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# PREDICTING THE SERVICE LIFE OF WOOD POLES USING LIFE CYCLE ANALYSIS TECHNIQUES

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## 1 SUMMARY

This paper describes the use of the Weibull cumulative density function (CDF) for characterizing the life data of wooden poles. The Kaplan-Meier technique is used for point estimates of cumulative probabilities. Correlation is evaluated using the coefficient of determination (COD) for the CDF transformed to a linear relation by means of two successive natural logarithmic operations.

The analysis can be used for the following purposes.

- To determine whether the failure rate is decreasing, constant or increasing.
- To forecast the number of failures as a function of age.
- To compare the performance of different species and different preservation techniques.
- To assist in developing a replacement strategy.


## 2 INTRODUCTION

The four decades following World War II represented a period of considerable expansion for utilities in North America. Many of the products installed during that era are now approaching the end of their physical or economic life. The challenges for utilities have therefore shifted from those associated with construction to the cost effective, safe, and environmentally acceptable replacement of aging products. Included within these aging products are wooden poles of a variety of species and preservation techniques. Many of these poles are now approaching the end of their useful life because rot is jeopardizing their structural integrity.

Statistical techniques for quantifying the reliability of products as a function of age have been developed and applied in the aircraft and aerospace industries during the past five decades. Similarly statistical techniques have been developed and applied for many decades in the medical field for quantifying various phenomena as a function of age. More recently these techniques have been successfully applied to assist in assessing business risks and to improve the quality of decisions associated with the replacement of products.

The Weibull function is the most appropriate probability function in the vast majority of situations. The classical Weibull technique for estimating point values of the cumulative probability requires reasonably accurate life data for the population of interest, from the date of installation. Unfortunately this information is often unavailable in utilities. However utilities often have data for a complete population at a particular time and as a function of age. The Kaplan-Meier technique (developed within the medical industry) is suitable for this kind of data. The Kaplan-Meier technique is also more suitable than the Weibull technique for large amounts of data, which is often the case with wooden poles.

Using Kaplan-Meier point estimates to estimate the parameters of the Weibull CDF usually yields a Weibull CDF with acceptable correlation. However even when the correlation is unacceptable the curve provides insights into the reasons for poor correlation.

Of course inferences from the assumed function are meaningless if the fit between the function and the data is poor. Fortunately the fit can be quantified by means of the COD used commonly for liner relations. The Weibull can be transformed to a linear function by two successive logarithmic operations, from which the COD can be calculated.

It is important to note that statistical analyses are not a substitute for engineering judgement and common sense.

## 3 METHODOLOGY

Results of inspections of populations of wooden poles are often available for an interval. The results are usually arrayed by age, species, and preservation techniques. In this case the Kaplan-Meier technique is appropriate for point estimates of the cumulative probability of failure (R.B. Abernethy, 2000).

$$P[t \geq t_k] = \prod_{i=1}^{k} \left( 1 - \frac{f_i}{n_i} \right)$$

$$F(t_k) = 1 - P[t \geq t_k]$$

where:

"$P[t \geq t_k]$" is the probability of survival to time $t_k$.

"t" is time in years.

"$t_k$" is the time to the end of the $k^{th}$ inspection interval.

"$f_i$" is the number of failures at the end of the $i^{th}$ inspection interval.

"$n_i$" is the number of poles inspected in the $i^{th}$ inspection interval.

"k" is the number of inspection intervals.

"$F(t_k)$" is a point estimate of the probability of failure by time $t_k$.

The associated cumulative density function is the Weibull function.

$$F(t) = 1 - e^{-\left( \frac{(t - t_0)}{h} \right)^b}$$

where:

"F(t)" is the cumulative probability of failure by time t.

"$t_0$" is the time correction.

"η" is the characteristic life (scaling factor).

"β" is the shape factor.

The parameters β and η are estimated using least squares techniques.

$$Y = mX + b$$

$$Y = \ln\left[\ln\left(\frac{1}{1 - F(t_k)}\right)\right]$$

$$X = \ln(t_k - t_0)$$

$$b = \overline{Y} - b\overline{X} = -b\ln h$$

$$m = b = \frac{N\sum X^2 - \left(\sum X\right)^2}{N\sum XY - \sum X \sum Y}$$

$$h = e^{-\left(\frac{b}{b}\right)}$$

The coefficient of determination (COD) is determined as follows.

$$COD = \frac{\left[\sum XY - \frac{\sum X \sum Y}{N}\right]^2}{\left[\sum X^2 - \frac{\left(\sum X\right)^2}{N}\right]\left[\sum Y^2 - \frac{\left(\sum Y\right)^2}{N}\right]}$$

The COD varies from zero to unity A value of zero means that there is no correlation. A value of unity means that the correlation is perfect. Correlation improves as the COD approaches unity. There are graphs available to judge whether correlation is acceptable. The graphs are a function of the type of probability density function and the number of inspection intervals (in this case). If the value of the COD is too low, the graph of the data should be examined for possible batch problems, mixtures of failure modes, and mixtures of failure mode classes.

The shape factor β indicates whether the failure rate is decreasing, constant, or increasing.

- A value of β less than unity generally indicates that wear-in is represented within the population.
- A value of β of unity indicates that random failures are represented within the population.
- A value of β exceeding unity indicates that wear-out is represented within the population.

The scale factor η indicates the age by which 63.2% of the population is estimated to fail.

The performance of different species and preservation techniques can be compared, either by specific age or by the mean time to failure (MTTF).

$$MTTF = t_0 + h\Gamma\left(1 + \frac{1}{b}\right)$$

Future failures can be forecast for each age group.

$$T = \sum_{i=1}^{k} s_i \left[ \frac{F(t_i + u) - F(t_i)}{1 - F(t_i)} \right]$$

where:

"T" is the total number of failures.

"$t_i$" is the age of the $i^{th}$ age group.

"u" is the interval.

"$s_i$" is the number of survivors in the $i^{th}$ age group.

"$F(t_i)$" is the probability of failure by age "$t_i$".

"$F(t_i + u)$" is the probability of failure by age "$t_i + u$".

"k" is the number of age groups.

Note that the forecast is sensitive to correlation and is usually not effective for forecasting beyond a few units of time.

The cost per unit time can be expressed as follows (R.B. Abernethy, 2000).

$$C(t) = \frac{P[1 - F(t)] + UF(t)}{\int_0^t e^{-\left(\frac{x}{h}\right)^b} dx}$$

where:

C(t) is the unit cost.

P is the planned replacement cost.

U is the unplanned replacement cost.

F(t) is the cumulative probability of failure to time t.

## 4 RESULTS AND DISCUSSION

Mr. Wayne Ortiz of Manitoba Hydro kindly provided inspection data on wooden poles. The following data were analyzed as examples of the application of the techniques described in this paper. The analyses were done with an incomplete knowledge of the data collection so is for illustrative purposes only.

- Jack Pine poles with creosote preservation
- Jack Pine poles with penta preservation
- Western Cedar poles with creosote preservation
- Western Cedar poles with penta preservation

Tables 1 to 4 inclusive and Figures 1 to 4 inclusive show the regression analyses and results. General observations are as follows.

- Correlation is satisfactory for the four analyses.
- The failure rate is increasing in all cases. Wear-out is therefore represented in all populations.

The best correlation for the Jack Pine and Western Cedar poles with creosote preservation was obtained with a positive time shift. This suggests that with this preservative rot does not occur for a finite time. The best correlation for the Jack Pine poles with penta preservation was obtained with a two-parameter Weibull function (i.e. without a time shift). This suggests that rot proceeds more quickly than for creosote preservation or that the poles may have been stored for some time before being installed. The best correlation for the Western Cedar poles with penta preservation was obtained with a negative time shift. This suggests that the poles may have been stored for some time before being installed. Of course these comments are only conjecture. A technical assessment is necessary to fully explain the differences in performance. The values of COD are as follows.

- Jack Pine poles with creosote preservation – 0.987
- Jack Pine poles with penta preservation – 0.994

- Western Cedar poles with creosote preservation – 0.990
- Western Cedar poles with penta preservation – 0.988

The expected number of failures for the next three-year period was estimated as follows.

- Jack Pine poles with creosote preservation – 480
- Jack Pine poles with penta preservation – 100
- Western Cedar poles with creosote preservation – 980
- Western Cedar poles with penta preservation – 1330

In this case the Jack Pine poles with creosote preservation appear to have significantly greater longevity on average than the Jack Pine poles with penta preservation. Jack Pine poles also appear to have greater longevity than Western Cedar poles. The mean times to failure are as follows.

- Jack Pine poles with creosote preservation – 126 years
- Jack Pine poles with penta preservation – 63 years
- Western Cedar poles with creosote preservation – 54 years
- Western Cedar poles with penta preservation – 58 years

From the values of the shape factor it seems that once rot has started it proceeds more rapidly in penta treated poles than creosote treated poles. It also seems that once rot has started it proceeds more rapidly in Western Cedar poles than in Jack Pine poles.

Sometimes safety or environmental concerns dictate a maximum allowable value of the cumulative probability. The analysis provides the corresponding age, so replacement can be planned. Replacement ages for a maximum cumulative probability of 10% are as follows.

- Jack Pine poles with creosote preservation – 52 years
- Jack Pine poles with penta preservation – 40 years
- Western Cedar poles with creosote preservation – 31 years
- Western Cedar poles with penta preservation – 38 years

Sometimes the cost of unplanned maintenance exceeds the cost of planned maintenance significantly. The analysis yields the age at which planned replacement represents the least per unit cost. For example the least cost replacement age for Jack Pine poles with creosote is approximately 90 years if the cost of unplanned replacements is five times that of planned replacements, and 60 years if the cost of unplanned replacements is ten times that of planned replacements.

## 5 CONCLUSIONS

The Weibull cumulative probability function, using the Kaplan-Meier technique for point estimates of the cumulative probability of failure, can be used for the following.

- To quantify the relation between the cumulative probability and age.

- To forecast required replacements.
- To compare species and preservation techniques.
- To estimate the age at which poles should be replaced for safety or environmental reasons.
- To estimate the age at which planned replacement represents the least cost alternative.

## 6 LITERATURE


- The New Weibull Handbook, Fourth Edition, Dr. R.B. Abernethy
- Probability and Statistics for Engineers, I. Miller and J.F. Freund, Second Edition, Prentice-Hall
- Probabilistic Risk Assessment and Management for Engineers and Scientists, Second edition, H. Kumamoto and E.J. Henley, IEEE Press

## Table 1. Manitoba Hydro Jack pine poles with creosote

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| $t\text{-}t_0$ (y) | $f_i$ | $n_i$ | $1\text{-}f_i/n_i$ | KM | 1-KM | 'X' = ln(A) | 'Y' = ln(ln(1/(1-F))) | '$Y^2$' = $H^2$ | 'YX' = G*H | '$X^2$' = $G^2$ |
| 3.30 | 2 | 593 | 0.997 | 99.7% | 0.3% | 1.19 | -5.69 | 32.38 | -6.79 | 1.43 |
| 6.30 | 4 | 755 | 0.995 | 99.1% | 0.9% | 1.84 | -4.75 | 22.52 | -8.73 | 3.39 |
| 9.30 | 8 | 2036 | 0.996 | 98.7% | 1.3% | 2.23 | -4.37 | 19.11 | -9.75 | 4.97 |
| 12.30 | 32 | 1684 | 0.981 | 96.9% | 3.1% | 2.51 | -3.45 | 11.89 | -8.65 | 6.30 |
| 15.30 | 4 | 579 | 0.993 | 96.2% | 3.8% | 2.73 | -3.25 | 10.57 | -8.87 | 7.44 |
| 18.30 | 11 | 554 | 0.980 | 94.3% | 5.7% | 2.91 | -2.83 | 8.03 | -8.24 | 8.45 |
| 21.30 | 8 | 1065 | 0.992 | 93.6% | 6.4% | 3.06 | -2.71 | 7.36 | -8.30 | 9.36 |
| 24.30 | 17 | 1133 | 0.985 | 92.2% | 7.8% | 3.19 | -2.51 | 6.29 | -8.00 | 10.18 |
| 27.30 | 23 | 1647 | 0.986 | 90.9% | 9.1% | 3.31 | -2.35 | 5.51 | -7.77 | 10.94 |
| 30.30 | 120 | 12309 | 0.990 | 90.0% | 10.0% | 3.41 | -2.25 | 5.07 | -7.68 | 11.64 |
| 33.30 | 52 | 7391 | 0.993 | 89.4% | 10.6% | 3.51 | -2.19 | 4.78 | -7.66 | 12.29 |

## Table 2. Manitoba Hydro Jack pine poles with penta

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| $t\text{-}t_0$ (y) | $f_i$ | $n_i$ | $1\text{-}f_i/n_i$ | KM | 1-KM | 'X' = ln(A) | 'Y' = ln(ln(1/(1-F))) | '$Y^2$' = $H^2$ | 'YX' = G*H | '$X^2$' = $G^2$ |
| 16.00 | 3 | 1332 | 0.998 | 99.8% | 0.2% | 2.77 | -6.0947 | 37.15 | -16.90 | 7.69 |
| 19.00 | 4 | 1105 | 0.996 | 99.4% | 0.6% | 2.94 | -5.1360 | 26.38 | -15.12 | 8.67 |
| 22.00 | 6 | 1142 | 0.995 | 98.9% | 1.1% | 3.09 | -4.4964 | 20.22 | -13.90 | 9.55 |
| 25.00 | 5 | 1677 | 0.997 | 98.6% | 1.4% | 3.22 | -4.2591 | 18.14 | -13.71 | 10.36 |
| 28.00 | 7 | 630 | 0.989 | 97.5% | 2.5% | 3.33 | -3.6766 | 13.52 | -12.25 | 11.10 |
| 31.00 | 6 | 465 | 0.987 | 96.2% | 3.8% | 3.43 | -3.2624 | 10.64 | -11.20 | 11.79 |
| 34.00 | 8 | 361 | 0.978 | 94.1% | 5.9% | 3.53 | -2.8017 | 7.85 | -9.88 | 12.44 |
| 37.00 | 9 | 362 | 0.975 | 91.8% | 8.2% | 3.61 | -2.4548 | 6.03 | -8.86 | 13.04 |
| 40.00 | 5 | 147 | 0.966 | 88.6% | 11.4% | 3.69 | -2.1162 | 4.48 | -7.81 | 13.61 |
| 43.00 | 5 | 217 | 0.977 | 86.6% | 13.4% | 3.76 | -1.9393 | 3.76 | -7.29 | 14.15 |
| 46.00 | 8 | 348 | 0.977 | 84.6% | 15.4% | 3.83 | -1.7894 | 3.20 | -6.85 | 14.66 |

## Table 3. Manitoba Hydro Western Cedar poles with creosote

| A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| $t\text{-}t_0$ (y) | $f_i$ | $n_i$ | $1\text{-}f_i/n_i$ | KM | 1-KM | 'X' = ln(A) | 'Y' = ln(ln(1/(1-F))) | 'Y$^2$' = H$^2$ | 'YX' = G*H | 'X$^2$' = G$^2$ |
| 10.1 | 2 | 104 | 0.981 | 98.1% | 1.9% | 2.31 | -3.9416 | 15.54 | -9.11 | 5.35 |
| 14.1 | 1 | 164 | 0.994 | 97.5% | 2.5% | 2.65 | -3.6677 | 13.45 | -9.71 | 7.00 |
| 18.1 | 11 | 250 | 0.956 | 93.2% | 6.8% | 2.90 | -2.6517 | 7.03 | -7.68 | 8.39 |
| 22.1 | 69 | 1367 | 0.950 | 88.5% | 11.5% | 3.10 | -2.1011 | 4.41 | -6.50 | 9.58 |
| 26.1 | 112 | 1185 | 0.905 | 80.1% | 19.9% | 3.26 | -1.5068 | 2.27 | -4.92 | 10.64 |
| 30.1 | 264 | 3354 | 0.921 | 73.8% | 26.2% | 3.40 | -1.1921 | 1.42 | -4.06 | 11.59 |
| 34.1 | 158 | 1956 | 0.919 | 67.9% | 32.1% | 3.53 | -0.9472 | 0.90 | -3.34 | 12.46 |
| 38.1 | 203 | 1788 | 0.886 | 60.1% | 39.9% | 3.64 | -0.6766 | 0.46 | -2.46 | 13.25 |
| 42.1 | 231 | 2358 | 0.902 | 54.3% | 45.7% | 3.74 | -0.4919 | 0.24 | -1.84 | 13.99 |
| 46.1 | 41 | 376 | 0.891 | 48.3% | 51.7% | 3.83 | -0.3190 | 0.10 | -1.22 | 14.68 |
| 50.1 | 20 | 87 | 0.770 | 37.2% | 62.8% | 3.91 | -0.0120 | 0.00 | -0.05 | 15.32 |
| 54.1 | 10 | 63 | 0.841 | 31.3% | 68.7% | 3.99 | 0.1492 | 0.02 | 0.60 | 15.93 |
| 58.1 | 1 | 5 | 0.800 | 25.1% | 74.9% | 4.06 | 0.3250 | 0.11 | 1.32 | 16.50 |
| 62.1 | 12 | 41 | 0.707 | 17.7% | 82.3% | 4.13 | 0.5483 | 0.30 | 2.26 | 17.05 |

## Table 4. Manitoba Hydro Western Cedar poles with penta

| 7 A | B | C | D | E | F | G | H | I | J | K |
|---|---|---|---|---|---|---|---|---|---|---|
| $t\text{-}t_0$ (y) | $f_i$ | $n_i$ | $1\text{-}f_i/n_i$ | KM | 1-KM | 'X' = ln(A) | 'Y' = ln(ln(1/(1-F))) | 'Y$^2$' = H$^2$ | 'YX' = G*H | 'X$^2$' = G$^2$ |
| 13.1 | 1 | 1263 | 0.999 | 99.9% | 0.1% | 2.5726 | -7.14 | 50.99 | -18.37 | 6.62 |
| 17.1 | 1 | 1565 | 0.999 | 99.9% | 0.1% | 2.8391 | -6.55 | 42.89 | -18.59 | 8.06 |
| 21.1 | 3 | 2302 | 0.999 | 99.7% | 0.3% | 3.0493 | -5.90 | 34.83 | -18.00 | 9.30 |
| 25.1 | 31 | 5348 | 0.994 | 99.1% | 0.9% | 3.2229 | -4.76 | 22.68 | -15.35 | 10.39 |
| 29.1 | 108 | 7966 | 0.986 | 97.8% | 2.2% | 3.3707 | -3.81 | 14.50 | -12.83 | 11.36 |
| 33.1 | 218 | 9097 | 0.976 | 95.5% | 4.5% | 3.4995 | -3.07 | 9.42 | -10.74 | 12.25 |
| 37.1 | 333 | 12918 | 0.974 | 93.0% | 7.0% | 3.6136 | -2.62 | 6.88 | -9.48 | 13.06 |
| 41.1 | 300 | 9003 | 0.967 | 89.9% | 10.1% | 3.7160 | -2.24 | 5.02 | -8.32 | 13.81 |
| 45.1 | 185 | 3333 | 0.944 | 84.9% | 15.1% | 3.8089 | -1.81 | 3.28 | -6.90 | 14.51 |
| 49.1 | 94 | 2162 | 0.957 | 81.2% | 18.8% | 3.8939 | -1.57 | 2.47 | -6.11 | 15.16 |
| 53.1 | 82 | 1085 | 0.924 | 75.1% | 24.9% | 3.9722 | -1.25 | 1.56 | -4.96 | 15.78 |
| 57.1 | 55 | 532 | 0.897 | 67.3% | 32.7% | 4.0448 | -0.93 | 0.86 | -3.75 | 16.36 |
| 61.1 | 28 | 914 | 0.969 | 65.3% | 34.7% | 4.1125 | -0.85 | 0.72 | -3.50 | 16.91 |
| 65.1 | 2 | 48 | 0.958 | 62.5% | 37.5% | 4.1759 | -0.76 | 0.57 | -3.16 | 17.44 |
| 69.1 | 1 | 3 | 0.667 | 41.7% | 58.3% | 4.2356 | -0.13 | 0.02 | -0.57 | 17.94 |
| 73.1 | 1 | 3 | 0.667 | 27.8% | 72.2% | 4.2918 | 0.25 | 0.06 | 1.06 | 18.42 |

**Figure 1**
**Manitoba Hydro**
**Jack Pine Poles w/ Creosote**

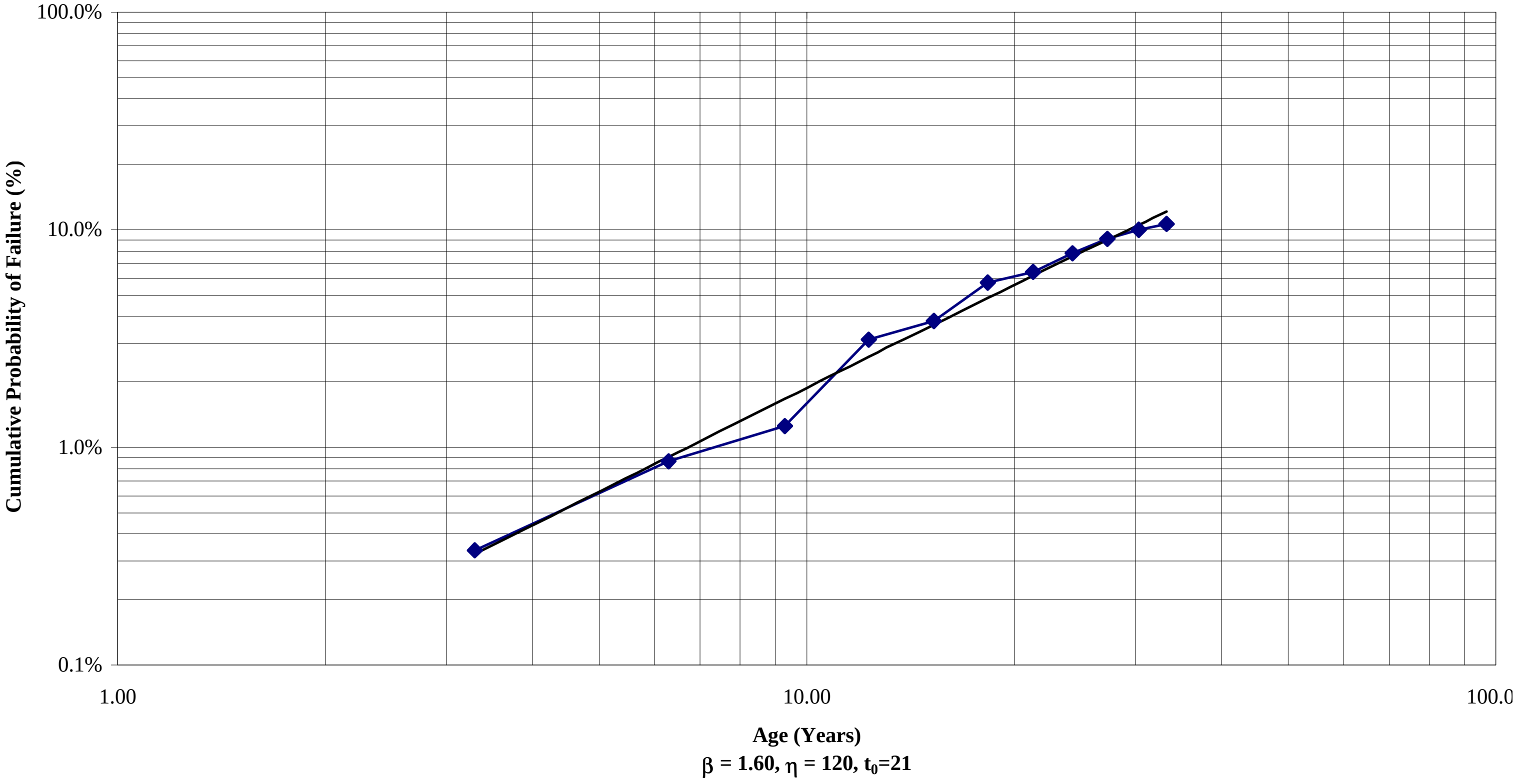

**Figure 2**
**Manitoba Hydro**
**Jack Pine Poles w/ Penta**

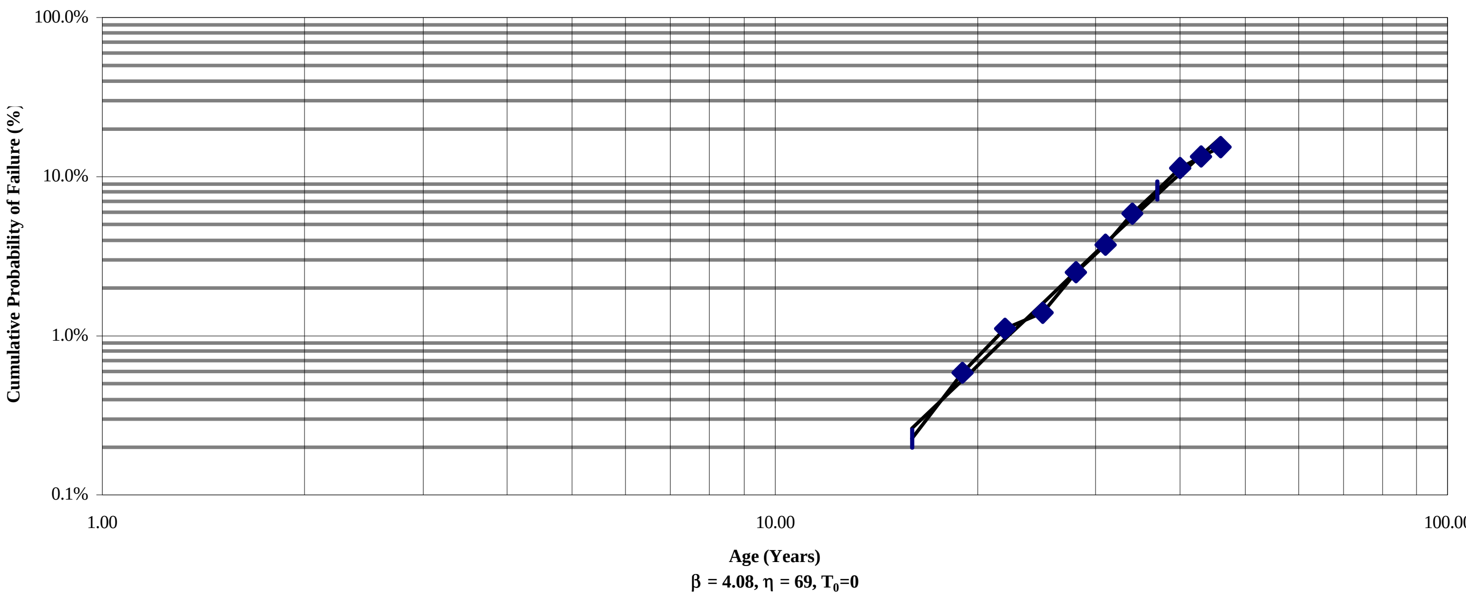

**Figure 3**
**Manitoba Hydro**
**Western Cedar Poles w/ Creosote**

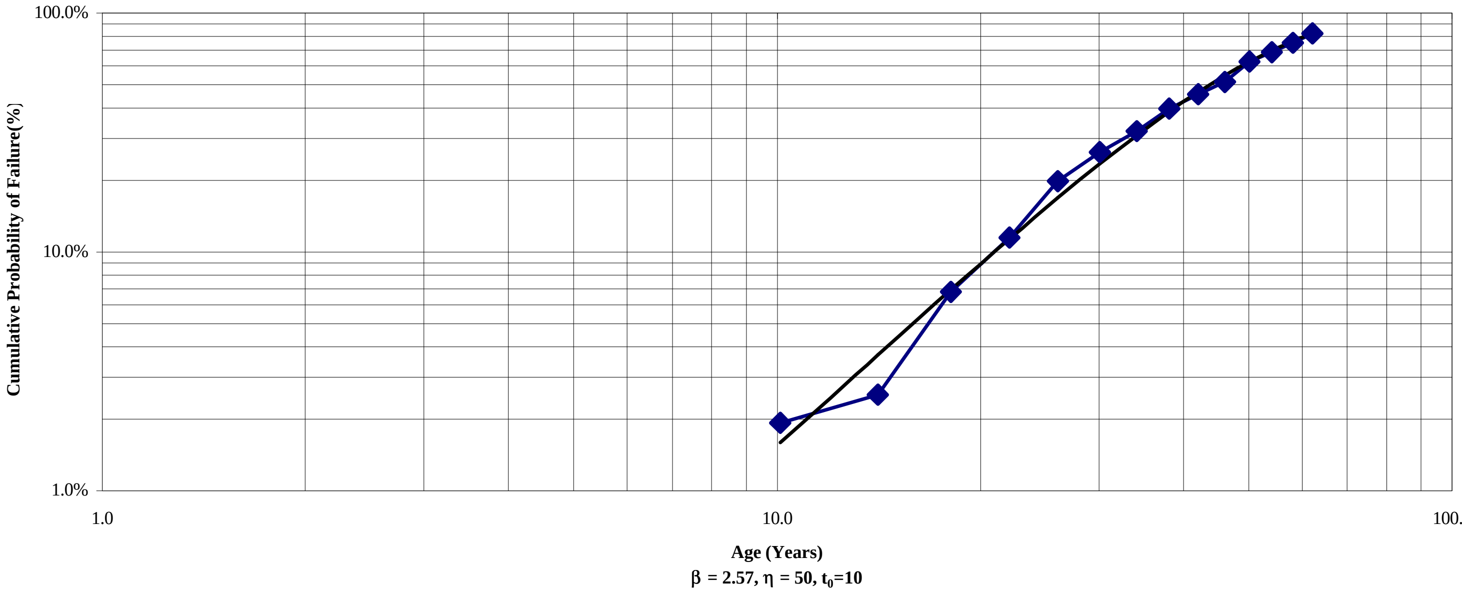

**Figure 4**
**Manitoba Hydro**
**Western Cedar Poles w/ Penta**