Analysis of Turbopump Failures Using Advanced Weibull Techniques

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Abstract

This paper is an example of how Weibull analysis played an important role in the solution of a gas turbine fighter engine problem encountered in service operation. An extremely small sample of failure data (3 points) was available for analysis. Even with this short fall of information, the Weibull analysis provided invaluable information that led to quick corrective action that solved a major problem.

Introduction

Waloddi Weibull indicated in his hallmark paper (Ref. 1) that over a broad range of examples his Weibull analysis "may sometimes render good service". The authors certainly agree. The Weibull technique has become the standard approach for analyzing failure data at Pratt & Whitney Aircraft Government Products Division. As applied to failure analysis, it affects major program decisions involving development, production and service problems. Weibull distributions are the foundation of our maintainability, safety, support cost and risk models, and provide the basis of much of the dialogue with our customers. To illustrate specifically how Weibull analysis is used, a case study associated with a fighter engine augmentor turbopump will be discussed. Bearing failures in this pump may allow escaping fuel to ignite and produce fire in the nacelle. Because of this hazard we were asked to assign top priority to our analysis of any and all data that might help in resolving this problem.

Initial Analysis - Small Sample

The first analysis performed was the evaluation of the three failures through Weibull analysis. Note that this is an extremely small sample. At that time there were 978 turbopumps operating in the fleet. The data was ordered by run time, treating the successful pumps as censored units and the resulting Weibull plot is shown in Figure 1. Median rank order statistics were used as plotting positions (Ref. 2).

Even with this small sample we were able to make some valuable observations. First, the very steep slope, Beta = 10, indicates that the failure mode is one of rapid wearout preceded by a relatively safe period. Inspection of Figure 1 shows that the probability of a turbopump failure prior to 200 hours is negligible but after 250 hours the probability increases very rapidly. The shape parameter, Beta, will help identify the type of failure mode. Betas less than 1.0 imply an infant mortality problem—perhaps quality control or misassembly. See Figure 2. A Beta of 1.0 indicates a random failure, that is, a failure mode that is independent of time. A slope between 1 and 3 indicates gradual wearout. Slopes greater than 3 indicates a more rapid wearout.

FIGURE 1
WEIBULL PLOT FOR AUGMENTOR PUMP BEARING

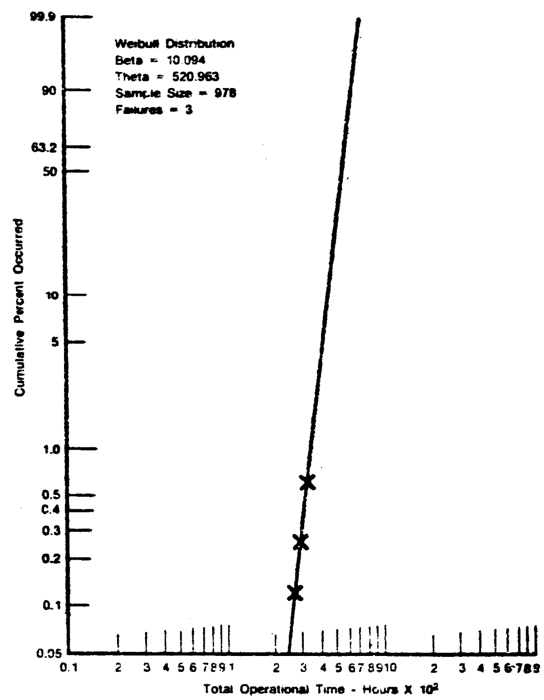
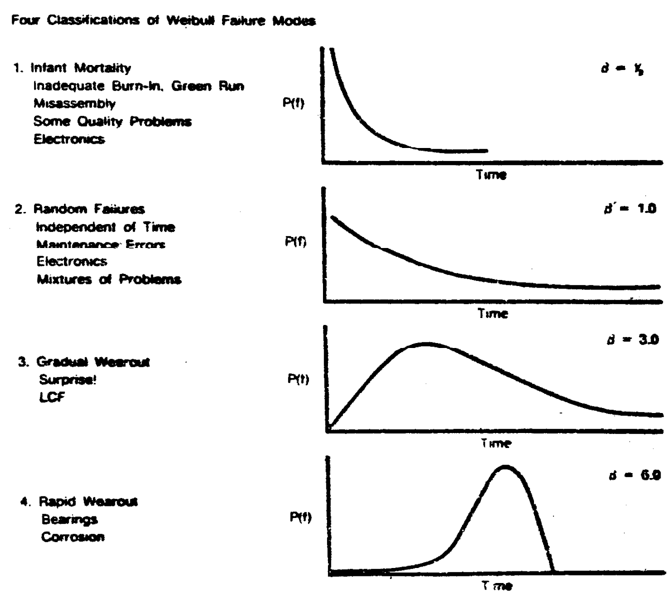


FIGURE 2. CLASSIFICATION OF FAILURES



The second inference made from the Weibull analysis was that the problem could be a batch problem. i.e., it may not apply to the entire fleet of turbopumps. The method that we use to determine whether or not a given failure mode is a batch problem is to evaluate the Weibull equation with the parameters calculated (see Figure 1) for each successful and failed turbopump. For each pump, we determine the probability of failure from the Weibull equation and these probabilities are then summed. If the failure mode applies to the entire fleet, the sum of the cumulative hazards, as they are called, should approximate the number of failures observed, in this case 3. However, with this data, the answer was 117 failures. This was an important clue that the failure mode applied to less than the entire fleet of turbopumps. Recommendations were made to Project Engineering that the turbopump vendor and the bearing vendor should review their processes to see if anything had changed either in the process, the material, or the assembly. Initially, no changes were found that supported the batch hypothesis.

Two Months Later - Batch Identified

At this point in the analysis there were 7 failures (see Figure 3). It was noticed that the serial numbers of the failed pumps were all quite high ranging from No. 671 to No. 872 in the sample of approximately 1000 pumps. This supported our hypothesis that a batch problem was involved. There were two more unconfirmed failures in the field for a total of 9 failures. If we assume that the batch started at Serial No. 671 and assumed our batch extended from there to the latest pumps produced, we generated less than 9 failures. By iterating we found that if we assumed the batch started at Serial No. 650 we would generate 9 failures corresponding to those observed and those unconfirmed. This implied that there are 353 pumps in the batch.

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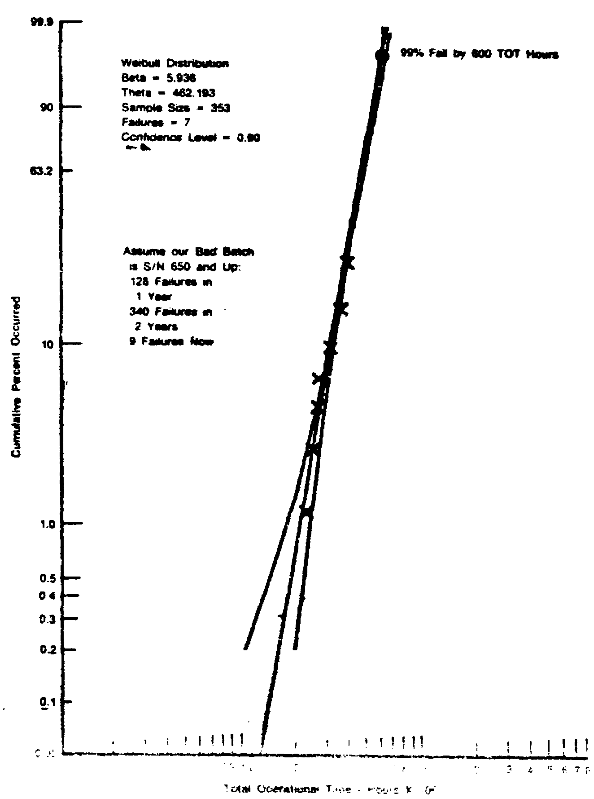
FIGURE 3. AUG PUMPS 650 ON UP



Risk Prediction

With a serious problem involving approximately 350 pumps, the next step was to forecast the number of failures we could expect in the near future. This is fairly straightforward. We limited the analysis to the 353 pumps. We also know that each pump accumulates an average of 25 hours of total operating time per month. Knowing the Weibull distribution, it is simply a matter of accumulating the probability of failure (cumulative hazards) for each pump as it moves (ages) in time. This risk analysis is illustrated in Fig. 4. With the 353 pump times for the Weibull curve in Fig. 3, we calculated a cumulative total of 9.17 failures for the "now" time as explained above. Increasing each pump's time by 25 hours and accumulating the probabilities of failures, the value of 12.26 was obtained. The delta between 9.17 and 12.26 indicated that we might expect approximately three more failures in the next month. This analysis was continued for 24 months of operation and the results are presented in Fig. 5.

FIGURE 4. RISK ANALYSIS

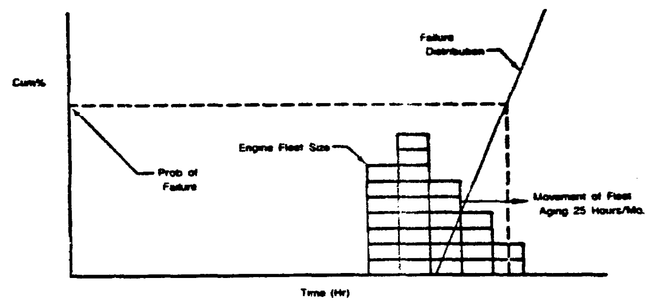


FIGURE 5. PROJECTED PUMP FAILURES

CUMULATIVE FAILURES	FORECASTED FUTURE FAILURES
9.17	0.00 MORE FAILURES IN 0 MONTHS
12.26	3.12 MORE FAILURES IN 1 MONTHS
16.22	7.06 MORE FAILURES IN 2 MONTHS
21.14	11.90 MORE FAILURES IN 3 MONTHS
27.18	18.02 MORE FAILURES IN 4 MONTHS
34.50	25.33 MORE FAILURES IN 5 MONTHS
43.21	34.05 MORE FAILURES IN 6 MONTHS
53.44	44.27 MORE FAILURES IN 7 MONTHS
65.24	56.07 MORE FAILURES IN 8 MONTHS
78.65	69.48 MORE FAILURES IN 9 MONTHS
93.64	84.47 MORE FAILURES IN 10 MONTHS
110.14	100.97 MORE FAILURES IN 11 MONTHS
128.01	118.85 MORE FAILURES IN 12 MONTHS
147.11	137.94 MORE FAILURES IN 13 MONTHS
167.21	158.05 MORE FAILURES IN 14 MONTHS
188.06	178.91 MORE FAILURES IN 15 MONTHS
209.40	200.24 MORE FAILURES IN 16 MONTHS
230.62	221.06 MORE FAILURES IN 17 MONTHS
251.69	242.73 MORE FAILURES IN 18 MONTHS
272.07	262.90 MORE FAILURES IN 19 MONTHS
290.75	281.58 MORE FAILURES IN 20 MONTHS
307.32	298.16 MORE FAILURES IN 21 MONTHS
321.27	312.11 MORE FAILURES IN 22 MONTHS
332.29	323.12 MORE FAILURES IN 23 MONTHS
340.34	331.18 MORE FAILURES IN 24 MONTHS

BETA = 5.94 THETA = 462. N = 352

As the forecast indicates, almost all of the suspect lot was expected to fail within the two year time frame. This was obviously a serious problem if our analysis was correct.

Based on this analysis, we recommended to Project Engineering that turbopumps No. 650 and up with more than 175 hours of time be replaced in the fleet. Fortunately, there were sufficient spare turbopumps to allow this to be accomplished without grounding aircraft. This action was effective as no bearings have failed since.

Laboratory analysis of the failed pumps indicated that the failure mode was caused by swelling of the plastic ball bearing cage to the extent that the balls would skid and at that point, fail the bearing. Coordinating with the turbopump manufacurer, the bearing manufacturer, and the plastic manufacturer, a statistical factorial experiment was designed to determine the cause of the swelling of the plastic cages.

Four Months Later - Final Weibull Plot

Inspection of the turobpumps replaced in service (Serials 650 and up with 175 hours or more) produced 15 more bearings considered to be imminent failures. The addition of these failures to those originally seen in the field produced the final Weibull plot with 24 failures in a sample of 387 turbopumps (Figure 6). Note that this final Weibull curve was approximated by the original 3 failure curve four months earlier before we identified the batch. The only difference was that the earlier curve had a steeper slope (10 rather than 4.6) indicated on Figure 1. Although this slope difference sounds large, in fact, the inference from either curve would be substantially the same, that is, a rapid wearout problem. The second Weibull based on 7 failures was an accurate prediction of the final Weibull (Figure 6). Later Monte Carlo simulation studies on the accuracy and validity of the Weibull method with small samples indicates that the slope will generally be overestimated for very small samples (Figure 7).

FIGURE 6.
WEIBULL PLOT FOR AUGMENTOR PUMP

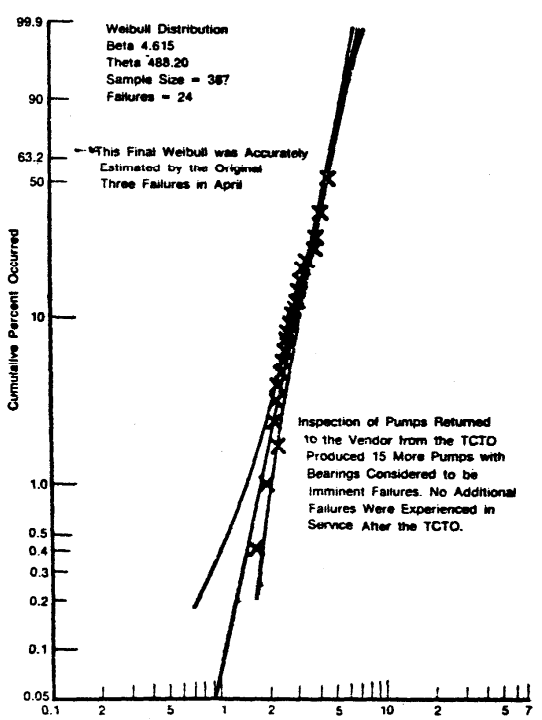
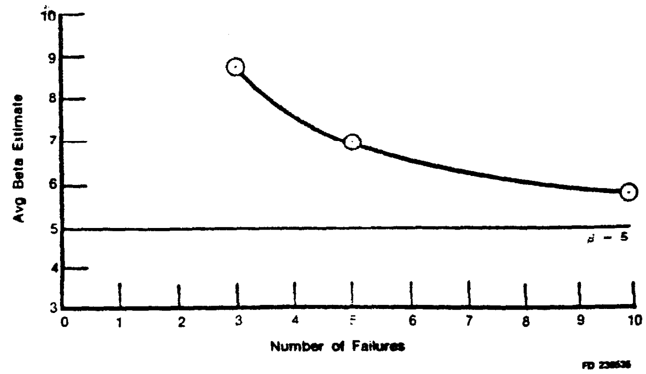


FIGURE 7. SMALL SAMPLE BETA ESTIMATES ARE TOO STEEP



By this time the results of the statistically designed factorial experiment were available. It was found that a process change had been made in the manufacture of the plastic cage to reduce costs. The change resulted in cages of lower density. When these lower density cages were subjected to the combination of heat from hot fuel and alcohol, the alcohol would diffuse through the plastic and cause it to swell and crack. All such cages were removed from service. (Alcohol is a deicing agent additive to jet fuel.)

Conclusions:

1. Weibull analysis provided Pratt & Whitney Aircraft with information necessary to quickly resolve the turbopump bearing problem:

o A batch characteristic was inferred and the batch identified.

o A risk projection scoped the problem.

o A safe period for the bad batch indicated by the Weibull, combined with the reduced number of pumps involved, allowed corrective action to be taken without impacting fighter availability.

o The physics of the failure based on failed pump analysis and a statistically designed experiment confirmed the inferences made from the Weibull analysis.

2. It is the opinion of the authors that this analytical tool is one of the most useful and versatile tools that can be used in handling failure data, particularly with small samples. Research, conducted after the case study reported, has:

o Identified both weaknesses and strengths of this method.

o Developed useful new Weibull methods.

o Investigated alternative distributions that may be preferred under certain conditions.

The authors plan to publish these results at a later date.

3. The successful application of Weibull analysis requires the close collaboration between the statistician and the engineer. The use of a statistician to resolve engineering problems without this relationship is usually nonproductive.

References

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Biographies

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Bob Abernethy is Manager, Reliability and Statistics. He has been with Pratt & Whitney Aircraft for 27 years. His B.S.M.E. and MSc Ind. Man. were done at Rensselear Polytechnic Institute. He was a Fulbright Scholar at University of London where he did a DIC and Phd. in Statistics. He is a Fellow of the Royal Statistical Society, member AIAA SESTC Committee, Chairman SAE Committee E33, Vice Chairman ASME Committee PTC 19.1, Past President Florida Chapter ASA, Short Course Instructor for ISA and ASME. He is the American Delegate to ISO TC30 SC9 and is listed in Who's Who.

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