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## STATISTICAL PERFORMANCE EVALUATION OF SPRING OPERATED PRESSURE RELIEF VALVE RELIABILITY IMPROVEMENTS 2004 TO 2014

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### ABSTRACT

The United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina, is dedicated to promoting site-level risk-based inspection (RBI) practices in order to maintain a safe and productive work environment. Inspecting component parts of operational systems, such as pressure relief valves (PRVs), is a vital part of SRS's safe operating envelope. This paper is a continuation of a SRS program to minimize the risks associated with PRV failures. Spring operated pressure relief valve (SOPRV) test data accumulated over the past ten years resulted in over 11,000 proof tests of both new and used valves. Improved performance is seen for air service valves resulting from changes to the maintenance program. Although, statistically significant improvement was not seen for liquid, gas, or steam service valves, analysis shows that the overall probability of failure on demand is trending down. Current SRS practices are reviewed and the reasons for improved performance are explored.

### NOTATIONS

| | |
|---|---|
| AICc | Akaike Information Criterion (corrected) |
| API | American Petroleum Institute |
| ASME | American Society of Mechanical Engineers |
| $\beta$ | Weibull shape parameter |
| $\eta$ | Weibull characteristic life parameter |
| CCPS | Center for Chemical Process Safety |
| CDF | Cumulative Distribution Function |
| $F(t)$ | The probability that a SOPRV will fail by the time it acquires $t$ years of operating time |
| PDF | Probability Density Function |
| PERD | Process Equipment Reliability Database |
| PFD | Probability of Failure on Demand |
| Proof Test | The practice of pressurizing the inlet of a new or used pressure relief valve on a test stand. Popping pressure and seat tightness are tested, and the as-found values are compared to the stamped set pressure. |
| PRV | Pressure Relief Valve(s) - ASME Power Test code 25-2008 definition |
| $R_p$ | Ratio of proof test pressure to set pressure |
| RBI | Risk-Based Inspection |
| RP | Recommended Practice |
| SOPRV | Spring-Operated Pressure Relief Valve(s) |
| SP | Set Pressure |
| SRS | Savannah River Site |
| TP | Test Pressure |
| VRS | Valve Repair Shop |

## INTRODUCTION

The United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina is dedicated to promoting site-level Risk-Based Inspection (RBI) practices [1] [2] in order to maintain a safe and productive work environment. Inspecting component parts of operational systems, such as pressure relief valves (PRVs), is a vital part of SRS's safe operating envelope.

As a result of past analyses, maintenance intervals have increased from three to four years on average [3],[4],[5]. Spring operated pressure relief valve (SOPRV) test data accumulated in the past four years has resulted in over 4,500 proof tests.

Improved performance is seen for air service valves resulting from changes to the maintenance program. Statistically significant improvement was not seen for liquid, gas, or steam service valves. Current SRS practices are reviewed and the reasons for improved performance are explored.

Early years of SRS test data (2004 through 2010) are available in the Center for Chemical Process Safety (CCPS) Process Equipment Reliability Database (PERD). The log-normal, Weibull [6] and Fréchet [7] distributions were applied to various subsets of proof testing data obtained from SRS's Spring-Operated Relief Valves (SOPRVs) to estimate the probability of failure on demand.

## SRS VALVES-BACKGROUND

Valves at SRS are grouped by working fluid type. Even though there are extensive varieties of working fluid types, they can be separated into four main categories: air, gas, liquid, and steam (Figure 1.1). The interpretation of the liquid and steam categories is intuitive. The "air" category refers to the aggregation of gases found in the atmosphere, while the "gas" category is an insulated system that deals with a particular type of gas, such as helium or nitrogen.

All valves at SRS are subject to periodic inspections, which occur on average every 4.25 years based on the past four years of proof test data. Valves are brought in from the field and proof tested in the SRS Valve Repair Shop (VRS) by steadily increasing inlet pressure until the valve pops open (Proof Test).

The performance of the valve is then analyzed by assessing the ratio of the *test pressure* (TP), or the "as found" lift pressure (proof test) at which the valve opened during the inspection test, over the *set pressure* (SP), the pressure at which the valve was designed to open $(R_p = \text{TP/SP})$. If $R_p \geq 1.50$, the valve is considered by industry and API 576 to be "stuck shut," meaning that the valve would not open to relieve excess pressure. It is a good indication that such a valve would fail on actual demand in the field. During an actual over-pressure event, failing to open by 1.5 times the set pressure would challenge process piping and vessel integrity. A ratio greater than or equal to 1.30 is considered a failed test, as in ASME PCC-3-2007 [1] and API RP 581 [2]. In the data set analyzed, any valve with $R_p \geq 1.30$ is categorized as a "failed" valve. During proof testing, any used valve whose proof testing reveals higher than 1.10 $(R_p \geq 1.10)$ times SP is disassembled for cleaning and repaired. The valve is subsequently reassembled, reset to its original set pressure, retested, and, after passing the retest, tagged and returned to the field as "like new."

**Figure 1.1: Conventional 2" by 3"steam valve**

**Figure 1.2: Sleeve Guide; note general corrosion after 3 years in service**

**Figure 1.3: Valve Stem and Spring Washer.**
Galvanic corrosion at the stainless steel / carbon teel interface causing adhesion and some pitting.

**Figure 1.4: Valve Spring**
Highly alloyed steel, and Top Spring Washer is carbon steel

**Figure 1.5: Valve Disc and Seat Area**
Shows minor cuts caused by steam leakage

**Figure 1.6: Body nozzle, seat with blowdown ring, as found**

**Figure 1.7: Nozzle w/o blowdown ring, lapped.**
Returned to like new condition

**Figure 1.8: Valve Spring bead blasted and ready to be re-used**

Figure 1.9: Typical rain hat

## PROGRAMMATIC IMPROVEMENTS

As shown in Figure 1.3 to Figure 1.8, after a period of time, the spring washers begin to corrode due in the main to galvanic action. Based on lessons learned from testing and repairing valves, improvements were made to reduce corrosion related failures. SRS programmatically promoted the use of valves with packed levers especially for valves exposed to weather. The use of soft plastic caps on valve discharge piping (Figure 1.9) were encouraged to keep out rain, insects, sand, dust, and bird nests. Direction in a local Engineering Standard prohibits certain make/model valves with high failure rates. The program also encouraged replacing carbon steel spring washers with stainless steel washers. Based on our experience in 1 or 2 years more if the valve is not exercised, the washers will hold the stem from sliding and prevent the valve from lifting at design set pressure. SRS benefits greatly from using root cause failure analysis to pinpoint material compatibility issues, dimensional problems, wrong parts (springs) being installed, and manufacturing defects. Our past studies and conclusions validated adjusting maintenance times [3],[4],[5].

## STATISTICAL ANALYSIS OF USED VALVES

Data from 1,447 SRS used valves from May 21, 2003 to August 19, 2014 were analyzed, with 578 valves from the *air* working fluid category, 373 from the *gas* category, 179 from the *liquid* working fluid category, and 315 from the *steam* category (Table 1).

Table 1 provides the corresponding summary of descriptive statistics. The mean ratio was 1.034 while the individual ratios ranged between 0.67 and 3.41 overall fluid services. Statistical testing indicated that there was no statistical difference in mean ratios among the fluid services.

**Table 1. Summary Statistics for Ratio by Working Fluid.**

| Working Fluid | Code | Number | Mean | Std Dev | Min(Ratio) | Max(Ratio) |
|---|---|---|---|---|---|---|
| Air | A | 578 | 1.03 | 0.09 | 0.99 | 1.02 |
| Gas | G | 373 | 1.03 | 0.07 | 0.67 | 2.14 |
| Liquid | L | 179 | 1.06 | 0.22 | 0.94 | 1.90 |
| Steam | S | 315 | 1.04 | 0.17 | 0.93 | 3.41 |

The time sequence of ratio $(R_p)$ versus date color coded by working fluid type is displayed in Figure 2.

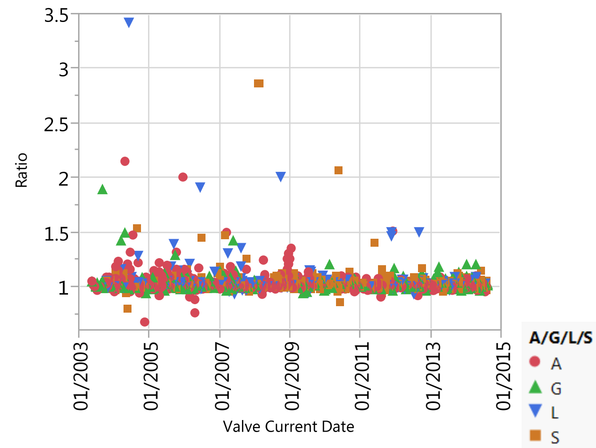



**Figure 2. Ratio vs. Date by Working Fluid.**

The data did not exhibit any trending by working fluid type over the data range. A dot-plot for ratio by working fluid is presented in Figure 3.1.

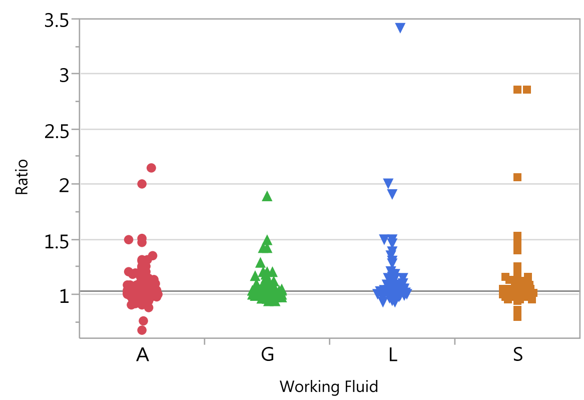



**Figure 3.1. Ratio by Working Fluid.**

There were 29 valves out of the 1,447 valves with $R_p \geq 1.30$. Of these 29 valves, 15 valves were stuck shut $(R_p \geq 1.50)$. The average time between installation and testing of a valve is 3.92 years, with a median of 3.15 years. These measures of central tendency vary slightly depending on which working fluid group is being considered. Valves with a censored time to failure (e.g., passed proof test: $R_p < 1.30$) are called "suspensions."

For suspensions, the time used in this study is the time between installation and the actual proof test of the valve after removal. The maintenance interval measures the time between installation of a valve in the field and removal of that valve for inspection. The proof test time, on the other hand, measures the time between installation of a valve in the field and actual testing of the valve. When a valve is taken out of the field for maintenance, it may spend some time waiting to be tested at the SRS VRS. Occasionally, there may be a substantial time between the maintenance interval and the proof test time. SRS's procedure only specifies that a valve must be installed within six months after its proof test, not when testing should be performed after removal from the field. A valve is assumed to age at the same rate in and out of the field, so the proof test time, not the maintenance interval, gives the best indication of a valve's anticipated performance at the time of testing.

For valves classified as failed with $R_p \geq 1.30$, the time to failure was estimated by disassembling and inspecting the valve. A range of probable failure times, i.e., when the ratio first exceeded 1.30, was estimated, and the midpoint of that range was recorded as the failure time. The dot plots provided in Figures 3 display a comparison of ratio by working fluid.

Changes were made to improve valve performance over the past several years as discussed above. Measurable improvements in failure frequency $(R_p \geq 1.10)$ can be seen when partitioning the data into two subsets: **1)** 05/21/2003 to 01/04/2011 and **2)** 01/20/2011 to 08/19/2014. A breakdown of summary statistics for ratio by data period is displayed in Table 2.

**Table 2.1. Summary Statistics for Ratio by Working Fluid for the Prior Data Set.**

| Working Fluid | N (Prior) | Mean (Prior) | Std Dev (Prior) |
|---|---|---|---|
| A | 453 | 1.032 | 0.099 |
| G | 258 | 1.026 | 0.080 |
| L | 121 | 1.067 | 0.256 |
| S | 191 | 1.054 | 0.213 |

**Table 2.2. Summary Statistics for Ratio by Working Fluid for the Recent Data Set.**

| Working Fluid | N (Recent) | Mean (Recent) | Std Dev (Recent) |
|---|---|---|---|
| A | 125 | 1.007 | 0.053 |
| G | 115 | 1.024 | 0.047 |
| L | 58 | 1.033 | 0.111 |
| S | 124 | 1.028 | 0.051 |

**Table 2.3. Difference in Means between the Prior and Recent Data Set**

| Working Fluid | Difference in Means (Prior-Recent) |
|---|---|
| A | 0.025 (*) |
| G | 0.002 |
| L | 0.034 |
| S | 0.026 |

(*) The difference is significant with 95% confidence.

The number of valves tested and number failing with $R_p \geq$ 1.10, 1.30, and 1.50 are displayed in Table 3 and further broken-down by working fluid in Table 4. The proportion failing for $(R_p \geq 1.10)$ is 9.5% for the earlier time period and 5.2% for the latter time period overall all working fluid types. The difference in proportions is 4.3% and is significant with a 95% confidence interval of (1.5%, 7.0%). The proportion failing for $R_p \geq 1.30$ is 2.3% for the earlier time period and 1.2% for the latter time period. The difference in proportions is 1.2% and is not significant with 95% confidence. Because of the lower failure rate for $R_p \geq 1.30$, it is believed that more time must pass before noticing a significant improvement at this ratio.

**Table 3. Number of Proof Tests Failing at $R_p \geq$ 1.10, 1.30, and 1.50 by Test Period**

Prior: 5/21/2003-1/4/2011
Recent: 1/20/2011-8/19/2014

| Period | N | Sum Failing at r≥1.10 | Sum Failing at r≥1.30 | Sum Failing at r≥1.50 |
|---|---|---|---|---|
| Prior | 1025 | 97 | 24 | 12 |
| Recent | 422 | 22 | 5 | 3 |

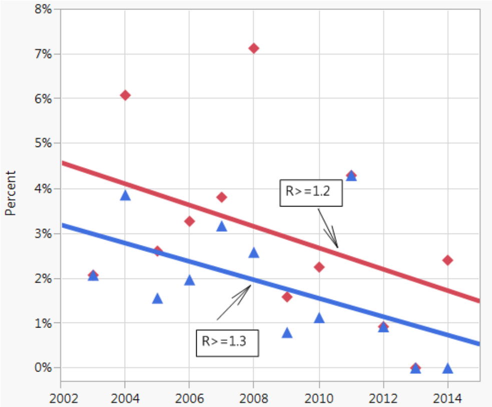



**Figure 3.2. Percent of Used Valves with Ratio ≥ 1.2 and 1.3**

Figure 3.2 displays the percentage of used valve proof tests with the Ratio exceeding 1.20 and also 1.30 by Year. There appears to be a downward trend. However, the trend is not pronounced enough to be significant but additional data may hold it to be real.

The percent failed $(R_p \geq 1.10)$ and confidence intervals were calculated for comparing failure rates by working fluid for each time period to explore working fluids inpacted by the aforementioned improvements. It can be seen in Figure 3.1 (and Table 4) that the improvement in failure rates was mainly within the air working fluid category.

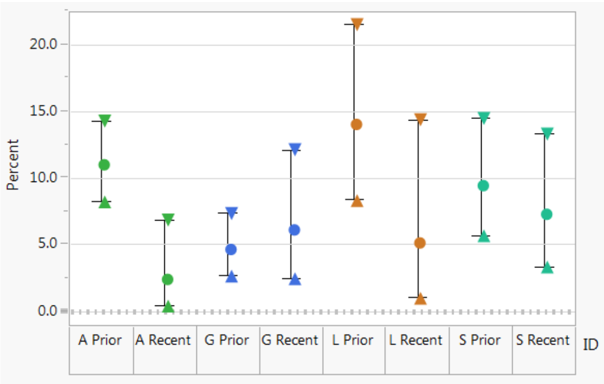


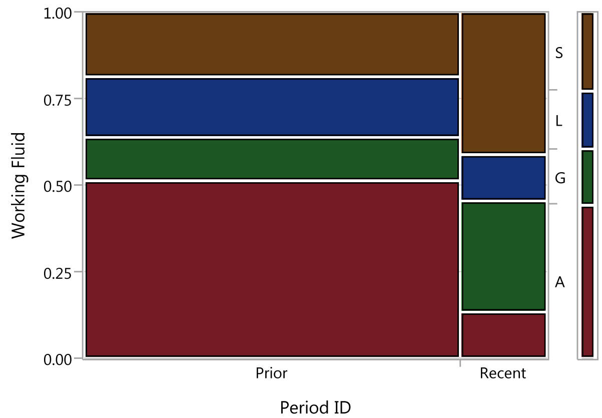

**Figure 4. Percent Failed and 95% Confidence Intervals by Working Fluid and Test Period for PRVs failed at** $R_p \geq 1.10$

**Table 4. 95% Confidence Intervals by Working Fluid for PRVs failed at** $R_p \geq 1.10$

| Data Set | WF | n | d | Lower Limit (%) | p (%) | Upper Limit (%) |
|---|---|---|---|---|---|---|
| Prior | A | 453 | 50 | 8.3 | 11.0 | 14.3 |
| Recent | A | 125 | 3 | 0.5 | 2.4 | 6.9 |
| Prior | G | 258 | 12 | 2.4 | 4.7 | 8.0 |
| Recent | G | 115 | 7 | 2.5 | 6.1 | 12.1 |
| Prior | L | 121 | 17 | 8.4 | 14.0 | 21.5 |
| Recent | L | 58 | 3 | 1.1 | 5.2 | 14.4 |
| Prior | S | 191 | 18 | 5.7 | 9.4 | 14.5 |
| Recent | S | 124 | 9 | 3.4 | 7.3 | 13.3 |
| Prior | All | 1025 | 97 | 7.7 | 9.5 | 11.4 |
| Recent | All | 422 | 22 | 3.3 | 5.2 | 7.8 |

## Mosaic Plots

A comparison of working fluid distributions was done for each time period. Figure 5 displays a mosaic plot [10] [11] while the corresponding cross-tabulation is displayed in Table 5. The mosaic plot is a graphical representation of the two-way frequency table. A mosaic plot is divided into rectangles, so that the area of each rectangle is proportional to the proportions of working fluid data are in each time period of data. Air service is substantially less in the more recent time period (approx. 14% of air service data vs. 52%) while gas is substantially greater (32% vs. 12%) across all working fluid types. Finally, the frequency of steam service valves increased (41% vs. 19%).




*Code Key on the right: Steam:Brown, Liquid:Blue, Gas:Green, Air:Red*

**Figure 5. Mosaic Plot of Working Fluid By Period ID for** $R_p \geq 1.10$ **Failures**

**Table 5. Number of Proof Tests by Test Period for $R_p \geq 1.10$ Failures**

| Count<br>Total %<br>Col %<br>Row % | A | G | L | S | |
|---|---|---|---|---|---|
| Prior | 50<br>42.02<br>94.34<br>51.55 | 12<br>10.08<br>63.16<br>12.37 | 17<br>14.29<br>85.00<br>17.53 | 18<br>15.13<br>66.67<br>18.56 | 97<br>81.51 |
| Recent | 3<br>2.52<br>5.66<br>13.64 | 7<br>5.88<br>36.84<br>31.82 | 3<br>2.52<br>15.00<br>13.64 | 9<br>7.56<br>33.33<br>40.91 | 22<br>18.49 |
| | 53<br>44.54 | 19<br>15.97 | 20<br>16.81 | 27<br>22.69 | 119 |

The overall time-in-service distribution is displayed in Figure 6 and broken-down by working fluid in Figure 7. Steam service has the lowest mean time-in-service (3.60 years), while air service has the longest average time-in-service (4.28 years) (Table 6). The time-in-service distribution by test period is displayed in Table 7 over all working fluids.

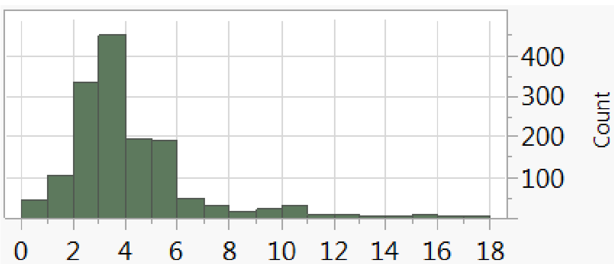



**Figure 6. Maintenance Time Distribution (Years)**

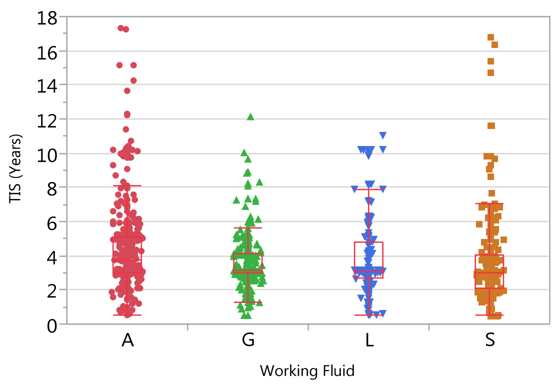



**Figure 7. Time (Years) by Working Fluid.**

**Table 6. Time-in-Service Distribution**

| Working Fluid | Code | Number | Min (Years) | Median (Years) | Mean (Years) | Max (Years) |
|---|---|---|---|---|---|---|
| Air | A | 578 | 0.56 | 3.72 | 4.28 | 17.30 |
| Gas | G | 373 | 0.49 | 3.15 | 3.64 | 12.16 |
| Liquid | L | 179 | 0.53 | 3.08 | 3.93 | 11.04 |
| Steam | S | 315 | 0.52 | 3.01 | 3.60 | 16.87 |

**Table 7. Time-in-Service Distribution by Test Period (Prior, Recent)**

| Working Fluid | N (Prior) years | N (Recent) years | Mean (Prior) years | Mean (Recent) years | Std Dev (Prior) years | Std Dev (Recent) years | Difference (Recent-Prior) years |
|---|---|---|---|---|---|---|---|
| A | 453 | 125 | 4.13 | 4.82 | 1.95 | 3.17 | 0.68 |
| G | 258 | 115 | 3.48 | 3.99 | 1.26 | 1.54 | 0.51 |
| L | 121 | 58 | 3.40 | 5.05 | 1.90 | 3.06 | 1.66 |
| S | 191 | 124 | 3.64 | 3.55 | 2.53 | 1.90 | -0.09 |

In order to estimate the distribution parameters, a life-censored approach to estimating the time to failure of the valves was used. Specifically, valves with $R_p < 1.30$ did not fail the proof test. However, they would fail their proof test at some unknown time in the future if left in service. These valves were considered to be suspensions by treating their time-in-service as a censoring time. Various distributions in reliability modeling [8] may provide an appropriate fit for the valve data. The log-normal distribution is best utilized when the log of the data values is normally distributed, and it is commonly used in metal fatigue crack growth, pitting, and corrosion studies. Log-normal distributions are used commonly for failure times when the range of the data is several powers of ten. This distribution is often considered as the multiplicative product of many small positive identically independently distributed random variables. It is reasonable when the log of the data values appears normally distributed. Examples of data appropriately modeled by the log-normal distribution include hospital cost data, metal fatigue crack growth, and the survival time of bacteria subjected to disinfectants. The PDF curve is usually characterized by strong right-skewness.

The Weibull distribution, characterized as an Extreme Value Distribution of type III, is versatile in its ability to model data with either increasing or decreasing hazard rates. This distribution has historically been used to model lifetimes of electronic components, roller bearings, capacitors, and ceramics. The Fréchet distribution [7] is characterized as an Extreme Value Distribution of type II and is used for diverse modeling applications, ranging from the statistical behavior of material properties for a variety of engineering applications to market-returns, which are often heavy-tailed.

The Weibull distribution can be used to model failure time data with either an increasing or a decreasing hazard rate. It is used frequently in reliability analysis because of its tremendous flexibility in modeling many different types of data, based on the values of the shape parameter. This distribution has been successfully used for describing the failure of electronic components, roller bearings, capacitors, and ceramics.

## Best Fit Model Evaluation

In order to assess the relative fit of the models provided by each of these distributions, the corrected Akaike Information Criterion $(AIC_c)$ [9] is compared for each distribution in which the lower values of each of the criterion indicate a better-fitting model (Table 8). The $AIC_c$ (1) can be thought of as the small-sample version of AIC [9] and is defined as

$$AIC_c = -2LL + 2k\left(\frac{n}{n-k-1}\right) \qquad (1)$$

where $k$ is the number of estimated parameters in the model, $n$ is the number of observations in the data set, and $LL$ is the log-likelihood under the assumed distribution. $AIC_c$ is used to rank potential models as a tool for model selection. $AIC_c$ does not show how well a model fits in the absolute sense, nor can it be used in comparing models between different data sets. For the Air, Gas, and Steam service data sets, the relative likelihood between the Fréchet model and log-normal model is exp( (260.15-261.91)/2)= 0.42. The interpretation is that the Lognormal model is not as probable as the Fréchet model (odds 1 to 2.5) to minimize information loss (Figure 6). The odds ratio is not unfavorable enough to rule out the log-normal model as reasonable for representing the data. Also for the Liquid service data set, the relative likelihood exp( (88.74-89.66)/2) = 0.63, so the Fréchet model was not preferred over the log-normal distribution (odds 1.6 to 1). The differences in the PFD versus time are graphically displayed in Figure 8 for Air, Gas, Steam services and Figure 9 for Liquid service.

**Table 8. AICc Statistics for Distribution Comparison Two Subgroupings: (Air, Gas, Steam) and Liquid.**

| Distribution | AGS AICc | L AICc |
|---|---|---|
| Frechet | 260.15 | 88.74 |
| Lognormal | 261.91 | 89.66 |
| Weibull | 265.31 | 91.32 |

The cumulative probability plots show very little practical difference in distributions over the observed range of times to failure. Substantial differences in the upper tails can exist among the distributions in predicting the time to failure when forecasting outside the range of data.

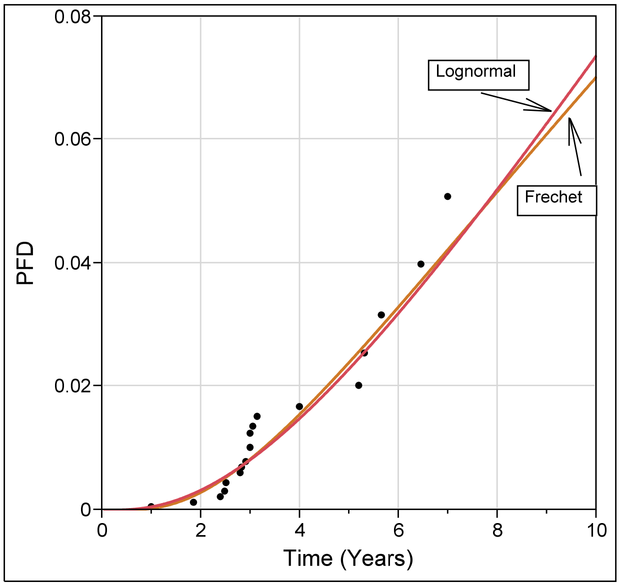



**Figure 8. PFD for the Frechet and Log-normal Distributions for Air, Gas, and Steam Services.**

The log-normal distribution is chosen as the most appropriate distribution to analyze the lifetime model for the combined Air, Gas and Steam service data.

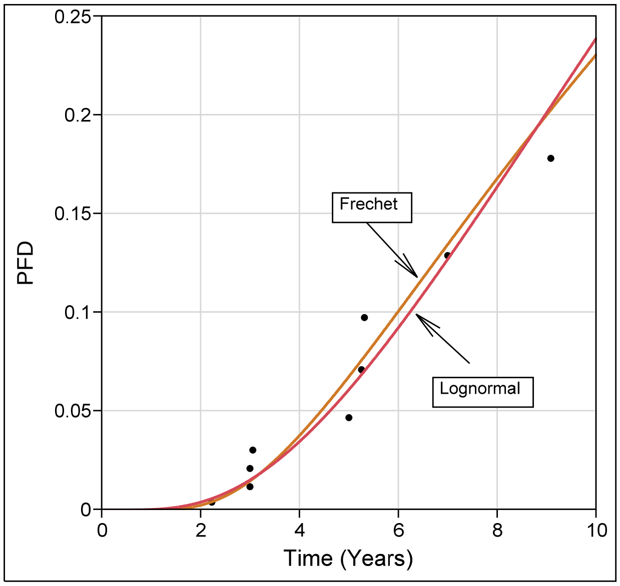



**Figure 9. PFD for the Frechet and Log-normal Distributions for Liquid Services.**

While the Fréchet distribution provided a marginally better fit for the Air, Gas, and Steam services, it was of no practical difference for this data set. The log-normal distribution was also selected for the Liquid service data because of the same reasons (Table 9 and Figure 8). The cumulative distribution function (CDF) of the log-normal distribution is equivalent to the probability that a valve will fail before aging $t$ years $[PFD(t)]$. The log-normal distribution is a continuous probability distribution of a random variable whose logarithm is normally distributed. Thus, if the random variable X is log-normally distributed, then Y=log(X) has a normal distribution. Likewise, if Y has a normal distribution, then X=exp(Y) has a log-normal distribution. A random variable which is log-normally distributed takes only positive real values. A variable might be modeled as log-normal if it can be thought of as the multiplicative product of many independent random variables each of which is positive. The log-normal distribution is the maximum entropy probability distribution for a random variable $t$ for which the mean and variance are fixed.

### Combined Test Data

Based on the log-normal distribution, statistical tests indicated that the survival distributions for Air, Gas, and Steam are not significantly different from each other (Table 9).

**Table 9. Significance Tests for Merging Data P-value < 0.05 indicates significance**

| Working Fluid Service | P-value |
|---|---|
| GAS vs. AIR | 0.906 |
| GAS vs. STEAM | 0.264 |
| AIR vs. STEAM | 0.180 |

These three groups (Air, Gas, and Steam Services) were subsequently combined into one group in order to increase the effective sample size for estimation methods. The approach presented in this paper is based on probability distribution identification using the available data. The suspensions $(R_p < 1.30)$ in the data set were treated using statistical techniques for life estimation of censored data. As such the Weibull distribution was selected as a reasonable distribution for the combined Air, Gas, and Steam data set allowing for an increasing failure rate as valves age. Similarly, the Fréchet distribution was identified as a good distribution to model the Liquid service data.

**Table 10. Estimated Probability of Failure on Demand for Air, Gas, & Steam Service** $(R_p \geq 1.30)$

| Time (Years) | PFD | Lower 95% Limit | Upper 95% Limit |
|---|---|---|---|
| 1 | 0.0005 | 0.0001 | 0.0021 |
| 2 | 0.0033 | 0.0014 | 0.0070 |
| 3 | 0.0082 | 0.0047 | 0.0140 |
| 4 | 0.0149 | 0.0094 | 0.0231 |
| 5 | 0.0230 | 0.0148 | 0.0347 |
| 6 | 0.0320 | 0.0204 | 0.0486 |
| 7 | 0.0418 | 0.0261 | 0.0643 |
| 8 | 0.0521 | 0.0318 | 0.0816 |
| 9 | 0.0628 | 0.0374 | 0.1000 |

**Table 11. Estimated Probability of Failure on Demand for Liquid Service L** $(R_p \geq 1.30)$

| Time (Years) | PFD | Lower 95% Limit | Upper 95% Limit |
|---|---|---|---|
| 1 | 0.0002 | 0.0000 | 0.0050 |
| 2 | 0.0041 | 0.0006 | 0.0198 |
| 3 | 0.0154 | 0.0047 | 0.0425 |
| 4 | 0.0350 | 0.0148 | 0.0738 |
| 5 | 0.0614 | 0.0296 | 0.1151 |
| 6 | 0.0928 | 0.0467 | 0.1663 |
| 7 | 0.1276 | 0.0642 | 0.2251 |
| 8 | 0.1643 | 0.0816 | 0.2880 |
| 9 | 0.2018 | 0.0985 | 0.3520 |

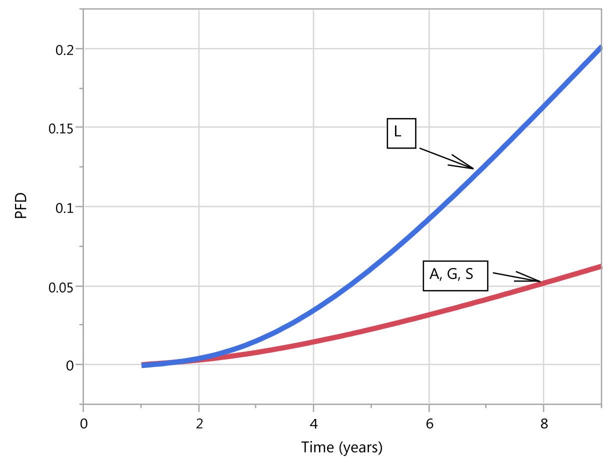



**Figure 10. Estimated PFD by Time (years) for Air, Gas, Steam Combined, and Liquid Service** $(R_p \geq 1.30)$

### CONCLUSIONS

Combining the data from three working fluids (Air, Gas and Steam) into one group increased the sample size to calculate more precise estimates of the parameters of the log-normal distribution for estimating the probability of failure on demand. Ideally, enough data (i.e. uncensored failures) would be available for each service group to calculate more precise distribution estimates. The decision to combine certain groups for analysis depended on the statistical similarities between the groups. The decision to group these particular working fluids was based solely on statistical tests, whereas larger data sets could indicate statistical differences among the groups. Improved performance is seen at $R_p \geq 1.10$ for air service valves resulting from changes to the maintenance program. Although, statistically significant improvement was not seen for liquid, gas, or steam service valves, our analysis shows that the probability of failure on demand is trending down.

SRS procedures require that valves must be installed within four to six months of repair and proof test which adds substantially to data quality. It is also considered desirable to proof test a valve within six months after being removed from service in order to better capture field conditions. We hope to make that improvement in the near term. The analysis provided in this paper is representative only of the valve data available from the SRS preventative maintenance program. The results obtained from this analysis will be corroborated with additional data from the SRS program as they become available.

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