STEAM TRAPS AND MEAN TIME TO FAILURE
An Analysis of Steam Trap Survival Over Time

ABSTRACT

A survival analysis of steam trap historical data from a Northern US refinery demonstrates that the Velan Steam Trap maintains a significantly longer Mean Time To Failure than other designs.

Contents

Purpose of Report

Estimating the life expectancy of steam traps has always been a difficult task. This is due to the many variables that exist in the service environment causing mechanical wear and eventual failure in a steam trap population. However, it is important to try and make accurate estimates about the life expectancy of different steam trap designs in order to determine which technology offers the lowest total cost of ownership over time.

The purpose of this study is to determine the average life expectancy of a steam trap under a variety of service conditions. We have used a data set comprised of 12 years of steam trap testing results from a Northern USA Oil Refinery. This data set includes Velan Multi-Segment Bimetallic steam traps as well as Thermodynamic steam traps. Two types of statistical models were used to evaluate this data and determine Mean Time To Failure as well as survival probability over time.

Executive Summary

The statistical models used to evaluate the data set confirm that the Velan Multi-Segment Bimetallic (MSB) steam trap maintains an average life expectancy over 106% longer than Thermodynamic Steam Traps under the same variety of service conditions on the 150 psig system.

On average, Mean Time to Failure was determined to be 10.7 years for the Velan MSB, versus 5.2 Years for the Thermodynamic traps on the 150 psig system.

On average, survival probability after 10 years in service was found to be 52.1% for the Velan MSB versus 16.5% for the Thermodynamic traps on the 150 psig system.

Mean Time To Failure on the 150 psig system		
	Descriptive Modeling (Kaplan-Meier)	Predictive Modeling (Weibull)
VELAN Multi-Segment Bimetallic	**10.5** Years	**10.9** Years
Thermodynamic	**4.5** Years	**5.9** Years

Survival Probability After 10 Years In Service on the 150 psig system		
	Descriptive Modeling (Kaplan-Meier)	Predictive Modeling (Weibull)
VELAN Multi-Segment Bimetallic	**53.6** %	**49.0** %
Thermodynamic	**15.1** %	**17.6** %

Overview of Data

Beginning in 1999 and continuing for 12 years thereafter, the Murphy Oil, Superior Refinery conducted a plant wide evaluation of the steam traps in their facility. This survey was conducted between one and two times annually for a total of 21 separate audits. The total population of steam traps in this facility is approximately 2800 steam traps.

Each trapping location was assigned a unique ID number so that the life of the steam trap could be studied over the long term. Steam traps found to be working properly during each audit were given a designation of "OK" and no work was issued. Steam traps found to be failed in the open position were given the designation of "Failed Open" and a work order was written for their replacements. Repairs on average were completed within the following four weeks.

Ambient conditions at the plant site range from a high of 100°F in the summer to a low of -40°F in the winter. Typical applications for steam traps in this facility are drip leg and tracing line service at pressures of 150 psig, 50 psig, and 15 psig. Also included in the data set are several process and heating applications for both product storage tanks and buildings within the plant. The data set used in this report will be from the 150 psig system.

Overview of Steam Traps

Steam traps are automatic valves used to control the discharge of condensate from steam systems. In addition to discharging condensate, they are designed to remain closed when steam is present, effectively "trapping" the steam. Because of this dual purpose, steam traps have the potential to cause significant equipment damage or to waste large amounts of energy if not working properly.

As with all mechanical equipment, steam traps have a finite life span. While individual service conditions have a large bearing on the life of a steam trap, the most significant determining factor in steam trap service life appears to be principle of design and materials of construction.

Steam Trap Designs

VELAN MSB
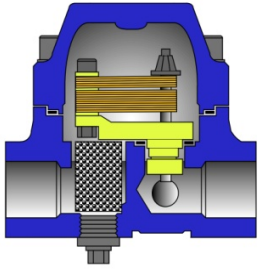
The VELAN Multi-Segment Bimetallic (MSB) design operates on a thermostatic principle. Consisting of a free floating, rotating ball valve actuated by a stack of bimetallic plates, the Velan MSB takes advantage of the lower heat content of cooling condensate to control water flow and prevent steam loss. Instead of a violent blast discharge, the VELAN MSB modulates condensate discharge resulting in lower amounts of mechanical wear than steam traps that operate with a blast on/blast off discharge pattern. In addition, the thermostatic operation of the trap prevents the loss of live steam and increases energy efficiency of the plant.

Velan MSB traps use a Stellite 6 faced valve seat and hardened 440C ball valve. Stellite 6 has 3 times the abrasion resistance of induction-hardened stainless steel.
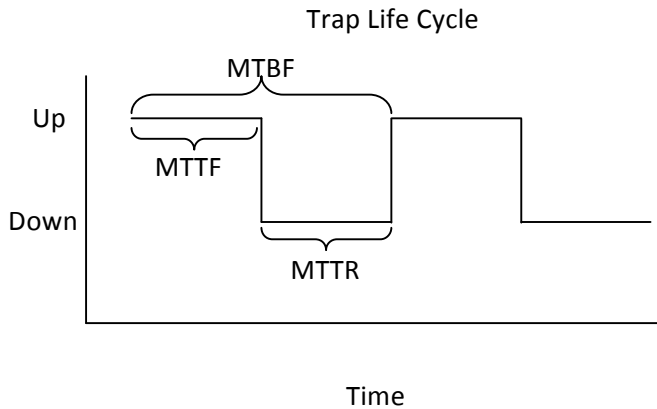
TD

The Thermodynamic Disc trap (TD) operates on the difference in flow velocity between a liquid and a gas. When condensate flows through the trap, the disc is pushed out of the way of the flow path allowing drainage of the equipment. However, when steam flows through the trap, the velocity of the flow increases and the disc is pulled onto the seat. When the disc keeping the disc closed condenses, the cycle repeats itself. TD traps operate with a violent blast on/blast off discharge pattern. Cycling rates are typically between 1 million and 3 million cycles per year, creating significant mechanical wear under normal working conditions. A measureable amount of live steam is lost during each cycle of the trap. This steam loss has been found to be 0.032 lb/cycle, making the annual steam losses from this type of trap typically in the range of $1,000 USD per year.

TD Traps typically use induction hardened stainless steel discs and seats.

Trap Life Cycle

Example:

Let in a given year 2% of the population fails. The inverse of 2% is 50, meaning the average traps will survive 50 years at that rate of failure.


Methodology

Mean Time to Failure

We define Mean Time To Failure (MTTF) as the expected time between two non-repairable, successive failures (Relex Software Corp.) This should not be confused with Mean Time Between Failure (MTBF) which includes in its definition not only the time in service before failure, but also the time after failure until the repair has been completed. MTTF measures only time in service before failure. Down time is represented by the Mean Time To Repair (MTTR). This measures the time it takes a trap to be repaired to working condition after it has failed. Thus, the *total* expected time for a repairable system is the up time plus the down time (MTBF = MTTF + MTTR). However, in the facility for which the data set originated, the MTTR represented a small percentage of the testing interval and therefore was not added to the MTTF.

One method to arrive at MTTF is to take the inverse of the sum of the failure rates (Carlsson 29). This is the quickest way of finding the MTTF. However, there are disadvantages to this method. One is that it can be hard to gather that kind of data. To obtain an accurate estimate you will need a large sample size that has failed. To wait and gather a sufficient amount of failure data would be very costly and time consuming. The second disadvantage is that it assumes the failure rate to be constant, which is not always the case as seen by the bathtub curve on the left.
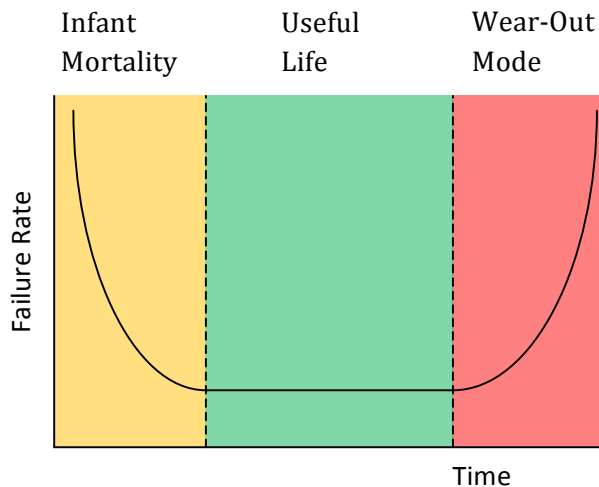
In the beginning of a life there is a high failure rate due to imperfection called infant mortality. Over time these unlucky steam traps die off rather quickly and the failure rate falls. The failure rate will fall until it becomes constant where failures are now random occurrences. This stage is known as the useful life. After the useful life is complete, the population enters the wear-out mode. The failure rates now increases again because the limitations of the design and materials of construction have been reached.

Population: The whole group of steam traps on a 150 psig system.

Data sample: A subgroup of the total steam trap population.

*Censored data:* Don't know the whole lifetime of a trap.

Censored Data

In many data samples it is not uncommon to have limited numbers of observations of an event relative to the size of the total population. In our case the challenge was finding the failure of a trap within the limitations of the observed time. When an experiment ends before the end of life for all the members of the population, it is called suspended, censored, or truncated (Romeu).

Censored data occurs when the installation date is unknown, the failure date of the steam trap is unknown, or the steam trap has been withdrawn from the system before a confirmed failure.

We can further categorize the data into right, left, and interval censored data. With right-censored data we know the start time but not the end time as it has not failed within the observed time period. For left-censored data, we do not know the start time but only a random time in the traps life to failure time. For interval- censored data we know neither the start time nor the time of failure but know only that it was functional for a certain period.

The data set used in this report is right-censored data as well as observed failures on the 150 psig system.
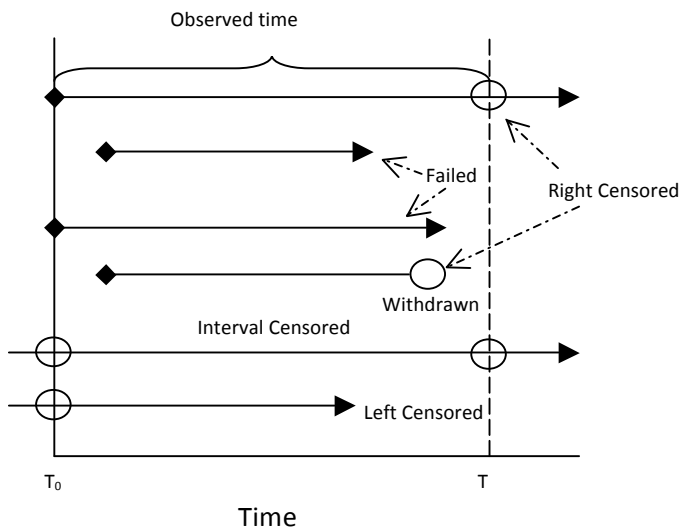
Overview of Data Sample

***Lifetime:*** The observed time from installation to failure or censored time.

The aggregate data sample is comprised of 4,656 individual steam trap lifetimes on the 150 psig system.

The VELAN MSB represents 3,785 individual lifetimes with 3,036 of those being censored.

The TD trap sample size is 871 individual lifetimes with 421 of those being censored.

The box plots on the left show the minimum, 1st quartile, medium, 3rd quartile, and maximum lifetime observations for the censored and failed data sets.

The pie charts at the bottom show the number of steam traps that are censored and failed for both the VELAN MSB and TD trap designs.

Summary of Data

Summary of Data

VELAN MSB Lifetimes

TD Lifetimes
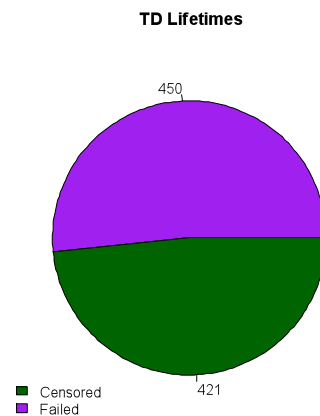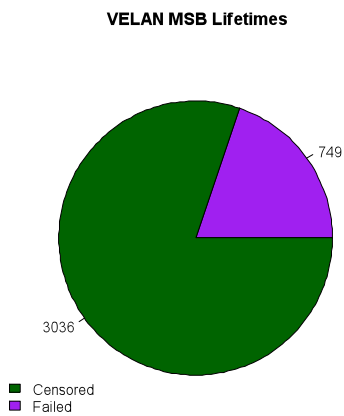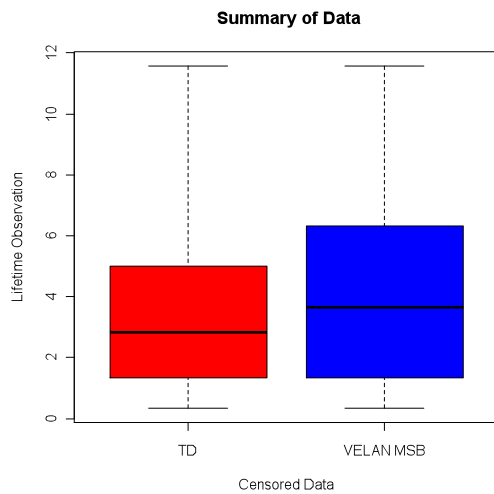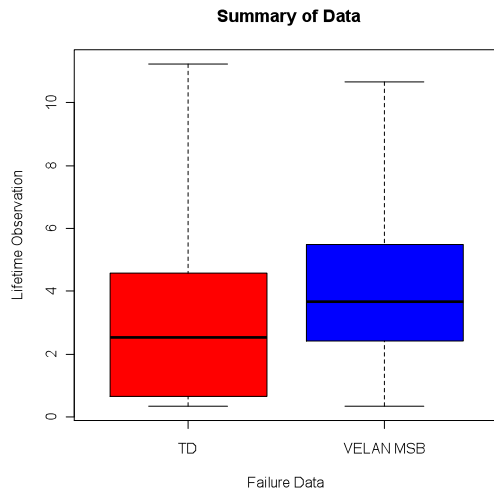
Non-Parametric

Non-parametric modeling enables one to view the sample without any restrictions. The advantage of using a non-parametric method is that it has no assumptions of the distribution of the failure times. The non-parametric test focused on here is the Kaplan-Meier survival curves.
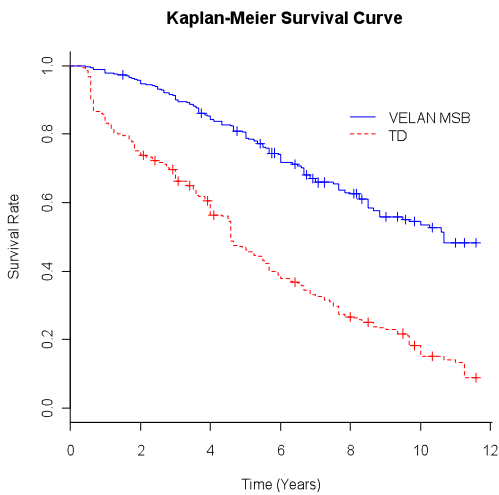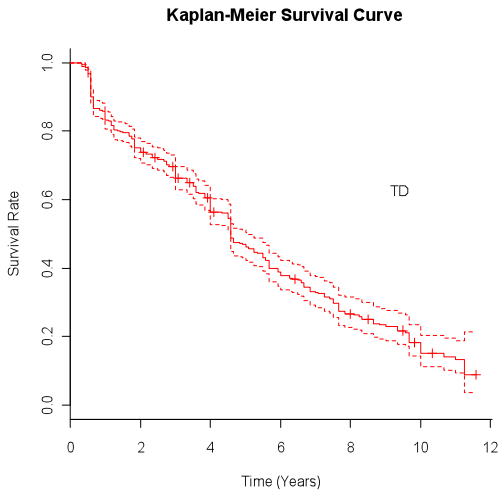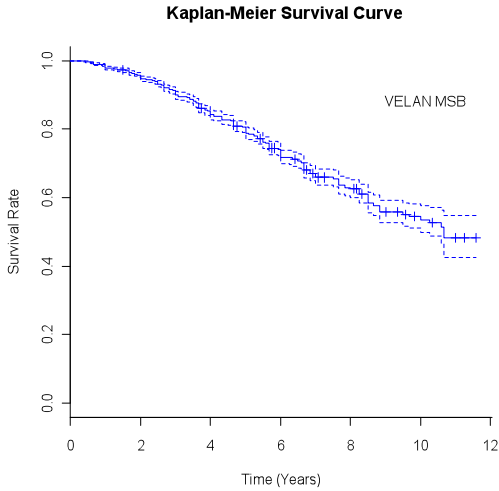
Kaplan-Meier

Kaplan-Meier survival curves make no assumptions about the distribution of failures, giving us a purely descriptive model. This is due to there being no parameters in the function, hence non-parametric. The KM function is only dependent on time. At a time of an event there are a number of possible failures of traps and a number of traps that actually failed. The KM function at time t finds the ratio of surviving traps and multiplies the terms up till the specified time t. When the data is censored those traps are taken out of the risk set. The KM curve depicts the probability of surviving past time t, granted that the steam trap has not failed before time t. Graphically the survival function looks like stairs going down from left to right. The step down implies a failure has occurred. Censored data is represented by a cross.

Kaplan – Meier Survival Function:

$$\hat{S}(t) = \prod_{i=1}^{k} \left(\frac{n_i - d_i}{n_i} \right)$$

n_i = # of steam traps in risk set at time t

d_i = # of failed steam traps at time t

Kaplan-Meier Survival Curve

At left are two Kaplan-Meier survival curves with 95% confidence intervals of our data. There is also a third graph comparing the KM survival curves. The horizontal axis is time, in years, that the trap population has been working. The vertical axis represents the probability of survival up to time *t*. The dashed lines in the top two figures are the confidence intervals.

To interpret these graphs at time *t* there is a corresponding value of the probability of a trap not failing. For example, at 10 years the VELAN MSB has a 53% probability of surviving to this time. Compare that to the TD design, which has a 17% probability of survival for the same time period.

Another way of looking at these graphs is by looking at the whole population of traps. Assume two populations of the VELAN MSB and TD models are installed at the same time. At 10 years the VELAN MSB trap population maintains 53% of the population still in working condition. While the TD trap population at 10 years maintains 17% of the population still in working condition. In other words, 47% of the trap population will have failed for the VELAN MSB traps in 10 years compared to 83% of the TD population failed in the same time period.

Log-Rank Test

We have used the Log-Rank test to make comparisons of the equivalency of the Velan MSB and TD Trap curves. The Log-Rank test is a Chi-Square test comparing the distribution of the two designs. To find the Log-Rank statistic we used the formula on the left. The Log-Rank assumes the Log-Rank statistic is approximately a Chi-Square. If the Log-Rank statistic is greater than the Chi-Square critical p value then we reject the null hypothesis that the two models have the same distribution.

The critical p value at the 95% confidence level is 3.84. At the 99.9% confidence level, the critical p value is 10.83.

Our sample has a Log-Rank statistic of 441, exceeding the 99.9% confidence level.

Log $-$ Rank Statistic:

$$LR = \frac{\sum_{t=1}^{n}\left(O_t - E_t\right)^2}{Var\left(\sum_{t=1}^{n}\left(O_t - E_t\right)^2\right)}$$

$O_t = \#$ of failures at time t

$E_t =$ expected $\#$ of failures time t

Survival Function:

$$\hat{S}(t) = \exp(-\eta t^{\beta})$$
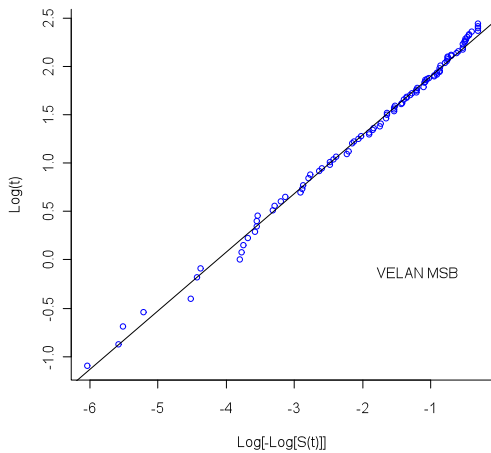
η = scale parameter

β = shape parameter

$$\ln\left[-\ln\left[\hat{S}(t)\right]\right] =$$
$$\ln\left[-\ln\left(\exp\left(\eta t^{\beta}\right)\right)\right] = \ln\left(-\eta t^{\beta} * -\ln(e)\right) =$$
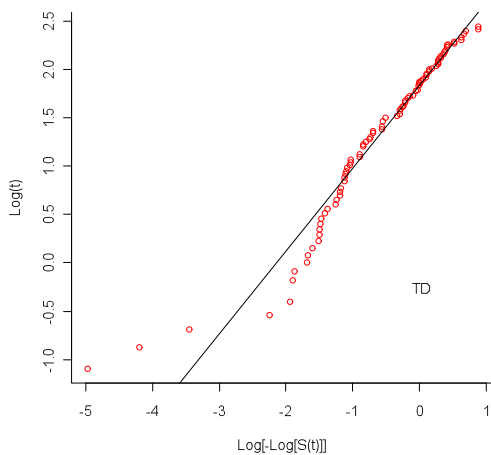$$\ln(\eta) + \ln(t) * \beta$$

↑   ↑
B   M*x

Weibull Fit

Weibull Fit

Parametric

Predictive or parametric models are more restrictive because of their use of parameters in the model that assume the distribution of failures will follow a certain pattern. We have chosen the Weibull Distribution Model due to its popularity among the reliability engineering community in modeling life cycles for mechanical equipment.

Weibull Distribution

The Weibull Distribution is one of the leading parametric models for explaining life data. There are three different versions of this model but we will be only concerned with the two parameter model. But, before we begin modeling we need to check to see if the Weibull model does a good job representing the data. To do this we need to understand the survival function of the distribution.

The Weibull survival function is the same as the KM curve in that it gives the probability that a steam trap survives longer than some specified time *t*. What is different between the KM and the Weibull is that the Weibull distribution assumes that the distribution can be explained by a certain equation seen on the left. Notice that the function is only dependent on time, the rest of the symbols are constants.

The test consists of taking the log negative log of the survival function and to plot it against the log of time. What you need to know is taking the log of the number multiples the exponents of that number with the log of the base of the number. And if the base is a product of two constants, the log of that number is the log of one constant plus the log of the other constant. So taking the log twice of the survival function actually transforms this function into a linear line, y=mx+b. This equation is now dependent on the log of time. Also λ (lamda) and *p* are constants parameters. So, if our data is a good fit for the Weibull model, it should fall in a straight line.

By going back to the KM survival curves and doing this transformation, reveals that our data sets can be represented by the Weibull distribution.
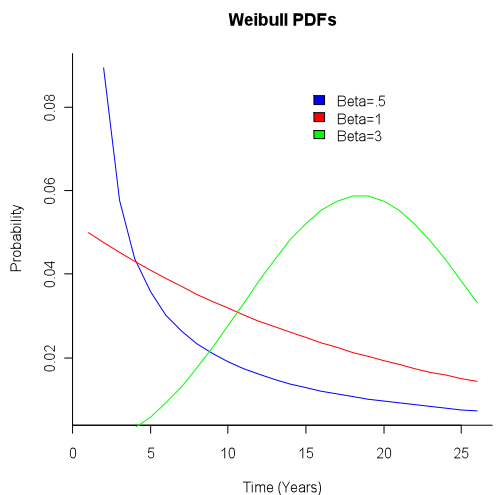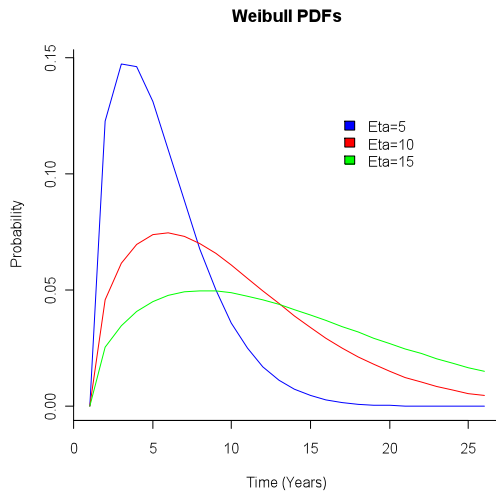
Probability Density Function:

$$f(t) = \left[\frac{\beta}{\eta}\right]\left[\frac{t}{\eta}\right]^{\beta-1} * \exp(t/\eta)^{\beta}$$

β = shape parameter

η = scale parameter

t = years in service

Weibull PDFs

Weibull PDFs

Cumulative Density Function:

$$F(t) = 1 - \exp(-t/\eta)^{\beta}$$

β = shape parameter

η = scale parameter

t = years in service

The Probability Density Function (PDF) is a function of time that gives the probability of the occurrence to take place. The flexible two parameter PDF is seen on the left.

The two parameters are η (eta) the scale parameter and β (beta) the shape parameter. These parameters have different effects on the model. The parameter η changes the distribution of the PDF. Larger the η, the more stretched out the graph becomes. Smaller the η the more compressed the graph is. The parameter β affects the shape of the graph. A β less than one its monotonically decreasing, equal to one downward sloping line, and greater than one a typical looking PDF curve.

Besides graphical consequences with the βs, different βs also have theoretical implication. When β is less than one implies infant mortality. When β equals to one means random failures. And when β is greater than one implies wear out failures are present.

An equivalent function to the PDF is the Cumulative Density Function (CDF) which can be seen on the left. It shows the percentage that will fail at any time period (Abernethy 1-4). A key note on this graph is to know that η is the time where 63.2% of failures will be predicted to have occurred. To show why look at the equation for the CDF. The special case happens when x equals η the fraction becomes one. Since one raised to any power is one it stays the same. A number raised to a negative power becomes it's reciprocal. Thus, the equation becomes is approximately 0.632.

Maximum Likelihood Function:

$$L = \prod_{i=1}^{n}\left(\left[\frac{\beta}{\eta}\right]\left[\frac{t_i}{\eta}\right] * \exp(t_i/\eta)^{\beta}\right)^{\delta_i}\left(\exp(-t_i/\eta)^{\beta}\right)^{\delta_i - 1}$$
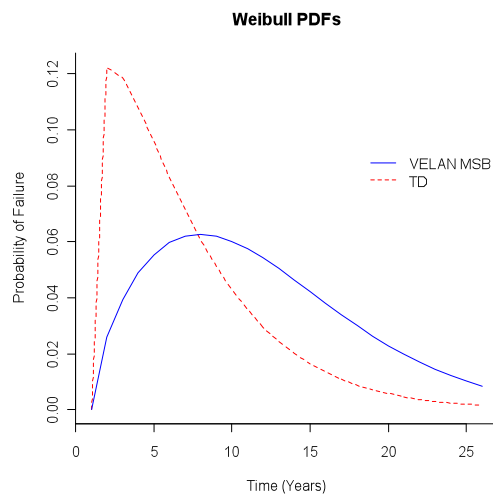
β = shape parameter

η = scale parameter

t_i = observed lifetime for steam trap

δ_i = censored trap (0)

Weibull PDFs

Many statisticians believe that the Maximum Likelihood Estimation (MLE) has become the workhorse of statistical estimation (Genschel and Meeker 7). According to Genschel and Meeker the MLE method is desirable because simulation studies have shown MLE are consistently hard to beat, versatile in using censored data, ease of finding confidence intervals, and along with other features.

MLE method was used to achieve the parameters in our models. It is widely known in the mathematical community for its beneficial properties. The MLE was credited to R.A. Fisher in 1922. In a nutshell the idea behind the method is given a certain data set; what is the most likely parameter (given a certain distribution) to give you that data set. This technique assumes that the events are i.i.d, or independent identical distribution.

Overview of the theory might help shed some light on to how this method works. Let n be the number of observations in a sample data set and the distribution to be Weibull. Since we assume failures to be random, independent events; we are able to multiply the probabilities together evaluated at the individual times. The likelihood equation can be seen on the left.
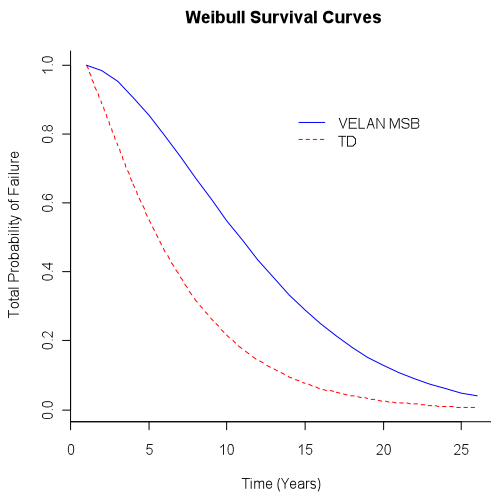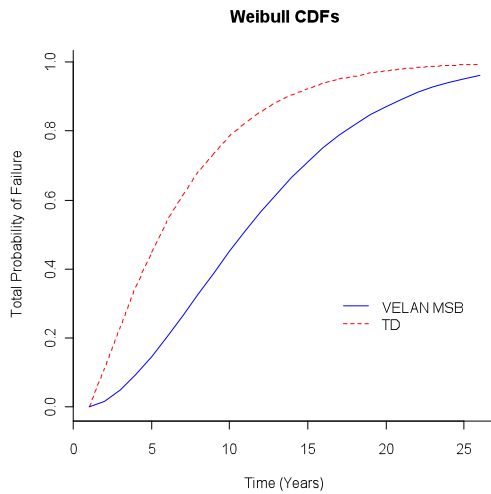
Maximizing the likliehood function reveals the parameters for the designs. For the VELAN MSB the η was 12.28 and the β being 1.64. For the TD the η was 6.23 and the β being 1.16. The confidence interval at the 95% level is shown on the left. A key note here is that not only is the ηs are different but also the βs are two.

Figuring our ηs and βs for the VELAN MSB and TD designs we now have our Weibull models. The PDF curves give the probability of failure at a given time *t*. For example, at five years the VELAN MSB has about .5% probability of failing while the TD has around a 1.1% chance of failing. Notice that these probabilities are chance of failure at that particular *point* in time.

VELAN MSB	High	Estimate	Low
η (scale parameter)	12.66	12.28	11.91
B (shape parameter)	1.69	1.64	1.59

TD	High	Estimate	Low
η (scale parameter)	6.50	6.23	5.98
B (shape parameter)	1.21	1.16	1.12

Weibull CDFs

Weibull Survival Curves

The Weibull CDFs represent the same information in a different light. The Weibull CDF is the integral of the Weibull PDF, meaning it is the Weibull CDF represents the total area under the Weibull PDF Curve. This area represents the probability of failure at time *t* or before. An example is the VELAN MSB at 12 years has around 63.2% probability of failing at 12 years or before. The TD at 6.5 years has the 63.2% chance of failure at this time or before. Notice that the numbers used where roughly the ηs of the models.

The Weibull survival curves show the probability of surviving longer than some time *t*. These curves are just 1 minus Weibull CDFs. They are also read as the same as the KM survival curve. At 10 years the VELAN MSB has a probability of survival of around 60% compared to about 20% for the TD model.

As before, you can interpret these models as whole populations of traps. Using the same time length of 10 years the VELAN MSB would have 49.0% working traps at a 95% confidence level with the TD having 17.6% working traps at a 95% confidence.

Finally we come to figure out the MTTF of the designs. To find the MTTF we need to use the gamma function. The gamma function is closely related to the Weibull distribution. The reason why we do not just find the 50% mark in the survival curve is because the distribution is skewed a little. The equation used to find the MTTF is shown on the left. After calculating using the formulas we have found the MTTF.

The VELAN MSB's MTTF is 10.988 years on the 150 psig system.

The TD's MTTF is 5.913 years on the 150 psig system.

$$\mathrm{MTTF} \; = \; \eta * \Gamma\left(\frac{1}{\beta}+1\right)$$

Gamma Function:

$$\Gamma(n) = \int_0^\infty e^{-x} x^{n-1} dx$$

Conclusion

Descriptive Modeling - Non-Parametric Modeling

At 10 years of service the VELAN MSB design maintains 53.6% of the population still in working condition compared to 15.1% of the TD trap population on the 150 psig system. The VELAN MSB model has a MTTF of 10.5 years while the TD trap has a MTTF of 4.7 years on the 150 psig system.

The Kaplan – Meier survival curves support the conclusion that the VELAN MSB model is significantly more reliable than the TD model on the 150 psig system.

Predictive Modeling – Parametric Modeling

At 10 years using parametric modeling, the VELAN MSB maintains 49% of the population still in working condition compared to 17.6% of the TD trap population. The VELAN MSB model has a MTTF of 10.9 years while the TD trap has a MTTF of 5.9 years on the 150 psig system.

The Weibull survival curves also support the conclusion that the VELAN MSB model is significantly more reliable than the TD model on the 150 psig system.

Summary

The VELAN Multi-Segment Bimetallic steam trap offers a significantly longer Mean Time To Failure than Thermodynamic Disc Type steam traps on the 150 psig system. The use of multiple statistical models confirms that MTTF for the Velan MSB is over 106% longer than for Thermodynamic Traps. Survival probability was found to be over 3 times greater after 10 years in service for the Velan MSB over the Thermodynamic trap.

Use of the Velan MSB over that of Thermodynamic type steam traps can save significant amounts of money and resources over time due to the longer life expectancy.

Survival Probability After 10 Years In Service on the 150 psig system		
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