, the ADR does not always capture 100% of the cycle

Paper presented at the RTO AVT Symposium on "Ageing Mechanisms and Control: Part B – Monitoring and Management of Gas Turbine Fleets for Extended Life and Reduced Costs", held in Manchester, UK, 8-11 October 2001, and published in RTO-MP-079(I).

counts. The missing information, essentially the difference between the pilot reported flight hours and the ADR registered hours, have to be filled in with a fill-in exchange rate defined as the number of cycles per hour.

Figure 1 is a plot of the exchange rate data over time from a high pressure turbine disk segregated by engine builds. Each point on the graph is an exchange rate calculated from the ADR data, namely, cycles used and accumulated flight hours over several flights. As noted on the top margin of this graph, this engine has gone through two builds in the 3-1/2 year period shown. Build 1 has also been installed in two different aircraft resulting in three data sets. In data set 1, there are 18 data points. Missing are 13 data points, inferred from pilots reported data, due to either ADR malfunction or other types of errors. This translates to a data capture rate of 58%. In set 2, no data were captured. In set 3, the capture rate was 62%.

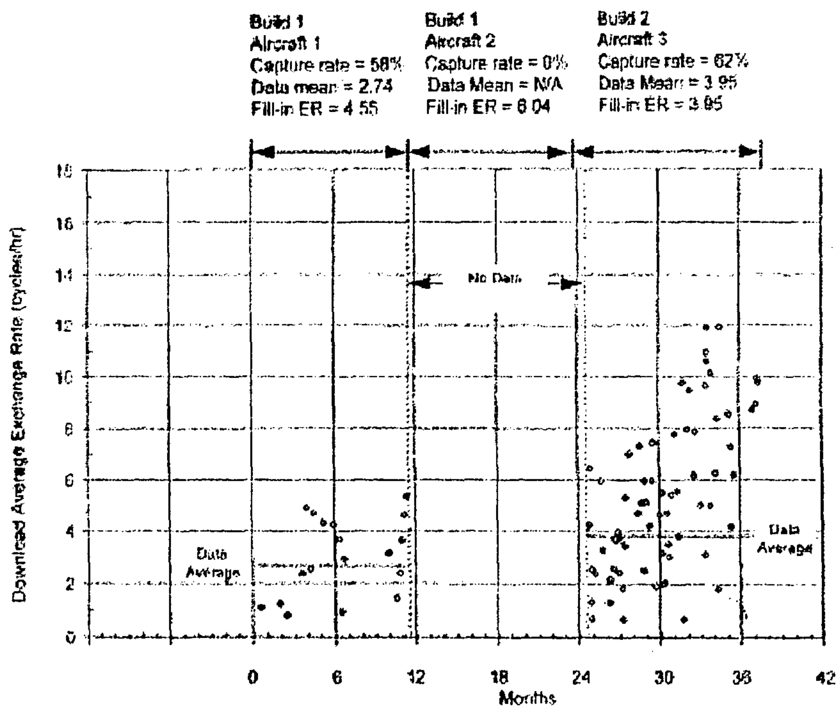

Figure 1 Exchange Rate Data of an HP Turbine Disk

Prior to 1998, the missing data were filled in with a set of "worst case" exchange rates derived from Weibull analyses. Using the example in Figure 1, the 13 missing data points in set 1 would each be assigned a fill-in exchange rate of 4.55 cycles/hour, significantly higher than the data average of 2.74 cycles/hour. Any flight in set 2 would be assigned an exchange rate of 6.04 cycles/hour, and the 38% missing data in set 3 would be assigned an exchange rate of 6.6 cycles/hour. This high degree of conservatism means a large number of critical parts are retired prematurely. An ad hoc procedure was adopted in 1998 to reduce conservatism. It was decided, based on a limited data analysis, that the worst case fill-in values would still be used if the capture rate in any particular engine build is below 60% (such as sets 1 and 2 in Figure 1). When the capture rate is above 60%, the average exchange rate from the captured data would be used as the fill-in value (as shown in Figure 1). The rationale for introducing such a threshold capture rate is of course the law of averages. Namely, one would not expect the missing data to be radically different from the vast majority of the captured data.

A statistically more rigorous methodology has since been developed to provide fill-in exchange rates. It owes its concept to the Student's t-law which can be found in most statistics books. The Student's t-law allows one to ascertain the value of the population mean from a given sample of data with known sample mean and standard deviation. In the case of the incomplete ADR data, the sample is the number of captured data points in a given engine build. The "population" is the larger set of data if all flights were captured. There are two important distinctions that preclude direct application of the Student's t-law. The first one being that the "population" referred to in the t-law is a sample of infinite size. The total number of data points, captured and missing, in a particular engine build is far from infinite. Thus using the Student's t-law would not be theoretically correct. The second distinction, a more troublesome one, is that the Student's t-function has only one independent parameter, namely, the number of samples, n. In the missing ADR data problem, there are two independent parameters: the number of captured data points in an engine build, n, and the capture rate, n/N, where N is the total. "population" had there been no missing data. The methodology described below involves generation of an equivalent t-function with two independent parameters using available ADR data. More details of this methodology can be found in Ref. 1. Use of this method can minimize premature retirement of expensive engine components while maintaining safe operation.

2.1 Methodology

The data available to us are contained in 282 data sets, each corresponding to either an engine build or an aircraft installation. That means for each of the four critical components (LP compressor drum, HP compressor drum, HP turbine disk, and LP turbine disk) that the ADR records their cyclic usages, there are 282 sets of exchange rate values or data points. Within each data set, there can be as few as two exchange rate values and as many as 130. The average number of points in a set is about 40.

In this exercise, we assume the number of points in a data set is the full "population" and denote that number by N. Random removal of points from this set will generate many subsets each has n points and a corresponding capture rate (n/N). Note that even though N is far less than infinite, we still define the full set as the population for ease of identification. The corresponding average of all N points will hence be denoted as the population mean, μ. The average of a subset is the sample mean, X. By this process of random removal, a $(\mu - X)/X$ versus n plot can be generated for a given N.

Figure 2 is such a plot for N = 80 (HPT data are used in this illustration). Within the 282 data sets, there are 36 sets that have 80 points or more. For sets that contain more than 80 points, excess points ~~are~~ removed by a random selection process so that each of the 36 sets starts with exactly 80 points, and a μ is calculated for each of these sets. Next, a point is removed, randomly, from each of these sets. Thirty six sample means with n = 79 are then obtained, from which 36 values of $(\mu - X)/X$ can be readily calculated. All 36 of these values are plotted along the abscissa value of n = 79. The process is repeated by randomly removing two points from each set resulting in further spreading of points at n = 78. As expected, the spread becomes wider and wider as n, or equivalently n/N, gets smaller. Assuming the vertical scatter seen along any value of n is Gaussian distributed, one can calculate the standard deviation of these 36 $(\mu - X)/X$ values. Two curves corresponding to +/- twice that standard deviation are plotted in this diagram. Since 2-sigma encompasses 95% of the area under a bell shaped curve, this means 95% of the points should lie between the two curves.

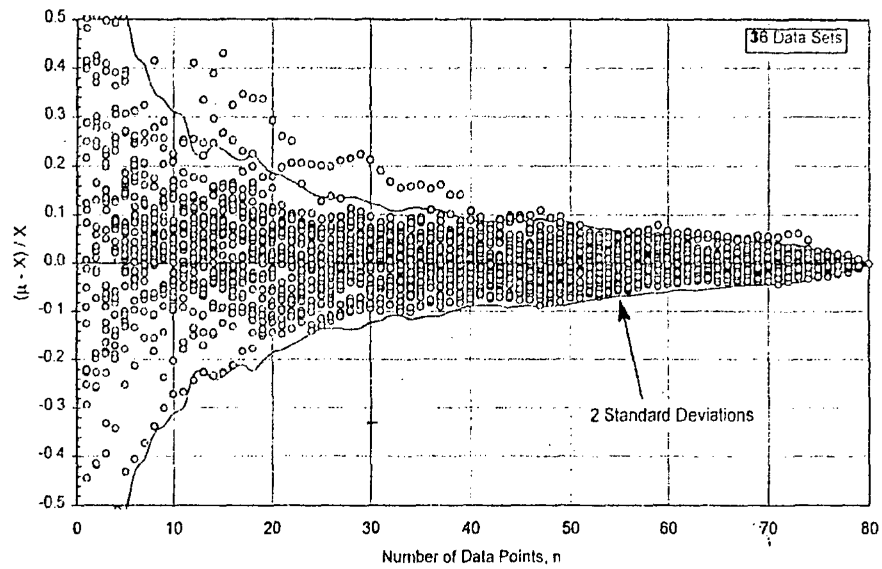

Figure 2
Effect of Capture Rate on Relative HPT Exchange Rate Means
(80 points per data set, i.e., N = 80)

As far as the exchange rate is concerned, the upper curve, along which $\mu > X$, is of interest. Since the Gaussian distribution is symmetrical about its mean, the probability that a point lies above the upper curve is only 2.5%. In other words, the upper curve marks the boundary at which one has 97.5% confidence that the sample mean X will not be greater than the population mean μ and gives the quantitative value of μ - X. For instance, at N = 80 (that is the basis of Figure 2) and n = 40, or equivalently a capture rate of n/N = 50%, μ - X is expected (with 97.5% confidence) to be 0.1X. This upper curve, without the underlying points, is re-plotted in Figure 3.

Plots similar to Figure 3 have been generated for N = 90, 65, 50, 30, 20 and 10. From each of these 2-sigma plots, (μ - X)/X as a function of n and the capture rate can be determined. For example, in the case of N = 80 (see Figure 3), (μ -X)/X = 0.2 for n = 18 and a capture rate of 23%. Table 1 summarizes these relationships for all N including this example of N = 80. For N = 50, three random reduction exercises were performed resulting in three slightly different two-standard deviation curves, hence three sets of values. These were done to get a measure of the scatter from different random reduction exercises.

Number of points n versus capture rate from Table 1 are plotted as squares, along with a linear regression, in Figure 4. Area to the upper right of this linear fit marks the region where (μ - X)/X < 0.2, whereas that to the lower left marks the region where (μ - X)/X > 0.2. Also shown in Figure 4 are points and lines for (μ - X)/X = 0.05, 0.10, 0.15, and 0.25.

Table 1 Threshold n and Capture Rate for (μ - X)/X = 0.2 with 97.5% Confidence

N	90	80	65	50	30	20	10
n	21	18	16	13, 16, 17	13	10	7
Cap. Rate	0.23	0.23	0.25	.26, .32, .34	0.43	0.50	0.70

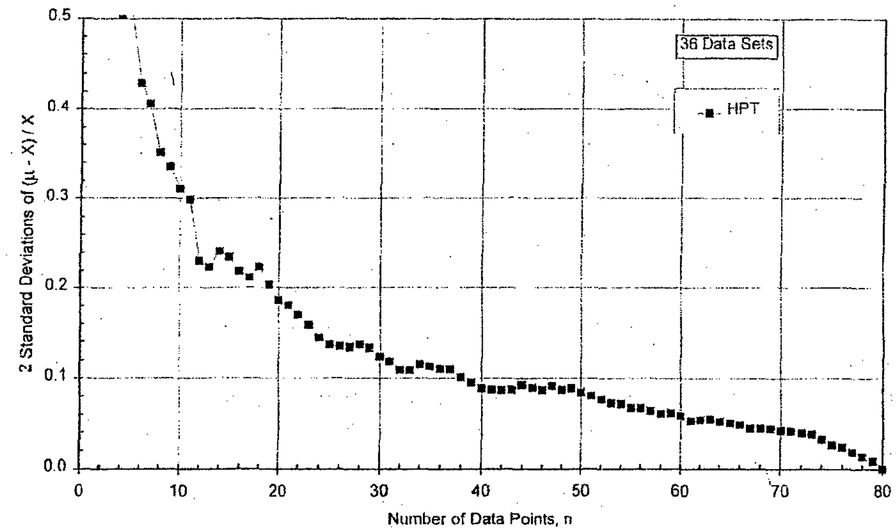

Figure 3
Two-Sigma of the Relative Exchange Rate Means
(80 points per data set, i.e., N = 80)

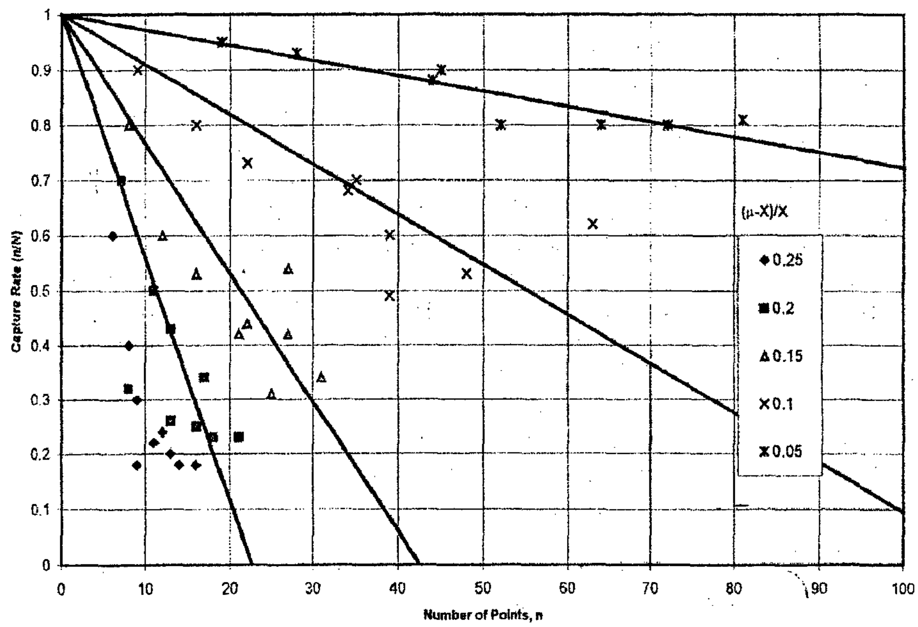

Figure 4 HPT Fill-in Exchange Rate Factor, (μ - X)/X

Figure 4 is the desired "t-function" with two independent variables n and n/N. This function is used to determine the fill-in exchange rate as follows.

1. Assemble an exchange rate data set for a specific engine build.
2. Determine the number of data points captured, n, and the number missing, N-n.
3. Calculate the average exchange rate X of the captured data.
4. Determine, from Figure 4, the value of (μ - X)/X corresponding to the n and n/N obtained in item 2. Interpolate if necessary.
5. Calculate the value of μ and use it to fill in all the missing data.

The linear regression lines in Figure 4 are made to converge at capture rate equals 1.0 and n = 0 because these values represent the physical limits of these two parameters. The lines' intersects with the x-axis, corresponding to a capture rate of zero, are equivalent to the Student's t-law. Indeed, Student's t predictions of (μ - X)/X from the individual 282 data sets (with a 97.5% confidence) are close to the results of Figure 4 at very small capture rates. (Note: A direct comparison to the Student's t prediction at n/N = 0 is not possible because for n = 0, i.e., no data captured, there is no standard deviation. Neither the Student's t-law nor the "t-function" for two variables derived above is meaningful.)

Even though we have illustrated our methodology using only the HPT data, similar data analyses have been done for the HPC, LPT, and LPC data. Provided that sufficient exchange rate, or equivalently, cyclic usage data exist on any engine, the same methodology can be used to derive the "t-function" for a specific critical part.

2.2 A Critical Part Usage Example

As an example of how different fill-in methods would affect the cyclic usage of a critical part, we have chosen a low pressure turbine disk example. This disk has been installed in five different engine builds over its service life. The data capture rates by the ADR range from 0 to 91% as seen in Table 2. Thus, fill-in is needed in every one of the five builds. All three fill-in methods are applied for comparisons. In the worst-case fill-in scenario, it has also been determined that the fill-in value should be 11.9 cycles/hour. This value is used to calculate the fill-in cycles based on the missing flight hours. The resulting total usage is calculated to be 22,876 cycles. If on the other hand, the 60% capture rate cutoff method is used, the total usage is slightly less, at 22,768 cycles. Finally the "t-function" method is used to calculate the usage. As can be seen in Table 2, the worst case exchange rate is still used for build 3 because it has zero capture rate. The fill-in exchange rates for all other builds are determined by an n versus capture rate plot similar to that shown in Figure 4. Not only the subjectivity is removed, but in this case, the usage is reduced by 10% to 20,579 cycles.

To date, the lives of scores of critical parts in this engine are being tracked using this Student's t-function equivalent method and resulting in life extension of hundreds of flights hours for each part.

3.0 Mission Specific Exchange Rates

It is common knowledge within the engine lifing communities that part usage, or equivalently the exchange rate, depends upon the mission profile. Certain missions are inherently more damaging to a part than others. The fill-in methodology described in Section 2.0 is component specific but not mission specific. That is, when we have missing ADR data, statistically corrected fill-in exchange rates are used for each of the critical parts but the type

Table 2 Fill-in Comparisons

Build No.	1	2	3	4	5	
No. of Dnload, n	13	6	0	99	97	
Pilot Hrs	116	81	337	896	828	
ADR Hrs	93	74	0	526	446	
ADR Cycles	779	592	0	4374	3815	
Cap. Rate	0.80	0.91	0.00	0.59	0.54	
Fill-in Hrs	23	7	337	370	382	
Av. ER, X	8.4	8.0	N/A	8.3	8.6	
Worst Case Fill-in						
Fill-in ER	11.9	11.9	11.9	11.9	11.9	
Fill-in Cycles	274	83	4010	4403	4546	
Total Cycles	1053	675	4010	8777	8361	$\Sigma = 22876$
60% CR Cutoff						
Fill-in ER	8.4	8.0	11.9	11.9	11.9	
Fill-in Cycles	193	56	4010	4403	4546	
Total Cycles	972	648	4010	8777	8361	$\Sigma = 22768$
"t-function" Method						
Fill-in ER	9.3	8.9	11.9	8.8	9.1	
Fill-in Cycles	214	62	4010	3256	3476	
Total Cycles	993	654	4010	7630	7291	$\Sigma = 20579$

of missions flown by these missing "flights" is not taken into account. Exchange rates, however, are mission dependent. The analysis, summarized below, can be combined with the equivalent t-law methodology to provide mission specific fill-in exchange rates for the missing ADR data. Once that is implemented, fidelity of parts usage tracking will be further enhanced.

3.1 Missions and Exchange Rates

The military aircraft under study performs 17 stated missions as listed in Table 3.

Exchange rates within a mission type are by no means uniform. In fact, they vary by a wide margin as seen in Figure 5. Plotted in Figure 5 are the ACM exchange rates (for an HP compressor drum) from 1604 flights over a one year period. Despite large variations, one can see that the vast majority of flights accumulate about 4 cycles/hour. These same 1604 exchange rates are plotted on a Weibull chart (Figure 6). The more or less straight line distribution seen on that plot means that exchange rates can be considered a Weibull distribution. The minimum and the maximum exchange rates are seen to be 0.3 and 11 cycles/hr. Their Weibull mean, Eta + t_0, is 4.69 cycles/hr, agreeing with the eye-ball estimate of 4 cycle/hr.

Similar Weibull plots for all the other mission types were produced, and their Weibull means noted. These mean exchange rates are plotted in Figure 7 in an ascending order. Considering the large amount of overlap in exchange rates from one mission to another, it is obvious that one does not need to treat each mission individually. For example, the slight difference in the means between the ACM and the OCF flights is really insignificant. On the

Table 3
Mission Names and Abbreviations

	Mission Name	Abbrv.
1	Air Combat Maneuver	ACM
2	Airway Navigation	AN
3	Basic Instruments	BI
4	Carrier Qualification	CQ
5	Familiarity	FAM
6	Formation	FORM
7	Gunnery	GUN
8	Instruments Rating	IR
9	"Not Applicable" (miscellaneous)	NA
10	Night Familiarization	NFAM
11	Night Formation	NFORM
12	Out-of-Control Flight	OCF
13	Operational Navigation	ON
14	Radio Instruments	RI
15	Tactical Formation	TACF
16	Target Towing	TOW
17	Weapon Delivery	WEP

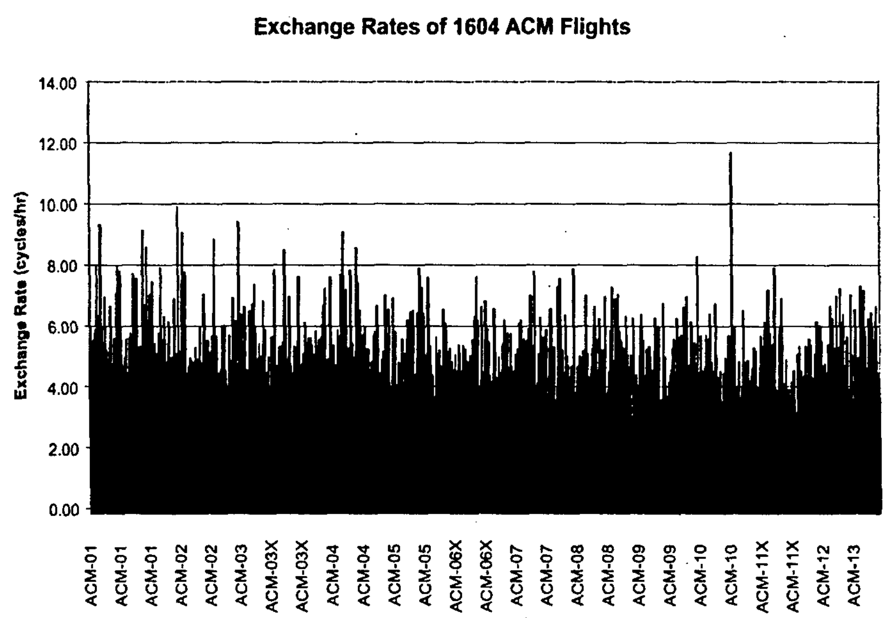

Figure 5 Variations in ER of the ACM Flights

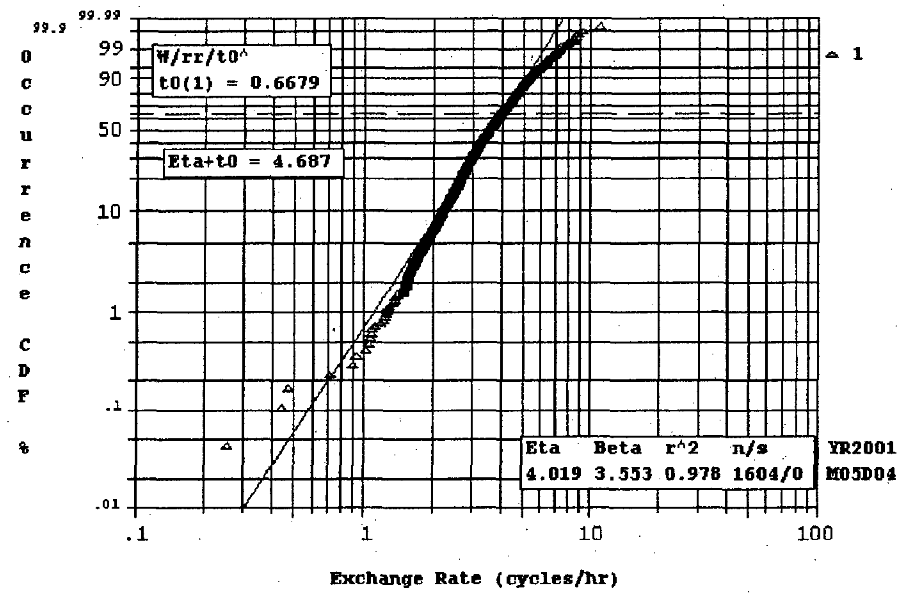

Figure 6
Weibull ER Distribution of ACM Flights

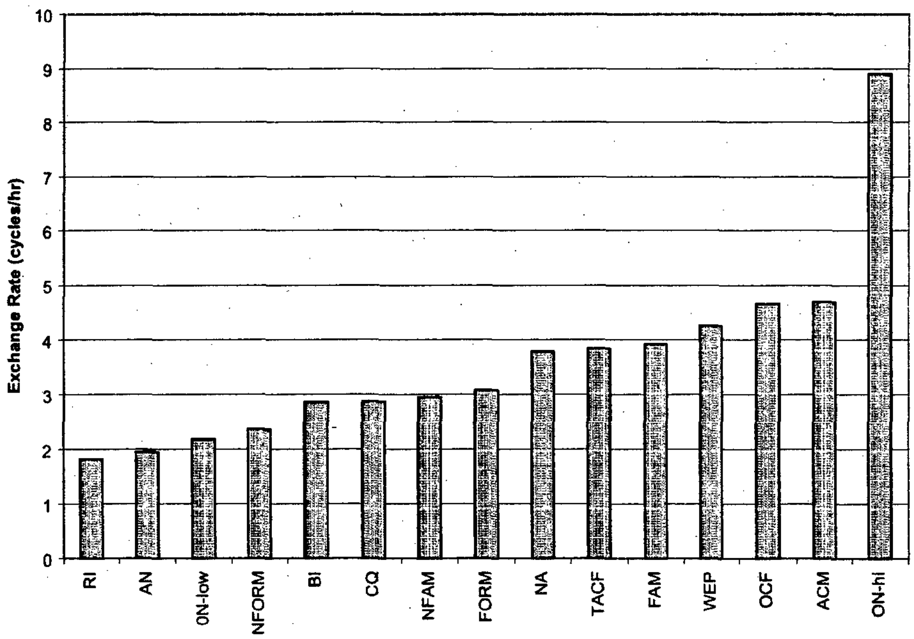

Figure 7
Weibull Mean ERs for Different Missions

other hand, an AN flight is definitely a low exchange rate mission compared with an ACM flight. We thus propose to group the missions into four categories:

low ER missions:	AN, IR, RI, TOW
medium ER missions:	BI, CQ, GUN, FORM, NFAM, NFORM, ON-low
high ER missions:	ACM, FAM, NA, OCF, TACF, WEP
ultra hi ER mission:	ON-hi

It is noted that the ON flights are divided into two sub-categories, low and high. The high ON flights are special missions in which the pilots are to reach check points along the way within specified time intervals. The extra throttle maneuvers needed to accomplish such a mission is the reason for the ultra high exchange rates. It is also noted that three of the 17 missions in Table 3 (IR, GUN, and TOW) do not appear in Figure 7, but their mean exchange rates are known and have been incorporated into the four categories.

Similar statistical analyses need to be done for the LP compressor, HP turbine, and LP turbine - the other three major critical parts in this engine.

3.2 Implementation of Mission Specific Fill-in Exchange Rates

When all the work is done, it is expected that flights with missing exchange rates will be filled in with one of 16 Weibull mean exchange rates. For low ADR capture rates, it would be desirable to devise 16 "t-functions" similar to that of Figure 4. However, the ADR capture rates in recent years have been well above 95%, making fill-in with mean exchange rates justifiable.

4.0 High Resolution Airborne Data Recorder

The existing ADR on this aircraft is of 1980s vintage. It does have sufficient processing power to calculate, in real time, the cumulative cycle counts of the four major critical parts in the engine from the 1 Hz engine performance data. However, its limited data storage dictates that the 1 Hz data cannot be saved for posterior analysis (Filtered 1/8 Hz data are saved but insufficient for critical parts lifing analysis).

In recent years, as Finite Element Modeling (FEM) becomes more sophisticated and accurate, a number of critical parts in this engine have been subjected to the much refined Thermal Transient Analyses (TTA). Complemented by additional spin tests and other appropriate tests, LCF lives of some of these parts have been increased. One component, on the other hand, had its life reduced (TTA promises more accurate stress predictions but not necessarily a reduction in stress. This also illustrates an important fact that TTA may extend the lives; but it certainly does not compromise safety). As we extend the TTA to cover more components, it became apparent that a real time TTA is highly desirable as it would extend the lives of majority of the components, thus saving both acquisition and maintenance costs in the long run.

A comprehensive cost benefit analysis was performed which showed that developing and fielding an advanced ADR with real time TTA capability would give a return on investment in 7 years. A contract is now in place to develop such an advanced ADR. It will incorporate a much more powerful processor to perform the complex TTA calculations in real time, and expanded memory to allow storage of all 1 Hz data.

5.0 Summary

Three specific schemes aimed at increasing critical part lives of a military engine are described. Quantitative life extensions, as a result of implementing these schemes, are given when appropriate. Any of these schemes could be applicable to other engines when sufficient field usage data are available.

Reference

Kiang, R.L., "A New Statistical Approach for Cyclic Life Tracking of Engine Critical Parts," Int. Soc. for Air Breathing Engines Conf., paper No. 99-7022 (1999)