Pipe Wall Thickness Decisions Using Weibull Analysis

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Abstract

Weibull analysis is used on the data from pipe wall thickness inspections to set inspection intervals and assign risks for exceeding the minimum wall thickness. A small data-set of actual pipe thickness readings, obtained from an actual operating loop, are used to illustrate the method and rationale.

Weibull Analysis

Weibull analysis is an engineering tool for analyzing life-data. The Weibull analysis quantification technique is the tool of choice for reliability engineers around the world (Abernethy 1996). Introduction of user friendly software has taken WA out from research organizations and made it a main line tool for use at every engineering level in many organizations (Fulton 1997)

The Weibull analysis issue for studying pipe wall thickness measurements is to defining the reliability (or the complement--which is unreliability) of the pipe to contain fluids or gases so that risks are manageable. Weibull analysis provides a tool for quantifying risks as wall thickness decreases with time and use. The WA tool is very appropriate for inclusion into the regime of risk-based inspection techniques for generating risk numbers and helping to accurately predict when, where, and how pipe will fail unless corrective action occurs to prevent pipe wall failures. Knowing the risk numbers allows setting strategies to manage the risk; i.e.:

1) Accept the risk and continue operating,
2) Reject the risk and take corrective action, or
3) Consider business alternatives considering time, money, and safety.

Risk is very closely related to reliability and product safety. Risk is defined as an economic aspect of safety as (Ireson 1996) : Risk$ = probability of a failure*exposure*$consequences. The probabililty of failure (POF) and exposure elements in the calculation lie between 0 and 1. Consequence $s for costs vary from 1 up to and including X millions of dollars. This statement of risk is the expected monetary value for an event or set of events.

Weibull analysis helps to define failure probabilities for risk calculations. Exposure issues relate to geographic boundaries or danger zones and the value is often taken as 1.0. Consequences (the dollar number) refer to the maximum financial liability incurred. Cost consequences include: 1) failure costs, 2) costs (capital and expense) for correction of future failures, 3) fines (and law suites) incurred as a result of the failure, and 4) lost gross margin when the economic function of the operation cannot be carried out because of the failure.

Risks are also described in general terms (Henley 1992 or Taylor 1996) as frequencies (events per unit of time) multiplied by the magnitude (consequences per event). As individuals, when the failure rates (deaths) are below 1 fatality per million years we are not so concerned. For operating plants, the death rates at which we become not so concerned depends on the number of deaths that can occur. If one person is killed in a plant, people are not so concerned when the death rate is below 7 fatalities per million years but if up to 100 people can die, people are not so concerned at a failure rate of about 1 fatality per 100 million years. For this paper, failure rates are of interest, however the approach is directed toward the POF rather than the failure rate. Of course risks are driven by failure probabilities--a statement of unreliability (Barringer 1993).

Reliability has many definitions (Omdahl 1988). If repairs are not possible, reliability is the duration or probability of failure-free performance under stated conditions. If repairs are possible, reliability is the probability that an item can perform its intended function for a specified interval under stated conditions. Dependability is a single word definition for reliability.

Reliability definitions include probabilities with values between 0 (reliability is absent--easy to get) and 1 (reliability is perfect--impossible). Reliability is difficult because probabilities change with time. Unreliability--the probability for failure--is the complement of reliability. Quantifying reliability also quantifies risks when monetary values are included and this is where Weibull analysis is helpful--a major issue is having data to analyze.

Weibull analysis was conceived by Waloddi Weibull in 1937 and publicly disclosed in the Journal of Applied Mechanics of the American Society of Mechanical Engineering in 1951. Weibull claimed the technique "…may sometimes render good service."--he did not guarantee it would always work. In the practice of reliability engineering, Weibull analysis has become the leading method for analyzing life data. Weibull analysis usually follows this format:

1) Accumulate discrete samples of life data
2) Plot the data on Weibull probability plots
3) Interpret the plot as if the data fit a continuos distribution
4) Use data for failure forecasting and prediction
5) Evaluate corrective action plans
6) When possible, introduce financial calculations into the analysis to avoid the use of probabilities, i.e., consider the money of risks and optimum replacement calculations involving both time and money.

Most engineers have trouble with life data because they cannot plot the data as it contains only "x" events measuring time to failure. When engineers can't make a plot of the data, they often lack a physical understanding of the facts.

Weibull analysis produces a straight-line plot of the data--if the data does not fall onto a straight line, then the wrong type of distribution has been selected or curvature in the data plots help diagnose what is physically occurring such as:

1) Mixtures of failure modes.
2) Time origins are not located a zero time
3) Aging scale parameters not accurately reflect the correct measurement for failure

One very valuable feature of a Weibull probability plot is the "y" axis showing the cumulative distribution function (CDF). For reliability data, the Weibull "y" axis magnifies the percentage of failures in the lower portion of the curve--this portion is usually of most interest to engineers. This condition is illustrated in Figure 1.

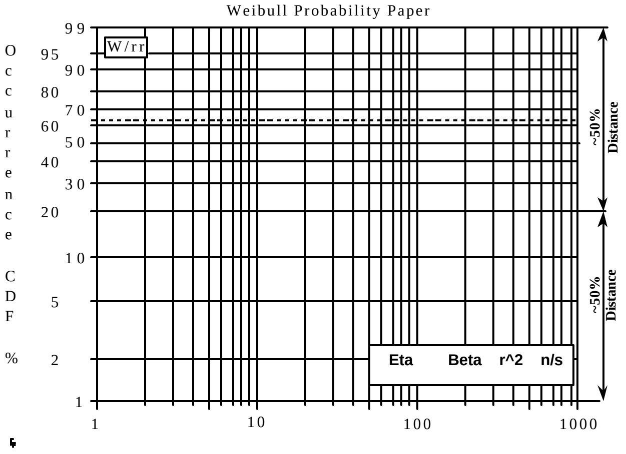

Figure 1: Weibull Probability Paper

The lower 20% of the failure data occupy roughly the lower 50% of the distance on the chart. This situation magnifies early failures.

On a Weibull plot, the "y" axis is a log-log function resulting in the unusual divisions. The "x" axis is a simple log function. Eta describes where the trend line crosses the 62.3% dashed line. Beta defines the trend line slope passing through the data. The coefficient of determination, r^2, describes the goodness of fit of the trend line to the data points. The total number of data points in the data set is described by n, and s defines the number of suspensions or censored units in the data set.

Weibull plots are well known for describing the life of ball bearings. Figure 2 shows a Weibull plot for 10 ball bearings tested at a constant heavy load. Each data points represent the number of revolutions at which each bearing fails. Ball bearings are rated at the B10 life (i.e., 10% of the population is expected to fail). For this bearing the B10 life is 1,000,000 revolutions. The definition of "B" is described (Geitner 1997) as 'Brucheinleitzeit where

Bruch = Fracture/breakage, Einleit = initiation, and Zeit = time, i.e. fracture initiation time".

The ball bearing industry uses a standard risk of 10% failure for the advertised load rating. Engineers selecting the bearings must judge if this risk level is too severe for the application--if so, the bearing loads must be derated. Or, if greater risks are allowed, the bearing may be heavier loaded. The Weibull curve, plus a few design rules, and the known consequences allow the engineer to make reasonable business decisions in selecting the appropriate bearing.

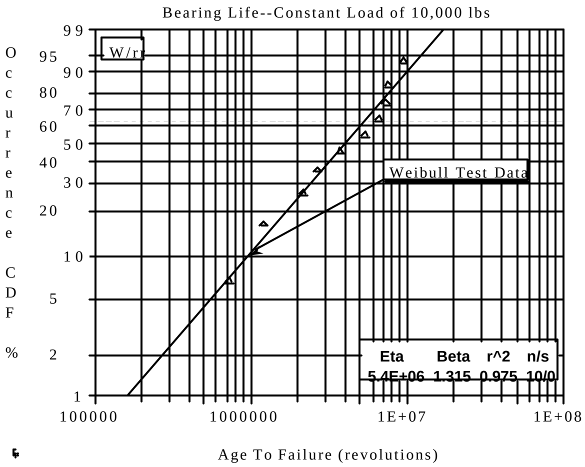

Figure 2: Ball Bearing Life Rated At B-10

Notice the "y" axis scale of a Weibull plot is a measurement of unreliability. Unreliability drives risk. For operating plants, a central business issue is the cost of unreliability (Barringer 1996).

Higher plant reliability reduces equipment failure costs. Failures decrease production and limit gross profits. Boosting reliability, by reducing the cost of unreliability, improves business performance. The clear reason for reducing unreliability is spelled: money. The motivation for improving reliability is straightforward for a business plan:

- Improve reliability,
- Reduce unreliability costs,
- Generate more profit, and
- Get more business.

We talk about reliability (a good word), but we measure failures (a bad word). Failures demonstrate evidence of unreliability with unfavorable cost consequences for businesses. Failures in most continuous process industries are measured in process downtime. Cutbacks/slow-downs in output are also failures. Failures require a clear definition for organizations making reliability improvements. Failures are loss of function when the function is needed—particularly for meeting financial goals.

Reliability requirements for business change with competitive conditions and business risks—the playing field is always tilting. Unreliability values change with business conditions. You don’t need the best reliability in the world for your business—you just need a cost advantage over your fiercest competitor. Even low cost industry providers need reliability improvement programs—reliability does not stand still and unreliability costs increase.

Motivations for reliability improvements are driven by the cost of unreliability—this tells the magnitude of the pain. Where the pain occurs within the plant is important. Why the pain occurs gets to the root cause of the problem for corrective improvement programs. Don’t rely on a magic bullet to fix reliability problems. Seldom will correcting one item cause a big change in overall reliability.

Reliability tools showed their real value in the 1930s, '40s, and '50s when used on exotic military programs. Fortunately many reliability tools such as Weibull analysis do not need a rocket scientist to use them cost effectively. Some simple reliability tools provide big gains quickly and defer the use of higher-powered tools for squeezing out the remaining improvements. In all cases, score cards for reliability improvements in business need measurements in dollars.

Use of reliability tools is evolutionary:

- Start reliability improvement programs with simple arithmetic and spreadsheets. Quantify important cost and failure numbers.
- Gain momentum with good maintenance practices. Improve teamwork using total

productive maintenance programs. Use root cause analysis to efficiently solve problems. Learn and use a host of straightforward reliability engineering tools to solve problems.

- Spur improvement programs by using statistics to quantify and understand scatter in the results.
- Weibull analysis tools are important statistical methods for squeezing facts from a few pieces of information.

Good facts about risks require an orderly process within plants to make sure things are done correctly and the correct things are performed. Figure 3 shows the hierarchy depending on having lower level programs operational as precedents to accomplish higher level objectives such as risk assessment. The data for Weibull analysis will be substantially flawed if a firm foundation is not established to control the chaos of failures.

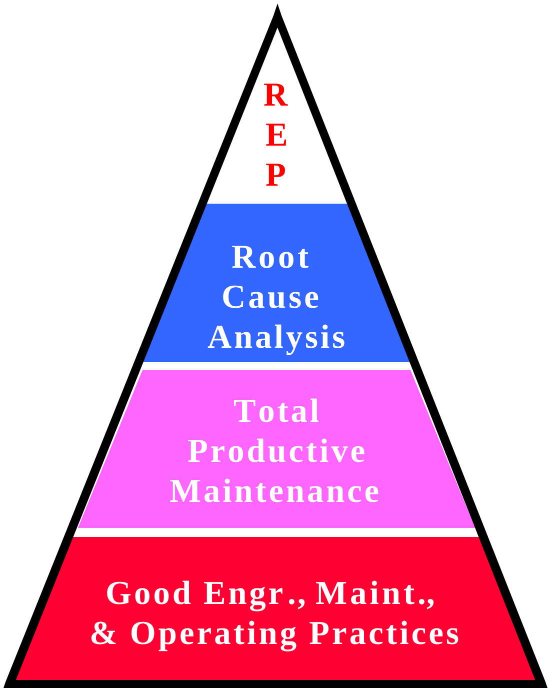

Figure 3: Reliability Heirarchy

The reliability improvement hierarchy uses a host of new tools to reduce both failures and the effects of failures. This work-process initiative is to gain a beachhead and expand territory by improvements. Few lasting improvements are maintained without improving reliability as a work-process using four important programs (which also produces good data):

- **Good engineering, maintenance, and operation practices** are good manufacturing practices (GMP) which uses the best-of-class practices for "doing" activities. This requires having trained people at various levels with a commitment to on-going training. Use good procedures and practices to avoid calamities. Teach new techniques and verify the workforce has accepted them as requirements for correct performance—such as precision alignment of rotating equipment along with precision alignment of all piping and equipment. Start teamwork between maintenance and production departments.
- **Total productive maintenance** (TPM) is a way of life for involvement of production personnel into appropriate maintenance tasks for tender loving care of both equipment and processes. Aim TPM for effective use of equipment and loss prevention by a preventive maintenance effort, get involvement of all people from top to bottom in the organization. Promote preventive maintenance through the TPM program by use of self-directed small work groups.
- **Root cause analysis** (RCA) works on defining problems into categories such as people, procedures, or hardware. Demonstrate RCA solutions to problems will prevent recurrence, meet the organization goal, and be within an individual control for preventing recurrence.
- **Reliability engineering principles** (REP) uses new tools to solve the vital few old nagging problems. Many tools use bathtub concepts to match correct tools to cost effective strategies by applying science and engineering to reliability-centered maintenance (RCM) efforts. Weibull analysis is one of the very valuable tools for making the data tell a quantifiable story about risks using age to failure data.

Acquiring good data for equipment failures sounds easy. It is a difficult task. Abernethy, ibid., says acquiring equipment failure data has three basic requirements (items 1-3); and for commercial businesses, add two other elements (items 4-5):

1) Define an unambiguous time origin,

2) Define a scale measuring the passage of time,
3) The meaning of failure must be entirely clear,
4) Measure cost consequences for failure, and
5) Gain data analysis expertise for using data.

A thoughtful plan to acquire a few pieces of carefully logged age-to-failure data for equipment is better than vast quantities of poorly planned data. People in many plants say they lack any data (Barringer 1995). In fact, data is all around them in various degrees of usefulness. Most industrial plants have been acquiring equipment failure data for many years and seldom is the data analyzed in a scientific manner.

Rarely do people acquiring the data see the data used to solve their problems. The net result is vast data banks of nearly useless information acquired haphazardly and annotated poorly. Today's task is to "mine" through piles of existing data while acquiring new age-to-failure data in a carefully thought-out manner so it can be used for an economic advantage. The key phrase to remember is "age-to-failure" and of course that requires a consistent definition of failure.

The field of reliability offers many technical guidelines for how data should be acquired, annotated, and used for analysis. In many cases, failures need a "death certificate" just as occurs with human failures. Death certificates for humans have been so productive in producing analyzable results, that it now illegal in the civilized world for a person to be buried without a death certificate listing age and cause of death (the root(s) cause of death).

Specific failure data is not always available. Substantial failure-rate data exist in the literature awaiting use of facts for improving plants and equipment (IEEE 1984) (RAC 1994) (Barringer 1997-website). New data initiatives by the Center For Chemical Process Safety (CCPS 1989) using proven skills of data analysis experts at Det Norsk Veratas (OREDA 1992), are underway for acquiring data from chemical plants and refineries.

Failure data is chaotic because of scatter in the data. Data scatter can be studied arithmetically for first, quick look results, or refined into statistical details providing richer descriptions when converted into straight line plots of time-to-failure against cumulative chances for the failure. Most engineers need graphical representation of data to fully understand problems. Probability tools are growing in importance with the use of personal computers that generate the curves with ease. Weibull probability charts are the tools of choice for failure problems because they often tell failure modes (how components die) and the probability of failure:

- Infant mortality—use a run to failure strategy,
- Chance failures—use a run to failure strategy, or
- Wear-out failure modes—consider a timed replacement strategy based on costs.

Data from Weibull plots support RCM decisions based on highly idealized bathtub curves. (Moubray 1992) Weibull plots tell component failure modes.

Weibull charts are particularly valuable for pointing correct direction for finding root causes of problems using a few data points. Larger quantities of data add confidence to the decision making process, but at considerable greater expense for acquiring both failures and data. The motivation for using probability charts is to understand failure data and reduce costly failures by appropriate corrective actions. Consider the curves in Figure 4.

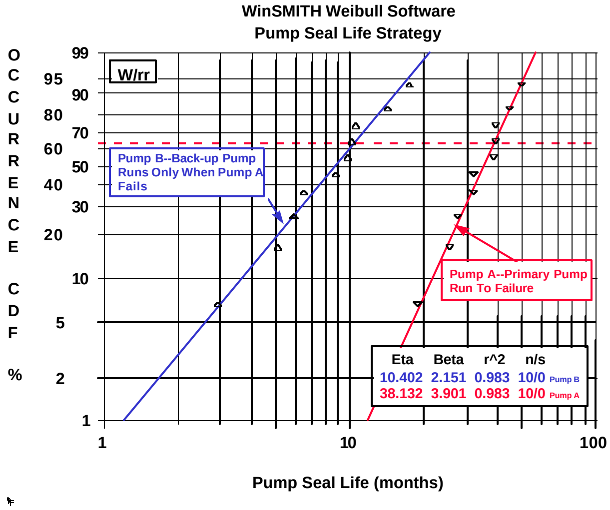

Figure 4: Weibull Plot For Pump Seal Life

The slope of the line tells the failure mode is wear-out and the probability for failure can be read directly from the Y-axis.

In Figure 4, Pump B's seal life is short. By standing and waiting for duty it experiences a service 38.1/10.4 = 3.7 times more severe than Pump A using the ratio of characteristic life values shown in the figure (watch for the characteristic value measures to appear again on pipe wall thickness measurements).

Knowing the probability for success/failure from probability plots is an important fact for assessing risks. Probability charts are easily interpreted, and simple plots of probabilities multiplied by costs can be plotted against time to quantify decisions and consider alternatives. In practice we seldom have too many data points for assessing risks. Weibull plots use few data and help the decision making process—some data is better than no data for making cost effective decisions.

Pipe Wall Thickness Data

Pipe wall thickness data is being record in large quantities over long periods of time in chemical plants and refineries (Snir 1997). Most pipe data is not significant but some data has great importance.

Snir reports the ARCO Los Angeles refinery, with 437 miles of piping and 321,000 thickness monitoring locations, has recorded 591,000 data points (i.e., the lowest reading found at each thickness monitoring location). P&IDs (piping and instrument diagrams) resulted in isometric drawings of piping circuits, and the drawings were studied for localized effects of damage mechanisms. Points susceptible to localized deterioration such as injection points or known corrosive systems were studied to find areas or zones which represent the highest corrosion rates so that pipe wall thickness measurements are recorded at the worst case conditions. Most data was recorded by ultrasonic testing. Placing a watch on the pipe wall thickness has resulted in a significant reduction in fires during the six years this study has been underway because piping is replaced before it has reached the end of life as the risks are managed.

In continuous processing plants, most data is acquired at periodic intervals based on readings from four, eight, or 12 locations in a band around the circumference. In most plants the practice of taking only one wall thickness measurement has been abandoned as a good working practice because the practice has not been particularly effective in finding the smallest wall thickness.

Major questions arise from plant pipe survey efforts:
1) Seldom is a wall failure recorded at loss of containment--how does this match Weibull requirements for age to failure data?
2) Since catastrophic failure is not often recorded what and how is the failure criteria established?
3) How are periodic measurement intervals determined?

Piping systems failure occurs when the pipe cannot contain the internal contents--either the strength is too low (from wrong material selection, fatigue, stress corrosion, etc.) or the stress is too high (overloads, loss of wall thickness, unobserved abuses, etc.) resulting in an interference zone between loads and strengths. Pipe failure is often (not always) driven by high circumferential stresses or through-wall holes from slugs, etc. A prioritizing system must be used to consider the vital few situations to be quantified by separating the vital issues from the trivial many that are not worthy of a quantifiable study.

Table 1 shows the thickness data from a periodic inspection program. Data is taken from a pipe cross section over a period of time reflecting the age/use of the pipe at six locations in measurement plane. This data shows small variations within each year.

Table 1: Wall Thickness measurements (mils)

Loc	YR 1	YR 2	YR 4	YR 6	YR 8	YR 10	YR 12	YR 14
1	311	311	311	314	309	308	308	305
2	316	318	310	315	305	300	302	298
3	308	300	298	301	295	291	295	292
4	305	305	302	304	295	294	290	289
5	318	311	304	305	300	299	295	285

6	321	318	313	313	308	305	300	295

The service for this pipe has a high risk for fire and lost production from the plant along with a high probability of injury to a large number of people and death to a few people. The financial consequence of a failure has the potential for a total loss of $85,000,000. The risk for this condition must be controlled to less than $10,000; and since human fatalities are likely, the maximum allowed probability of failure permitted is 0.01%.

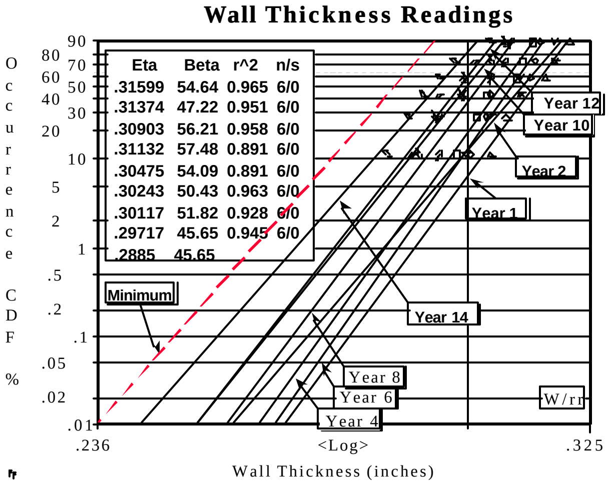

Figure 5: Weibull Plot Of Wall Thickness

A straightforward calculation of the probability of failure using Risk$ = POF*$Consequences shows the POF = $10,000/$85,000,000 = 0.00012 = 0.012%. For human life at risk-- the probability of failure is desired at less than 0.01% or 99.99% reliability.

The minimum wall thickness needed for pressure containment is estimated from Barlow's stresses at 0.047" with an additional estimated 0.033" for bending stresses, plus and estimated 0.051" for miscellaneous small abuses for a total estimate of 0.131". This minimum estimate, as judged by members of the assessment team, may be too low for some unusual conditions by a factor of 1.8 to cover unknown conditions and thus the practical minimum estimate is 0.236".

A Weibull plot in Figure 5 shows how wall thickness varies.

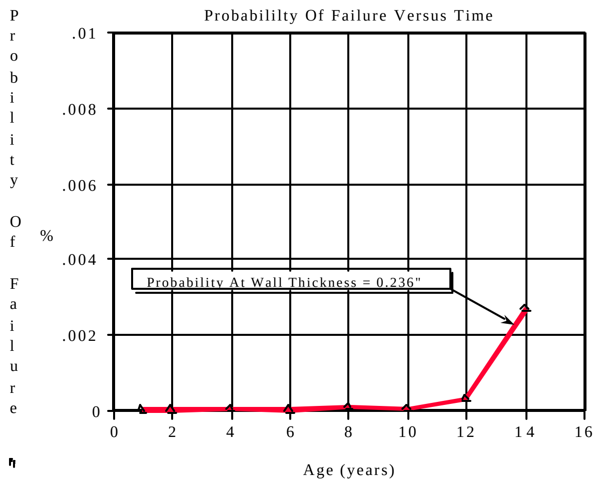

Figure 6: Probability Of Failure Versus Time

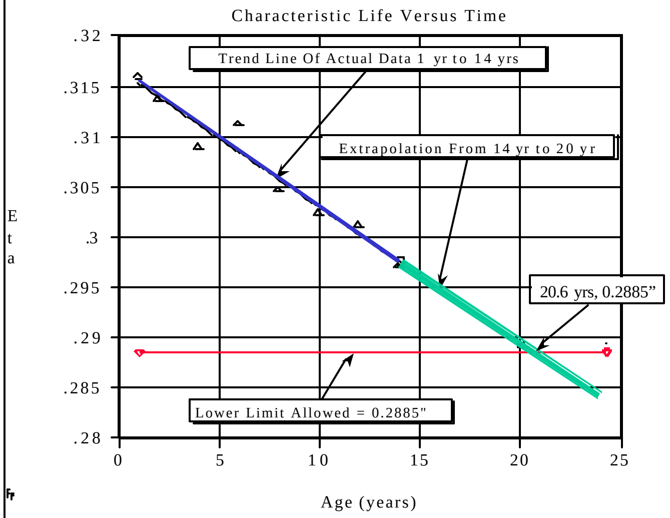

Figure 7: Characteristic Thickness Versus Time

Notice thickness values at 0.01% are approaching the minimum limit of 0.236" as time passes. Table 2 shows the probability of failure at the limit of 0.236" set to control the risk at 0.01%.

Table 2: Probability of Failure (%) For A Minimum Wall Thickness of 0.236 inches							
YR 1	YR 2	YR 4	YR 6	YR 8	YR 10	YR 12	YR 14
1.2E -05	1.4E -05	2.6E -05	1.2E -05	9.8E -05	3.7E -05	3.2E -04	2.7E -03

The trend chart in Figure 6 shows a plot of the data from Table 2. It is not clear from this plot when the trend line will intersect the probability of failure at 0.01%. Most of the information lies at low values for POF. If the y-axis is converted to a log scale, the trend line is also not obvious.

Characteristic wall thickness values from Figure 5 provide a clearer signal for projecting the end of useful life as shown in Figure 7. The minimum line, a Weibayes estimate, is established in Figure 5 by using the slope of wall thickness lines and passing the minimum wall line through the maximum allowed risk--this finds the minimum allowed value or eta as 0.2885". This minimum value for eta becomes the lower limit value for Figure 7, i.e., a critical value. The regression trend line for eta values versus time is projected from year 14 through the minimum eta and they intersect at 20.6 years.

When should the next pipe wall inspection occur? The last inspection was at 14 years and end of useful life is projected to occur at 20.6 years? Perhaps a reasonably prudent method would be to inspect at the remaining half-life (maybe 1/4 life if money is not tight and worries are high) at ~17 years--followed by subsequent testing at future half-lives.

In general, pipe wall thickness evaluations often get the car before the horse. Too much testing is performed when risk are very low (year 2 through 10) and too little testing occurs near end of life (year 17 through 21). The economic issue is to perform cost effective testing where risks warrant the test--which says as risks rise, more inspection should be performed to know and validate the risks.

By the way, when the pipe is removed from service at the end of it's useful life (say 20.6 years) without failure, the age would be recorded as suspended data and would not be recorded as a literal failure.

Using the data trend line data from Figure 7 and the Weibayes line slope from Figure 5, a consistent data set of POF can be develop. When this data is used with the replacement cost, a cost curve can be constructed. The cost would be comprised of mean time to replacement, chance of unplanned failures times the unplanned cost and chance of planned failures times the planned cost. The resulting economic curve may produce an optimum replacement interval different than the 20.6 year life described above. This calculation requires information on the planned replacement cost not provided in this example.

Summary

Background information has been provided for how Weibull plots are used. A variety of situations were shown for Weibull plots including how products are load-rated based on the probability of failure.

Weibull analysis was conducted on a data set of pipe pipe wall thickness. Risk level was established for the pipe loop based on human safety requirements. Weibull plots were prepared and trends of the risks were produced. The Weibull trends for risk changes were not particularly helpful for projecting end of life because of the scatter in the data. Scatter in the data is what complicates the analysis of typical data sets.

A method was described for finding the projected end of life using the characteristic wall thickness values and plotting the characteristic thickness values on a trend chart. The trend chart included the critical wall thickness value determined from the Weibull plot. When the trend line of decreasing characteristic thickness values intersected with the critical minimum wall thickness, the maximum allowed risk was reached which resulted in a functional end of life based on human safety considerations. This technique helped predict end of life.

The next inspection interval was based on using the projected remaining half-life. Subsequent inspections would also occur based on the remaining half-life--this condition requires moderation of the viewpoint based on expected corrosion rate. For example, if poor operating practices occur and corrosion rates rise, it would not be prudent to ignore the actual deteriorating effects to sustain a calculated half-life for the next inspection. The argument for the next inspection period is to perform the inspection at a cost effective interval without exceeding the risk budget.

Use plant deterioration and failure data with new tools to solve reliability problems in practical ways. Businesses cannot afford too-little nor too-much reliability—reliability must be harmonized with cost issues by solving top level items on the Pareto list.

As expertise in using failure data (or deterioration data) grows, use Weibull analysis to help with problem solving by putting statistics to work on practical problems. This usually requires training staffs in use of new reliability tools to gain a competitive business advantage by increasing skills to reduce costs.

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