Mechanical Integrity And Risk Based Decisions Using Weibull Analysis With Small Datasets

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Mechanical Integrity And Risk Based Decisions Using Weibull Analysis With Small Datasets

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Mechanical integrity problems often involve few failures and large quantities of potential future failures. The questions are: When will mechanical integrity be lost as the next failure occurs, or, will the equipment survive with no/few failures until the next scheduled turnaround? A factual dataset, with few failures, is used to illustrate how Weibull analysis can forecast the risk of failures based on a small dataset. Three perspectives are described: 1) the statistical view, 2) the engineering view, and 3) the management view.

The Problem-

Mechanical integrity and risk analysis for refineries and chemical plants are often based on very few actual failure data. The risk issue is to forecast future failures. Corrective action must find ways to mitigate the forecasted failures.

Operating from a fact-based system requires making failure forecast with small datasets of actual data. The dataset usually includes information in the form of suspensions (censored data). Good use of engineering judgment and data are used with Weibayes estimates (Weibayes is Weibull analysis using an estimate of the failure mode characterized by a slope β to produce a Weibull distribution relating age and probability of failure) to make the datasets understandable and practical. For some datasets, confidence intervals can be established.

At least three perspectives exist for evaluating the problem.

1. ***The statistical view***: What do the statistics say and what is the uncertainty?
2. ***The engineering view***: What facts can be applied to engineering art and science to provide engineering estimates and graphics?
3. ***The management view***: What facts exist for a succinct and useful management statement about the problem to accept or reject the risk?

Dataset #1 Reactors-

Three reactors are in a chemical plant. The reactors are in similar service and they make the same product. They have the following ages:

Reactor 1- 27 years with no failures
Reactor 2- 27 years with no failures
Reactor 3- 17 years at tubing failure
Reactor 3a- 8 years and no failure

Reactor 3a is the replacement for reactor #3 that failed at 17 years. The entire dataset consists of one failure and three suspensions. Censored data are also known as suspensions (Abernethy 1998). The dataset is: -27, -27, 17, and -8 where the minus sign indicates a suspension.

Problem #1: What is the risk of reactor failure today at 27 years? When is the next failure predicted? What costs will we see? What action should we take?

Leakage failure is detected when product produced by the reactor deteriorates as the leak slowly increases. Costs for a planned reactor replacement is US$1,500,000. Costs for an unplanned outage is US$5,000,000.

Dataset #2 Heat Exchanger-

A high temperature heat exchanger is in refinery service and it has 907 tubes. Two tubes have been removed from service by plugging the tube sheet.

The record shows the following:

Tube 1- 7 years and removed.
Tube 2- 11 years and failed

Tube 1 was removed from service (but not yet failed) as a suspect potential failure based on physical inspection at a scheduled turnaround interval. Tube 2 leaked in service. The dataset is: -7, 11, and -11*905 (i.e., 905 tubes are suspended at 11 years of age).

Problem #2: What is the risk of tube failure today at 11.5 years? When is the next failure predicted? What costs will we see? What action should we take?

Leakage failure is detected when product cooled by the exchanger deteriorates as the leak slowly increases. The heat exchanger bundle must be replaced if 90 tubes have failed. Likewise, if too many failures are predicted in a short interval, then the bundle must be replaced before 10% of the tubes are considered unusable. Costs for an exchanger replacement is US$1,000,000. Cost for an unplanned tube leak repair is US$100,000 and US$2,000 for a planned repair.

Failure Modes-

Every surviving component, sub-assembly, and assembly has many ways to die--but few ways to survive. Death can occur by normal aging or by specific events (not time/age related). Equipment death can also occur by combinations of events (such as inferior workmanship) and aging (such as acceleration by out-of- control fluids, which consumes years of life in months of exposure)--this is often a batch type reliability problem described in Abernethy's book where some components may have a problem (i.e., short life and unexpected failure modes) and others have long expected life with traditional failure modes.

How long will the equipment survive is sometimes a significant emotional event summarized with "since we don't know, let's shut the process down to gather facts about the problem". The shut down statement produces severe business conflicts. Most businesses must take risks to survive--few businesses want to take foolish risks. Factually this requires quantification of risks and the financial exposure incurred—use the numbers to overcome the emotion. Most risk averse businesses have measurable failure rates---even where human life is involved. Emotion is eliminated by making factual calculations by use of well known risk based inspection equations such as:

$$\$exposure = probability\ of\ failures * \$consequence\ of\ failure$$

For datasets 1 and 2, the questions are:

1) Will equipment be killed by an unplanned event such as an error,
2) Will (or has) a competing failure mode come into play, or
3) Will a known failure mode prevail?

For both datasets 1 and 2, each failure mode is detectable by precursors. None of the failure modes are suddenly and violently catastrophic. The failures pose hazards only to the process and not to humans.

The above datasets show each device is robust enough to tolerate insults from normal operations based on the lack of reports of killing events for the equipment. Using only the data shown above and assuming a killing event occurs tomorrow produces a forecasted failure rate that is an "upper bound", or we can use the actual history from the plant on similar equipment to get a larger population for more realistic failure rates. The chance failure concept is based on using the current data in the form of mean times between failure (MTBF), or its inverse which gives a failure rate.

Dataset #1 Reactors-

A Statistics Viewpoint Of Dataset #1 Reactors-

The first step is to find a statistic to use as a yardstick and the most often used value is mean time between failure. MTBF= (sum of life)/(sum of failures)= (27+27+8+17)/1= 79/1 = 79 years/failure. Of course the failure rate is λ = 1/MTBF = 0.0127 failures/year.

Heldt (1998) shows Poisson confidence levels for one failure, at the 95% confidence level, and the expected failures are 4.7439. At the 5% confidence level, the expected number of failures is 0.3554. Thus the 95% confidence level for MTBF is 79/4.7439 ≈ 17 years/failure and the 5% confidence level is 79/0.3554 ≈ 222 years/failure. The 90% confidence interval (95%-5%) lies between 17 years/failure and 222 years/failure where 79 years/failure is a single point MTBF estimate. Notice that the confidence bounds around the point estimate of MTBF are not symmetrical. The equipment has already survived longer than the lower confidence level with today's life of 27 years and climbing as compared to the forecasted value of ~17 years shown by the uncertainty calculation. The tried and true statistical method for reducing uncertainty is to get more failure data---this comment is technically correct but sure to generate ire in management circles where help is needed for making decisions!

If one Poisson failure event occurs during the next year, the probability of failure is 1 - e^(-λ*t) = 1 - e^(-0.0127*1) = 1 - 0.9874 = 0.0126. The $exposure = 0.0126*$5E6 = $62,892/reactor based on past data.

A worst case assumption plans for a failure tomorrow (we've already journeyed beyond the 17 years/failure confidence level). The mean time between failure becomes 79 yrs/2 failures = 39.5 yrs/failure and the failure rate is 0.0253 failures/year. Thus 1 – e^(-0.0253*1) = 0.0250 is the expected probability of failure. The $exposure is 0.0250*$5E6 = $124,990/reactor.

So these details give a statistical viewpoint about the reactors with a mean value and worst case bounds—graphics are not presented, as most statisticians do not need graphs to understand or quantify the problem. Please note that if factual data from similar reactors is pooled, it may show an order of magnitude difference in failure rates and still be in "close" agreement.

The small dataset statistical facts are sparse and do not answer the questions.

An Engineering Viewpoint of Dataset #1 Reactors-

From an engineering viewpoint, we can make failure forecasts using good practices and Crow/AMSAA plots as described in Abernethy.

Start with the one failure that occurred in 3 reactors*17 years = 51 reactor-years. Assuming the distribution mode of failure is by chance events (in Weibull analysis parlance, β=1), the second failure would be predicted to occur N(t) = λ_I*t^β where N = cumulative failures, λ_I = intercept of the Y-axis at time =1 for cumulative failures, β = Weibull slope, and t = cumulative time.

For N = 1, t = 51, and β = 1 for chance failures, then λ_I = 1/51 = 0.0196. Thus for N = 2, and solving for t = 102 reactor-years or 34 years of wall clock time. This condition for chance failure is shown in the lower line of Figure 1 using Crow-AMSAA software (Fulton 1999a).

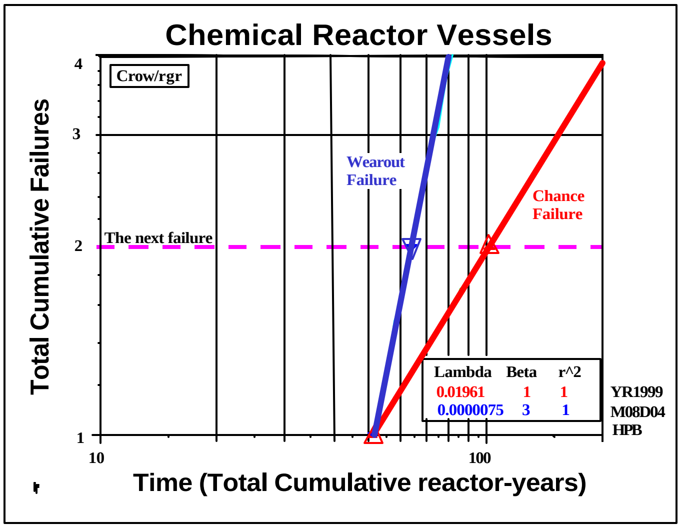


Figure 1: Crow-AMSA Plot For Next Failure

Now, if the first failure were a wearout failure mode indicative of increasing hazard rate (instantaneous failure rate), then the line slope β would be >1 (use ~3 for this example). The upper line is shown in Figure 1. For N = 1, t = 51, and β = 3 for wearout failures, then λ_I = 7.5E-06. The second failure is forecast at t = 64 reactor-years which is equal to 21.3 years of wall clock time compared to the current wall clock time of 27 years.

Figure 1 provides some credibility that the first failure may have been infant mortality (β<1) with a decreaseing hazard rate rather than wearout, as the characteristic age for the expected failure mode is much larger than illustrated in the failure at 17 years. So the evidence says the next problem is to the right of the trend lines in Figure 1. To this point, the evidence tells what the problem <u>is not</u>.

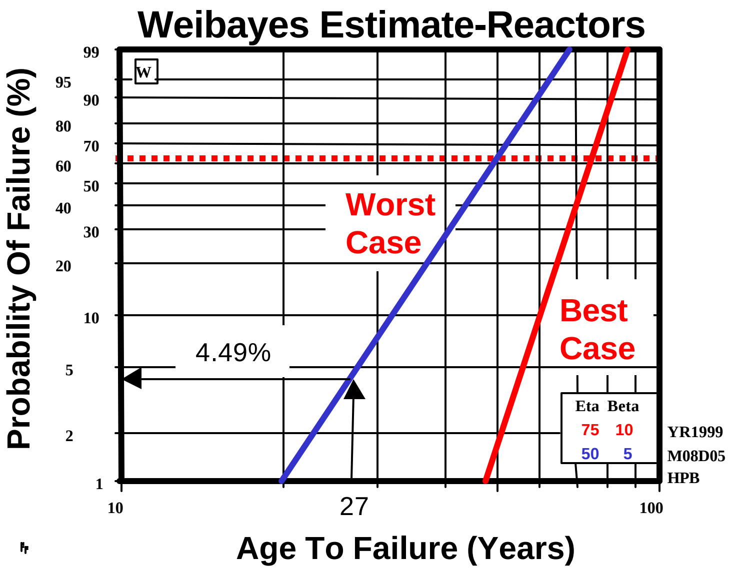


Figure 2: Weibayes Estimate of Expected Life

So what problem is expected and what are the risks? This is answered in Figure 2 by making a Weibayes estimate of how and when the reactor will fail. A well designed and fabricated reactor will likely have a characteristic life of 50 to 75 years (or more) and the failure mode would be wearout with a β ≈ 5 to 10. The probability of failure is shown in Figure 2, which is constructed with commercially available software (Fulton 1999b). For the worst case, the probability of failure is 4.49% and for the best case it is 0.000366%. Thus the $exposure is 0.0449*$5E6 = $224,500/reactor

The engineering reactor viewpoint (with graphics) brackets the failures and life based on the practical observations along with an estimate of the financial exposure. Three failure points on the best case curve would occur at 64.8, 72.8, and 78.5 years or for the oldest reactors, the earliest expected failure date is 64.8-27 = 37.8 years into the future. For the worst case curve, three failures would fall on the line at 37.3, 46.5, and 54.8 years--for the oldest reactors, the earliest expected failure date is 37.3-27=10.7 years into the future. So the engineering viewpoint says to expect failures at 10.7 to 37.8 years into the future.

A Management Viewpoint of Dataset #1 Reactors-

Management wants answers with dimensions in time, and money along with good judgments in consideration of potential paths to follow. Management is willing to use previous facts to estimate results considering a wider breadth of information (some factual and some inferred).

The statistical and engineering viewpoints above are helpful, but…! The nagging management question remains, “If each reactor is within it’s corrosion allowance, and the process is within control so we don’t kill the reactors, when will we see the next failure and how much will it cost?” This requires a different scenario for estimating when a failure will occur based on a hypothesis.

The statistical viewpoint says the reactors are within the failure range expected by the MTBF and more data is required. The engineering viewpoint says the reactors are past the time for an early wearout failure mode and the chance failure mode is not an active mode; and furthermore, the expected failure modes are shown in best case/worst case conditions for 10.7 to 37.8 years into the future.

Management’s issue is: When should we anticipate the next failure to occur? If it’s soon, then we need to order another reactor, however, if it’s far into the future, we’ll delay action. So, management asks for the optimum replacement strategy for the scenarios based on Figure 2 as this connects both time and money into one plot. Optimum replacement results are shown in Figure 3. For the 32 year replacement interval, the probability of failure is 10.1% and 3.06% for 55 years. The optimum replacement interval says to make timed replacements before the risk of failure gets too high. Of course if the reactors have capabilities for predictive maintenance such as acoustical emission, etc., then the replacement period can often be extended by use of smarter data.

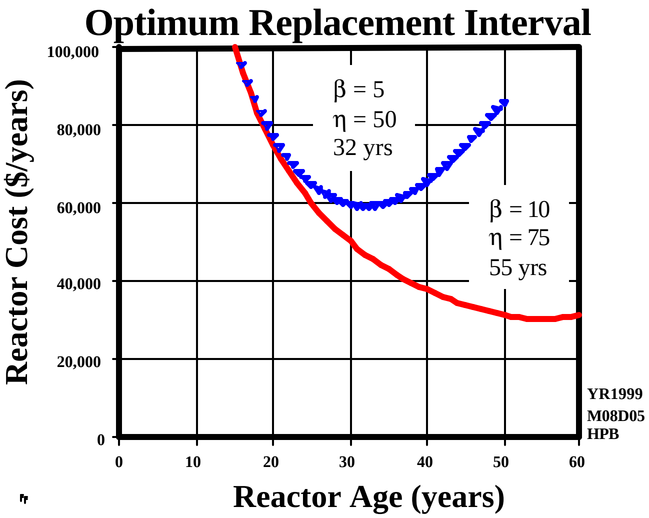


Figure 3: Optimum Reactor Replacement Intervals

The management decision is to continue running and use the time to better understand which wearout mode will prevail. If the worst case mode prevails, then it's time to start justifications for replacement. However, if the best case mode prevails, then you may retire before it's time to retire the equipment.

Summary for Dataset #1 Reactors-

The very small dataset of information is difficult to analyze accurately, and uncertainty of results is very large. However, some guidance from the analysis is better than no analysis at the current age of 27 years for two out of three reactors and given that one reactor has already failed and been replaced.

The MTBF is 79 years with a 90% confidence that the true answer lies between 17 years and 222 years/failure. Using the first failure data point as the predominate chance failure mode, the second failure is predicted to occur 7 years into the future (34 years of age) or if the failure mode is due to early wearout, the failure should have occurred 6 years ago (21 years of age) which suggest the first failure was not a normal failure mode. Other engineering estimates show the now risks (at 27 years) for expected failure modes lie between 0.000366% and 4.49%. Optimum replacement forecasts suggest the replacement interval lies between 5 years into the future (32 years of age) up to 28 years into the future (55 years of age). Management should accept the current risk of failure and continue running the reactors because of the optimum cost curve shown in Figure 3.

Dataset #2 Heat Exchanger Tubes-

A Statistical Viewpoint for Heat Exchanger Tubes-

MTBF= (sum of life)/(sum of failures) = (905*11.5+7+11)/1=104093/1 = 104,093 yr/failure, or λ = 1/MTBF = 9.607E-06 failures/year for an individual tube failure. Using the technique described for dataset #1, the 95% confidence level is 104,093/4.7439 = 21,942 years/failure and the 5% confidence level is 104,093/0.3554 = 292,890 years/failure. The 90% confidence interval lies between 22,000 and 293,000 years/failure with a point estimate at 104,000 for MTBF.

Considering one Poisson failure event during the next year, the probability of failure is 1 - e^(-λ*t) = 1 - e^(-9.607*1)=1 - 0.9874= 9.607E-06. The $exposure = 9.607E-06*$0.1E6 = $0.9607/tube. For the exchanger, 905 remaining tubes * $0.9607/tube = $869/exchanger.

All tubes in a heat exchanger are functionally in series (i.e., one tube failure causes the exchanger to fail). The failure rate for the heat exchanger is the sum of all individual failure rates. Thus the heat exchanger failure rate is 905*9.607E-06 failures/year = 0.0086943 failures/year which makes the MTBF for the exchanger 115 years/failure based on a constant failure rate assumption. The 90% confidence limits are 115/4.7439 = 24.3 years and 115/.3554 = 323.6 years. The current age of the heat exchanger is 11.5 years and the expected mode of failure will be wearout rather than chance failure.

An Engineering Viewpoint for Heat Exchanger Tubes-

Dataset #2 can be used to draw a probability plot shown in Figure 4. The technique of using maximum likelihood estimates (MLE) with small datasets has many biases--but, as a starting point, some graphics are better than no graphics. Notice the line slope with $\beta > 1$ infers a wearout failure mode. As you would expect, the confidence interval for Figure 4 is very large!

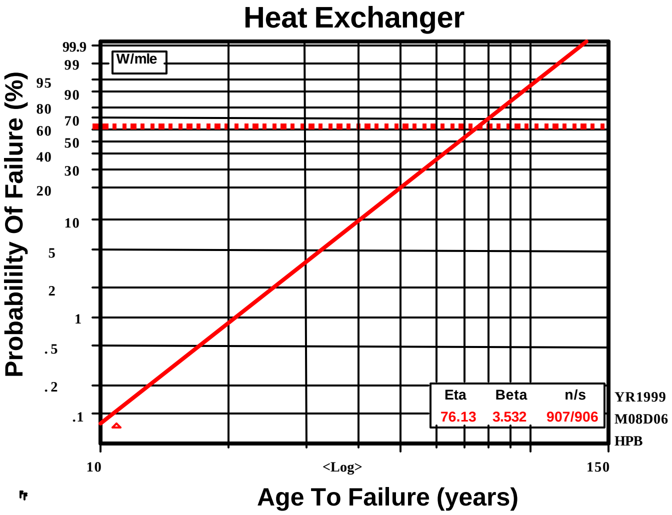


Figure 4: Heat Exchanger Weibull Plot

Figure 4 supports the hypothesis that tubes should be in a wearout failure mode even though most people are very uncomfortable with how the MLE mathematics allow a plot of data on a curve with only one data point. Based on the single data point, and the biased MLE line with β=3.5, expect 10% of the tubes will fail by year 40.3 which is 28.8 years into the future.

A heat exchanger from similar service had previously been examined for failure and showed two modes of failure:

1) Corrosion with β = 11, and
2) Carburization with β = 26.

This data was reported by Beamer (1997). These two conditions are shown in Figure 5.

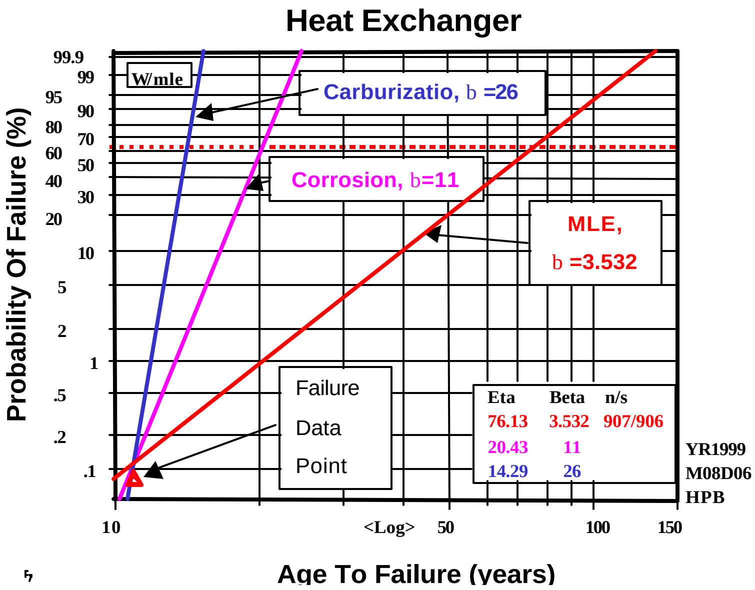


Figure 5: Weibayes Estimates With MLE Estimates

The carburization and corrosions lines were added to Figure 5 by using the facts available [1 failure at 11 yrs , 1 suspension at 7 years, and 905 suspensions at 11 years] plus telling the software to impose a one parameter (beta) Weibayes solution using the data--notice that for this case, the two Weibayes lines (one line for each failure mode) pass very close to the actual failure data point.

Careful categorization of failure modes and analysis of the similar data by Weibull analysis is particularly useful for adding other failure data assessment of end of life. Data from Figure 5 tells that it is important to record the reasons for failure. For this example, corrosion is influenced by time in service and carburization is influenced by time, temperature, and location. Each case gives a pessimistic prediction of when failures will occur.

Figure 5 says to expect 10% of the tubes will have failed by corrosion (β = 11) in 16.7 years (5.2 years into the future), and for the carburization (β=26) end of life for the heat exchanger will be 13.1 years (1.6 years into the future).

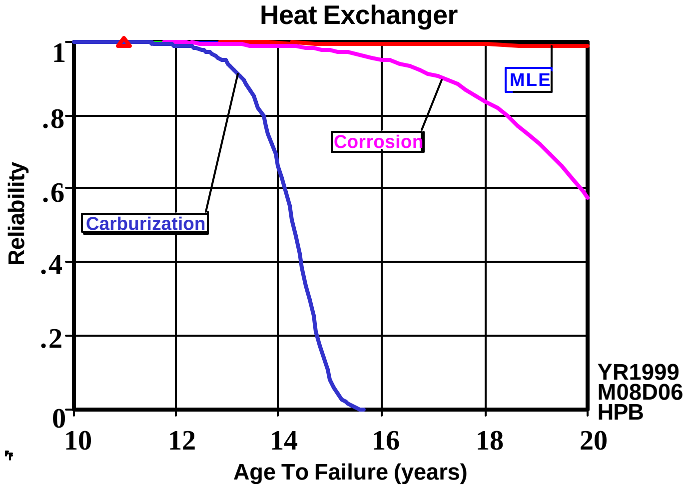


Figure 6: Reliability Curve For Heat Exchanger Modes

Both corrosion and carburization cases say to expect many failures in a short period of time because of the shape of the wearout hazard function as shown by the following generalized failure rates. For the corrosion mode of failure: (90-2)/5.2 = 15.4 failures per year, and the carburization mode of failure (90-2)/1.8 = 48.9 failures per year whereas the MLE prediction says (90-2)/28.8 = 3.1 failures per year. These conditions result in a large drop in reliability in a short time as shown in Figure 6.

A Management Viewpoint for Heat Exchanger Tubes-

Management must know the failure mode motivating failure at 11 years because the mode sets the pace for decisions shown in Figure 7 for optimum replacements.

If the failure mode is carburization or corrosion, then at our 11.5 year age, trouble is near when cost will rise quickly and dramatically as time accumulates!

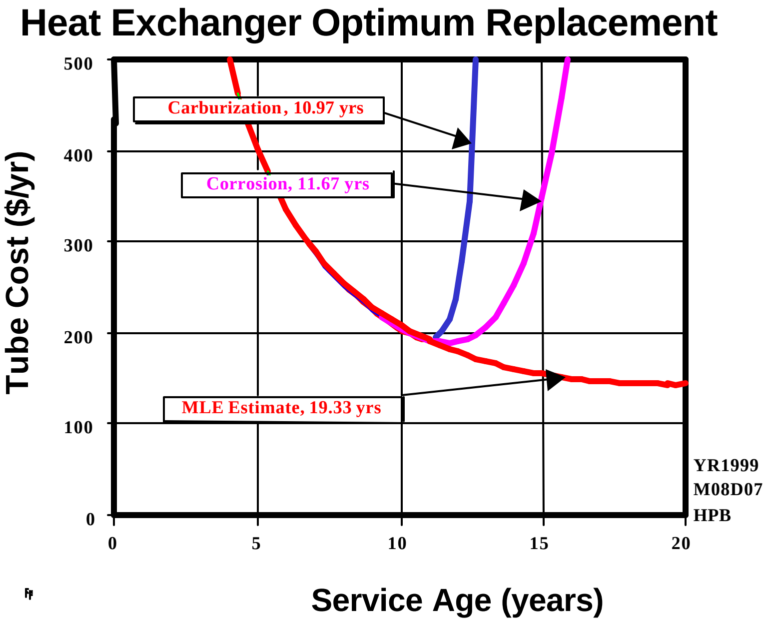
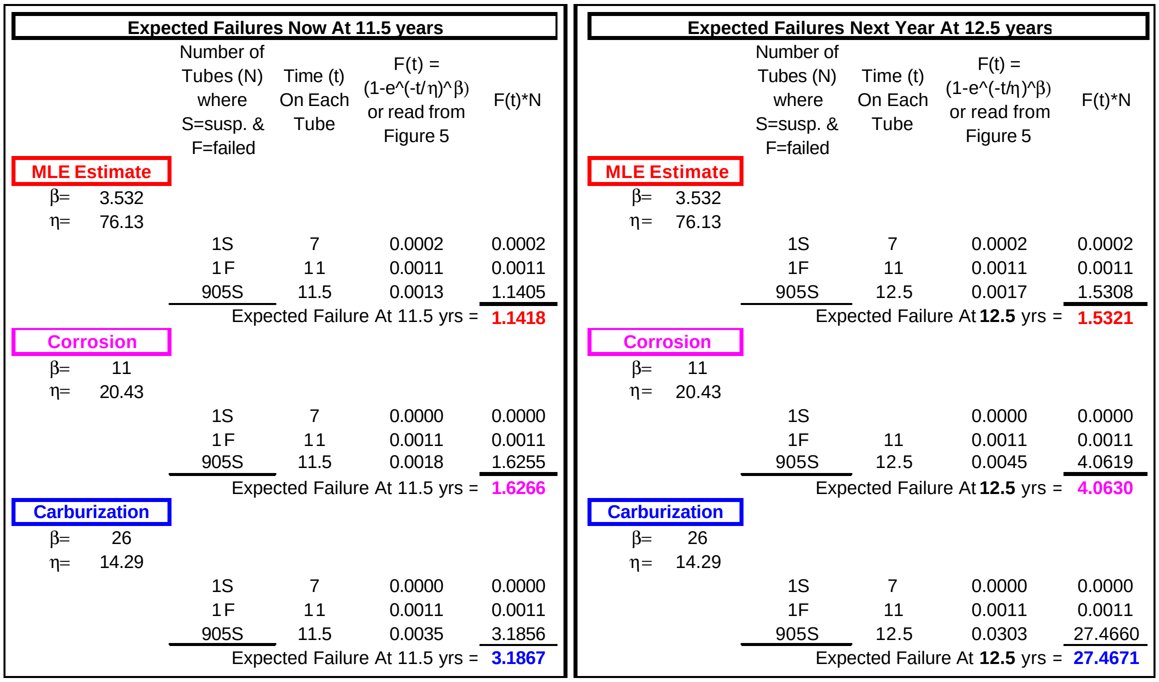


Figure 7: Optimum Tube Replacement Intervals

Use the Abernethy failure forecasting = risk model to predict the number of failures expected today at 11.5 years. Then for each failure mode, predict the number of failures expected to occur during the next 12 months of continuous service.

Failure modes should be determined physically rather than relying on inferences, however, Figure 8 gives some clues of what to expect. Notice the now risk at 11.5 years predicts 3.2 failures should have occurred if the mode was carburization--only one failure has been recorded. Thus if management is lacking physical evidence of the failure mode, the inference may be to expect the mode will be corrosion and thus avoid a panic reaction to 27.5-3.2 = 24.3 or 24 to 25 failures during the next 12 months. If corrosion is the expected failure mode, then plan for 4.1-1.6 = 2.5 failures during the next 12 months which says expect 2 to 3 outages at a cost of \$200,000 to \$300,000 for unplanned failures.



Expected Failures Now At 11.5 years

		Number of Tubes (N) where S=susp. & F=failed	Time (t) On Each Tube	F(t) = (1-e^(-t/η)^β) or read from Figure 5	F(t)*N
MLE Estimate					
β=	3.532				
η=	76.13				
		1S	7	0.0002	0.0002
		1 F	1 1	0.0011	0.0011
		905S	11.5	0.0013	1.1405
		Expected Failure At 11.5 yrs =			**1.1418**
Corrosion					
β=	11				
η=	20.43				
		1S	7	0.0000	0.0000
		1 F	1 1	0.0011	0.0011
		905S	11.5	0.0018	1.6255
		Expected Failure At 11.5 yrs =			**1.6266**
Carburization					
β=	26				
η=	14.29				
		1S	7	0.0000	0.0000
		1 F	1 1	0.0011	0.0011
		905S	11.5	0.0035	3.1856
		Expected Failure At 11.5 yrs =			**3.1867**

Expected Failures Next Year At 12.5 years

		Number of Tubes (N) where S=susp. & F=failed	Time (t) On Each Tube	F(t) = (1-e^(-t/η)^β) or read from Figure 5	F(t)*N
MLE Estimate					
β=	3.532				
η=	76.13				
		1S	7	0.0002	0.0002
		1F	11	0.0011	0.0011
		905S	12.5	0.0017	1.5308
		Expected Failure At **12.5** yrs =			**1.5321**
Corrosion					
β=	11				
η=	20.43				
		1S		0.0000	0.0000
		1F	11	0.0011	0.0011
		905S	12.5	0.0045	4.0619
		Expected Failure At **12.5** yrs =			**4.0630**
Carburization					
β=	26				
η=	14.29				
		1S	7	0.0000	0.0000
		1F	11	0.0011	0.0011
		905S	12.5	0.0303	27.4660
		Expected Failure At **12.5** yrs =			**27.4671**

Figure 8: Expected Failures Today (11.5 years) And Next Year (12.5 years)

However, if the expected failure mode is simple wearout explained by the MLE analysis, then plan for 1.5-1.1 = 0.4 failures during the next twelve months which says expect 0 to 1 outages at a cost of \$0 to \$100,000.

The key issue now is to carefully identify the failure mode and make decisions on a life cycle cost basis considering the cost of forecasted failures during each year of Figure 9 using a computational scheme of Figure 8. At \$100,000 per unplanned failure, the replacement actions are fairly obvious compared to a planned replacement of US$1,000,000 which includes lost gross margin.

Additional Tube Failures Forecasted At Mid Year

Time-->	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5	19.5	20.5	21.5
MLE		0.4	0.5	0.6	0.7	0.8	0.9	1.1	1.2	1.4	1.6
Corrosion		2.4	5.4	11.2	21.8	40.0	68.4	107.3			
Carburization		24.3	77.0	590.6							

Figure 9: Failures Expected In Each Year Into The Future

Summary for Dataset #2 Exchanger-

The statistical results are not very helpful. The engineering results are more enlightening, and the management issues show the most clarity but beg for a specified failure mode for the recorded failure.

All three failure modes show increasing failures each year. Recall the optimum replacement calculations in Figure 7 showed replacement at 19.3 years for MLE, 11.67 years for corrosion, and 10.97 years for carburization. Identifying the failure mode is a key requirement for making a good decision.

If the failure mode is slow wearout, take the risk and continue operations. If the failure mode is corrosion, move quickly to replace the bundle. If the failure mode is carburization, plug leaks and additional tubes in the heat-affected zone to reestablish a corrosion/wearout failure mode while purchasing a replacement bundle on an accelerated delivery schedule.

SUMMARY-

Small datasets do not provide good statistical results—the statisticians always will want more failures before they're willing to stick out their necks. Engineering details, using both art and science, along with past or similar situations add dimensions to the problem and their graphics are helpful for selling corrective actions. The management details of cost and time convert the problem into actionable items to help make decisions of whether to accept the risk and continue running, or reject the risk and replace the failing equipment. The real risk decision is money and time!

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BIOGRAPHIC INFORMATION-

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Manufacturing, engineering, and reliability consultant and author of the basic reliability training course **Reliability Engineering Principles**. More than thirty-five years of engineering and manufacturing experience in design, production, quality, maintenance, and reliability of technical products. Contributor to **The New Weibull Handbook**, a reliability engineering text published by Dr. Robert B. Abernethy. Named as inventor in six U.S.A. Patents. Registered Professional Engineer in Texas. Education includes a MS and BS in Mechanical Engineering from North Carolina State University. Visit the World Wide Web site at **http://www.barringer1.com** for other background details or send e-mail to **hpaul@barringer1.com** concerning similar reliability issues.

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