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Estimated SIL Levels and Risk Comparisons for Relief Valves as a Function of Time-in-Service

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ABSTRACT

Risk-based inspection methods enable estimation of the probability of spring-operated relief valves failing on demand at the United States Department of Energy's Savannah River Site (SRS) in Aiken, South Carolina. The paper illustrates an approach based on application of the Fréchet and Weibull distributions to SRS and Center for Chemical Process Safety (CCPS) Process Equipment Reliability Database (PERD) proof test results. The methodology enables the estimation of ANSI/ISA-84.00.01 Safety Integrity Levels (SILs) as well as the potential change in SIL level due to modification of the maintenance schedule.

Current SRS practices are reviewed and recommendations are made for extending inspection intervals. The paper compares risk-based inspection with specific SILs as maintenance intervals are adjusted. Groups of valves are identified in which maintenance times can be extended as well as different groups in which an increased safety margin may be needed.

NOTATIONS

AICc	Akaike Information Criterion (corrected)
API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
β	Weibull shape parameter
η	Weibull characteristic life parameter
CCPS	Center for Chemical Process Safety
CDF	Cumulative Distribution Function
$F(t)$	The probability that a SORV will fail by the time it acquires t years of operating time
MM	Million
PERD	Process Equipment Reliability Database
PFD	Probability of Failure on Demand
PFD_{avg}	Average Probability of Failure on Demand
PM	Preventative Maintenance
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)
R_p	Ratio of proof test pressure to set pressure
RBI	Risk-Based Inspection
RP	Recommended Practice
SIL	Safety Integrity Level
SIS	Safety Instrumented Systems
SORV	Spring-Operated 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.

A risk-based method with focus on the Weibull [3] and Fréchet [4] distributions is applied using proof testing of SRS's Spring-Operated Relief Valves (SORVs) available in the Center for Chemical Process Safety (CCPS) Process Equipment Reliability Database (PERD). The probability based method enables the comparison of risk and inspection costs as maintenance intervals are modified. In addition, the resulting Safety Integrity Level (SIL) is also estimated as a function of the time-in-service. The SIL is a widely-accepted industry standard for assessing the safety level of safety instrumented systems (SIS).

Risk-based inspection methods enable estimation of the probability of SORVs failing on demand. Additionally they enable the estimation of the potential change in SIL due to modification of the maintenance schedule.

Current SRS practices are reviewed and recommendations are made for extending selected inspection intervals. The paper compares risk-based inspection with specific SILs as maintenance times are adjusted. Groups of valves are identified in which maintenance times can be extended as well as different groups in which an increased safety margin may be needed.

SIL DESCRIPTION

SILs are based on the probability that a particular component of a system will fail on demand. The probability of failure on demand (PFD) is divided into 4 different groups, or SILs, in which the highest SIL corresponds to the lowest PFD, and thus, the highest safety level. Calculation of the PFD depends on the instrument being in-service in a low demand or high demand environment. The demand rate is classified as *low* if "the rate of periodic inspection is two or more times the demand rate." Valves at SRS could experience a demand rate of 0.01/Year, or 1/100 Years and are subsequently categorized as *low demand* because all inspection intervals are much shorter than 50 years. If data are not available for estimating a demand rate, recommended frequencies are contained in API RP 581 [2]. For low demand situations, the SIL is based on the average PFD (PFD_{avg}), as in Chart 1 where [*a*,*b*) means $a \le PFD_{avg} < b$.

Chart 1

SIL and Average Probability of Failure on Demand

SIL	PFD_{avg}
4	**$[10^{-5}, 10^{-4})$**
3	**$[10^{-4}, 10^{-3})$**
2	**$[10^{-3}, 10^{-2})$**
1	**$[10^{-2}, 10^{-1})$**

Here, PFD_{avg} is defined as: $PFD_{avg} = \frac{1}{T_I}\int_0^{T_I} PFD(t)dt$,

where T_I is the time to periodic inspection. As per Marszal and Scharpf [5], it is appropriate to use PFD_{avg} because the demand for a SORV to operate can occur at any time during the maintenance interval. Therefore, it can be unnecessarily conservative to apply the failure probability that reflects the full maintenance interval $PFD(T_I)$. The *PFD(t)* is equivalent to the cumulative distribution function.

While higher SILs are always preferred, the minimum safety level at SRS is SIL 1 [6]. A contrast is made in this paper between bench test performance and field performance similar to that in API RP 581 [2]. When the uncertainty in field performance vis-à-vis bench results is factored into the calculations, SIL 2 cannot be reached.

Bench proof tests, without application of factors for field performance, show that SIL 1 and often SIL 2 are reached by current valve maintenance practices and maintained after extending maintenance intervals for certain sub-groups of valves. However, once the uncertainty of field performance is propagated into the bench estimates, through the confidence factors [2], the SIL levels based on bench results seem to be overly optimistic.

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: liquid, steam, gas, and air. 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 3.88 years. 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 $(R_p = \mathrm{TP/SP})$. If

$R_p \geq 1.50$, then the valve is considered by industry and API 576 to be “stuck shut,” meaning that the valve is not open to relieve excess pressure. It is a good indication that such a valve would fail on 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 API RP 581 [2] and ASME PCC-3-2007 [1]. 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 1.1 times SP is disassembled for cleaning and repaired. The valve is subsequently reassembled, reset to its original set pressure, retested, tagged, and returned to the field as “like new.”

As an example, a conventional spring design steam service valve, with set pressure of 140 psig, brought into the VRS from SRS’s Defense Waste Processing Facility proof tested at 153 psig (9% high) after 3 years in service. Subsequently, it was disassembled and found to be in good condition. The cap and bonnet were removed (Figure 1a). This valve was not stuck shut $(R_p \geq 1.50)$, even with active corrosion on the valve stem, washers, and guides (Figures 1b, 1c, and 1d). However, the valve was repaired, tested and installed. This maintenance action verified that the time in service of 3 years was adequate for this valve.

Figure 1a. Conventional spring design steam service valve; cap and bonnet removed.

Figure 1b. Valve body and inlet nozzle; very few deposits on the seating surface and no cuts.

Figure 1c. Inside the valve bonnet; corrosion evident but not much loose debris.

Figure 1d. Spring, spring washers, disc holder and disc, stem, sleeve guide, and stem retainer.

STATISTICAL ANALYSIS OF SRS VALVES

Data from 935 SRS used valves from May 21, 2003 to January 11, 2011 were analyzed, with 418 valves from the *air* working fluid category, 269 from the *gas* category, 108 from the *liquid* working fluid category, and 140 from the *steam* category. The time sequence of ratio (R_p) versus date tested is displayed in Figure 2. The data did not exhibit any trending by working fluid type over the data range. In addition, there was no statistical difference in ratios among the fluid services (Figure 3). The mean ratio was 1.038 (Table 1) while the individual ratios ranged between 0.91 and 3.41 overall fluid services (Table 1).

There were 22 valves out of the 935 valves with $R_p \geq 1.30$. Of these 22 valves, 12 valves were stuck shut $(R_p \geq 1.50)$. The average time between installation and testing of a valve is 3.88 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 (i.e., passed proof test: $R_p < 1.30$) are called "suspensions."

For suspensions, it should be noted that the time used in this study is the time between installation and the actual proof test 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 6 months after its proof test, not when testing should be performed after removal from the field.

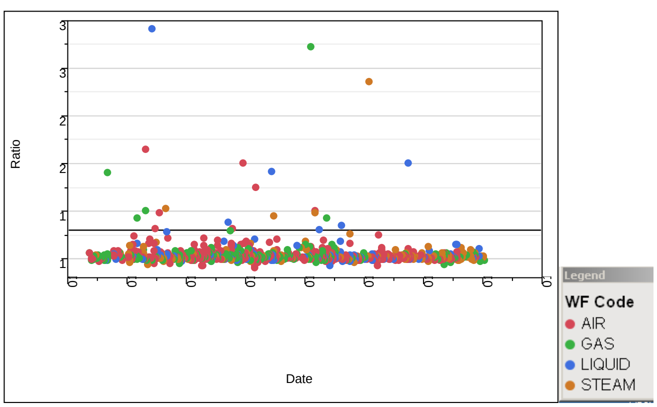


Figure 2. Ratio by Date Color Coded by Working Fluid.

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.

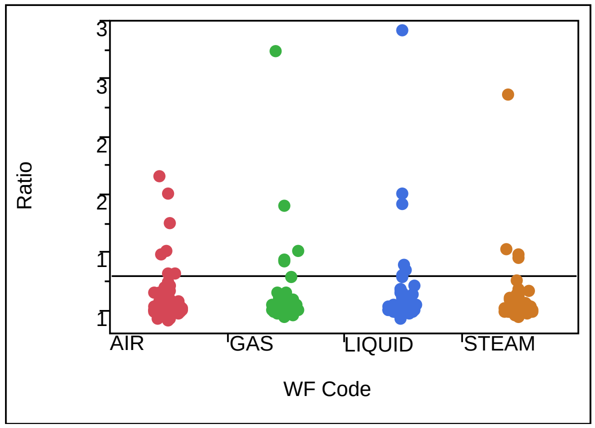


Figure 3. Ratio by Working Fluid.

Table 1. Summary Statistics for Ratio by Working Fluid.

Level	Number	Minimum	25%-tile	Median	75%-tile	Maximum	Mean
AIR	418	0.91	0.99	1.01	1.03	2.14	1.03
GAS	269	0.94	1.00	1.01	1.03	3.23	1.03
LIQUID	108	0.93	0.99	1.01	1.04	3.41	1.07
STEAM	140	0.93	1.00	1.02	1.04	2.86	1.05

Because the statistical analysis indicated that there is no correlation between maintenance time and test ratio, all data can be modeled by a fixed distribution over time. As such, there is no reason to apply a weighting mechanism as suggested by API RP 581 [2] which gives more importance to the most recent proof tests. One must bear in mind that subsets may exhibit different failure rates with respect to time in service. Furthermore, review of the data showed no apparent difference between valves with mild or moderate severity levels (working environments), so these groups were combined, and analysis was instead focused on differences in time to failure between working fluid groups.

Mild severity levels include working environments such as clean hydrocarbon products at moderate temperatures, which are low in sulfur and chlorides. Examples include low pressure steam and clean gases, such as nitrogen and air and with no aqueous phase present. Moderate severity levels include working environments that may include hydrocarbons that may contain some particulate matter. An aqueous phase that includes clean, filtered and treated water may be present. Some sulfur or chlorides and temperatures of up to 500 degrees Fahrenheit may exist for medium to high pressure steam.

The histogram and dot plots provided in Figures 4 and 5 display the overall distribution of the maintenance time (in years) as well as the distribution by working fluid group.

Table 2 provides the corresponding summary of descriptive statistics. Approximately 35% of the test times lie between 3.0 and 3.5 years. Liquid service has the lowest mean time in service (3.37 years), while air service has the longest average time in service (4.29 tears).

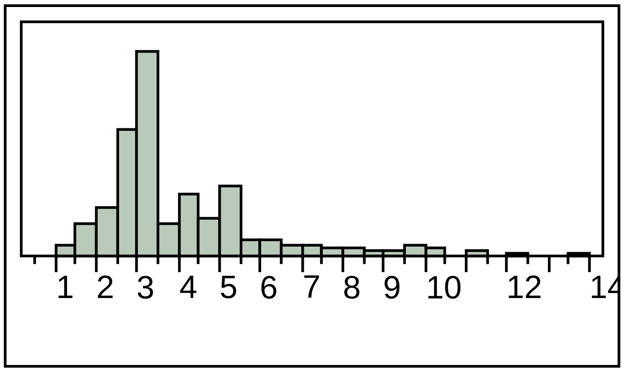


Figure 4. Maintenance Time Distribution (Years) Over All Working Fluids.

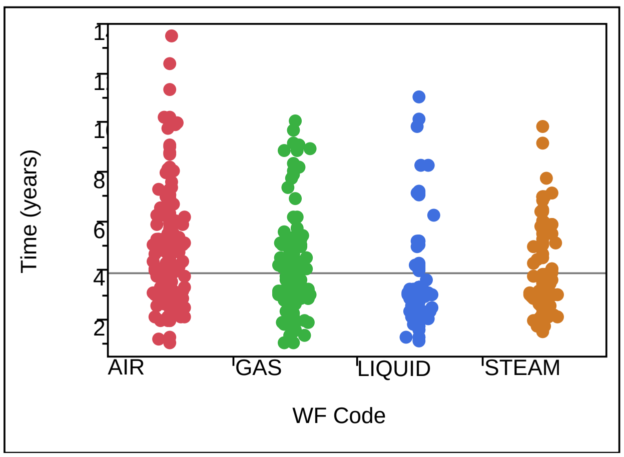


Figure 5. Time (Years) by Working Fluid.

Table 2. Time in Service Distribution.

Type	N	Minimum (Years)	2.50%-tile (Years)	Median (Years)	97.50%-tile (Years)	Maximum (Years)	Mean (Years)
Air	418	1.02	2.03	3.87	9.98	13.50	4.29
Gas	269	1.00	1.55	3.12	8.82	10.01	3.67
Liquid	108	1.13	1.24	3.02	9.88	11.04	3.37
Steam	140	1.44	1.70	3.01	7.41	9.77	3.49
Overall	**935**	**1.00**	**1.76**	**3.15**	**9.44**	**13.50**	**3.88**

In order to correctly 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 [7] may provide an appropriate fit for the valve data. The lognormal 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. 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 log-logistic distribution is similar to the lognormal, but has heavier tails- and is used in such applications as modeling cancer mortality or financial wealth. The Fréchet distribution [4] 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.

In order to assess the relative fit of the models provided by each of these distributions, the corrected Akaike Information Criterion (AIC_c) [8] is compared for each distribution in which the lower values of each of the criterion indicate a better-fitting model (Table 3).

The AIC_c can be thought of as the small-sample version of AIC [8] and is defined as

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

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 Weibull model is exp((192.2-194.4)/2)= 0.33. The interpretation is that the Weibull model is not as probable as the Fréchet model (odds 1 to 3) to minimize information loss (Figure 6). The odds ratio is not unfavorable enough to rule out the Weibull model as reasonable for representing the data. However, for the Liquid service data set, the relative likelihood exp((54.4-57.9)/2)= 0.17, so the Fréchet model was used instead of the Weibull distribution (odds 6 to 1). The differences in the PFD versus time are graphically displayed in Figure 7.

Table 3. AICc Statistics for Distribution Comparison

Two Subgroupings: (Air, Gas, Steam) and Liquid.

Distribution	AICc Air, Gas, and Steam	AICc Liquid
Fréchet	192.2	54.4
Lognormal	192.6	55.8
Loglogistic	194.2	57.3
Weibull	194.4	57.9

The Fréchet distribution provides the best fitting distribution for each subset. However, the AIC_c for the distributions fit to the Air, Gas, and Steam combined group are relatively similar, indicating that, most likely, none of the models provides a substantially better fit than any of the others. In addition, the cumulative probability plots show very little practical difference in failure times over the range of times to failure. However, substantial differences can exist among the distributions in predicting the time to failure when forecasting outside the range of data.

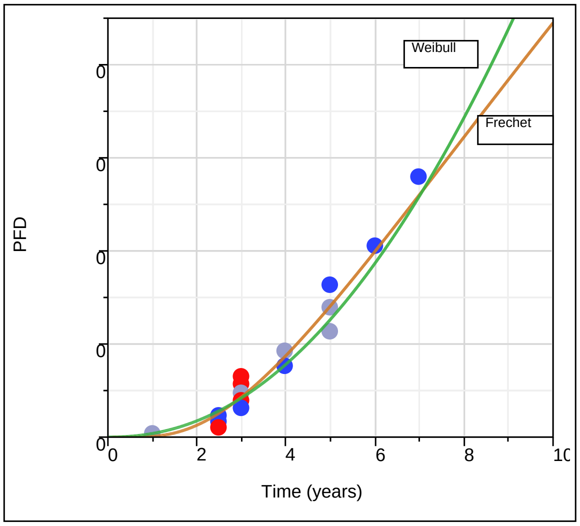


Figure 6. PFD for the Fréchet and Weibull Distributions for Air, Gas, and Steam Services.

Based on historical uses of each of these distributions for various types of lifetime data, the Weibull distribution is most commonly associated with failure times of system components, such as the valves of this data set. Furthermore, recent literature, particularly that of the American Petroleum Institute's Risk-Based Inspection Technology and ASME PCC-3-2007 [1], suggest use of the Weibull distribution to analyze lifetime distribution data sets for in-service pressure relief valves. For these reasons, the Weibull distribution is chosen as the most appropriate distribution to analyze the lifetime model for the combined Air, Gas and Steam service data.

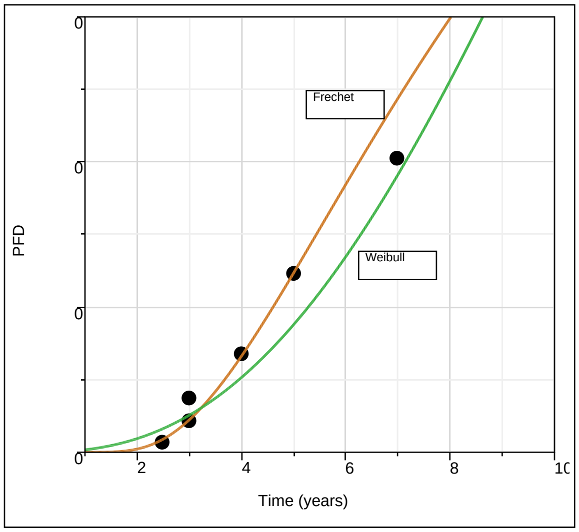


Figure 7. PFD for the Fréchet and Weibull Distributions for Liquid Services.

While the Fréchet distribution provided a marginally better fit, it was of no practical difference for this data set. The Fréchet distribution was selected for the Liquid service data because of the substantially better fit for that data set (Table 3 and Figure 7). The cumulative distribution function (CDF) of the Weibull distribution is equivalent to the probability that a valve will fail before aging t years $[PFD(t)]$. The two parameter CDF for a Weibull distribution is defined as:

$$F(t) = PFD(t) = 1 - \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad t \geq 0 \quad (1)$$

where $F(t)$ is the probability that a PRV will fail before it acquires t years of operating time.

The Weibull model was fit to the valve data with working fluid service type as a test variable. Based on this model, statistical tests indicated that the survival distributions for Air, Gas, and Steam are not significantly different from each other (Table 4).

Table 4. Significance Tests for Merging Data

P-value < 0.05 indicates significance

Working Fluid Service	P-value
GAS vs. AIR	0.388
GAS vs. STEAM	0.467
AIR vs. STEAM	0.130

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. There was a statistical difference between the Liquid Service group and the combined group with a p-value = 0.015. The probability models for these two groups and their corresponding statistics are provided below in Figures 7 and 8 and Tables 5 and 6. The 95% confidence bounds for the PFD are displayed in Figures 7 and 8 by the shaded regions. As observed, these limits are quite wide as a result of the number of failures (22) in the full data set of valves proof tested (N=935). As an example, from the combined Air, Gas, and Steam data set, at 5 years, the PFD is estimated to be 0.025 (Figure 8) with a 95% confidence interval of (0.016, 0.041). Therefore, pooling of industry data from highly reliable proof tests would be instrumental in furthering knowledge of valve in-service performance through enabling more precise estimates. This is exactly the motivation behind the CCPS\PERD project.

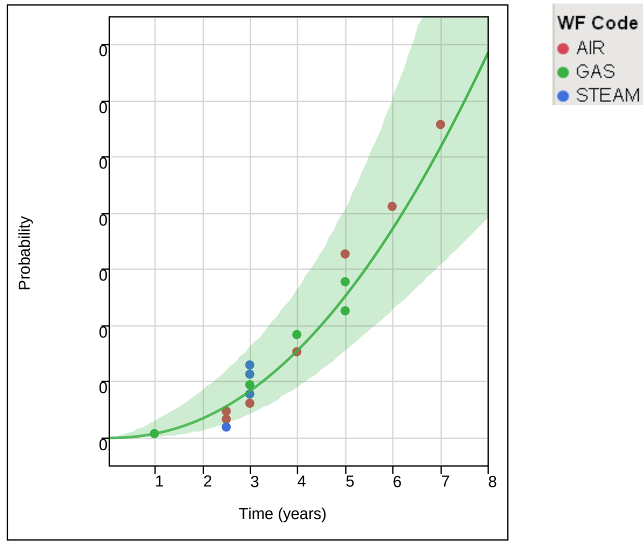
The distribution function for the Fréchet distribution with location (μ) and scale parameter (σ) is defined as:

$$F(t) = PFD(t) = \exp\left[-\exp\left(-\frac{\log(t)-\mu}{\sigma}\right)\right] \qquad (2)$$

where μ is the location parameter, σ is the scale parameter, and $t > 0$.

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 appropriately 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.

The typical method in applications is to use the exponential distribution, which has a constant failure rate, to model the data set giving rise to the approximation $PFD_{avg} = t/2\sigma$ where σ is the scale parameter [5]. This would lead to an estimate of PFD_{avg} that is approximately 60% higher for the combined Air, Gas, and Steam data set and approximately (0.0097 vs. 0.0060) 110% higher for the Liquid service data set (0.0267 vs. 0.127). Furthermore, completely ignoring the suspensions would lead to a 32 fold increase in PFD_{avg} for the Liquid service and an 88 fold increase in PFD_{avg} for the combined Air, Gas, and Steam services.

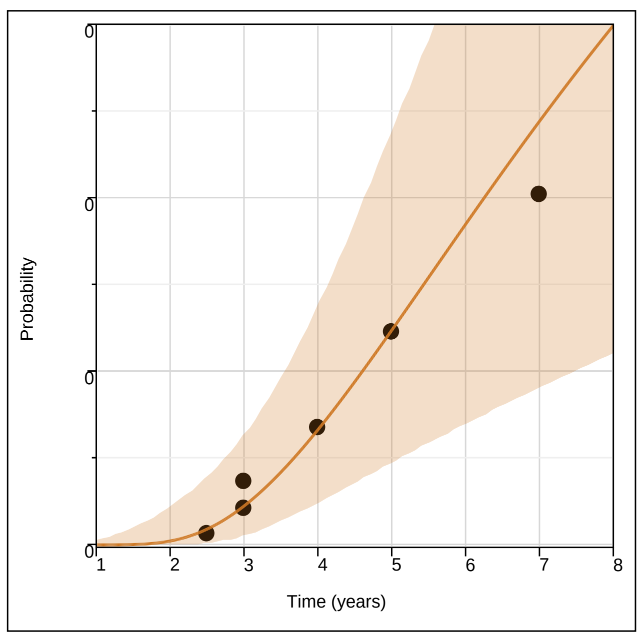


Summary of Data	
Proof Tests	827
Failed ($R_p \ge 1.3$)	16
Suspensions ($R_p < 1.3$)	811

Figure 8. Weibull Fit for the Probability of Failure, Air, Gas, and Steam Services Combined.

Table 5. Weibull Parameters for Air, Gas, and Steam Services Combined Group.

Parameter	Estimate	Std Error	Lower 95%	Upper 95%
Weibull Shape (β)	27.03	8.42	14.68	49.77
Weibull Scale (η)	2.17	0.39	1.61	3.35



Summary of Data	
Proof Tests	108
Failed ($R_p \ge 1.3$)	6
Suspensions ($R_p < 1.3$)	102

Figure 9. Fréchet Fit for the Probability of Failure for the Liquid Service Group.

Table 6. Fréchet Parameters for Liquid Service Group.

Parameter	Estimate	Std Error	Lower 95%	Upper 95%
location	2.240	0.302	1.65	2.83
scale	0.855	0.237	0.39	1.32

RISK AND RESULTS

As in API RP 581 [2] confidence factors are used to compare "as found" TP to the SORV's in-service "on demand" SORV performance. Conditional probabilities are used to reflect the probability that an inspection result will predict the valve's performance on demand while in service. The confidence factor k_{pass} is for the effectiveness of the proof test; specifically it is the probability that the SORV would have successfully functioned on demand while in service (Field). The $k_{pass} = 0.986$ is used for a passed proof test. The probability that a valve that failed bench test would have failed in the field is $k_{fail} = 0.886$. The unconditional PFD for an in-service SORV is calculated as follows:

$$F_{Field}(t) = k_{fail} \cdot F_{Bench}(t) + \left(1 - k_{pass}\right) \cdot [1 - F_{Bench}(t)]$$

where k_{fail} is the probability of failing on demand while in service for valves that have failed the proof test. Estimates were based on review of ratios over all working fluids combined (N=935). There were 22 failed proof tests and 913 passed proof tests. Of the passed proof tests, 25 ranged between 1.15 and 1.30. Possibly half of these would have failed on demand, yielding $k_{pass} = (913 - 12.5)/913 = 0.986$. Five proof tests failed between 1.30 and 1.40. Half of these could have passed on demand, yielding $k_{fail} = (22 - 2.5)/22 = 0.886$. Proof tests with $R_p < 1.15$ or $R_p > 1.40$ are considered to be highly reliable predictors of field performance (>99.9%).

A risk assessment was performed to determine the total cost of operations based on maintenance time. This function considers the annual cost of valve inspection [9] as well as the annual risk when determining the total cost of the maintenance plan based on the maintenance interval. The average inspection time is 3.88 years for the current site-wide PM plan. A demand frequency of 0.01/year was used [2]. The loss distribution from over-pressurization was 1 MM, 5 MM, and 20 MM with probabilities of 0.50, 0.30, and 0.20, respectively (6MM expected loss). "Risk" is defined as the product of *Demand Rate*, *Vulnerability*, and *Consequence*. *Demand Rate* is the frequency of overpressurization on systems with in-service valves and is quantified by number of events per year. *Vulnerability* is the susceptibility of the system to serious consequences and is measured by the PFD as a function of time. *Consequence* is due to the on-demand failure of a valve and is estimated in terms of U.S. dollar costs due to human injury and restoration of the process to its original state.

For the Gas, Air, and Steam service group, the average time in service is 3.95 years with corresponding risk of $1,164 (Figure 10 and Table 7). From the cost analysis (Figure 10), it appears that the time in service can be extended one year to approximately 5 years with essentially no impact on total cost. The increase in risk per valve per year ($160/valve) was offset by the decrease in inspection cost ($156/ valve per year). The average SIL decreases from 1.91 (103 SIL 1, 699 SIL 2 and 25 SIL 3) to 1.71(237 SIL 1, 590 SIL 2) based on the bench data. Once the confidence factors for reliability of the test are applied the on-demand SIL remains at 1.0. The average time in service for Liquid Service is 3.38 years with corresponding risk of $1,566/ valve per year (Figure 11). Increasing the maintenance interval one year incurs a $448 / valve per year increase in risk, which is far from being offset by the $156 savings in the cost on inspection (Table 8). The data suggest that reasons for the difference in performance between Liquid Service and the others be investigated.

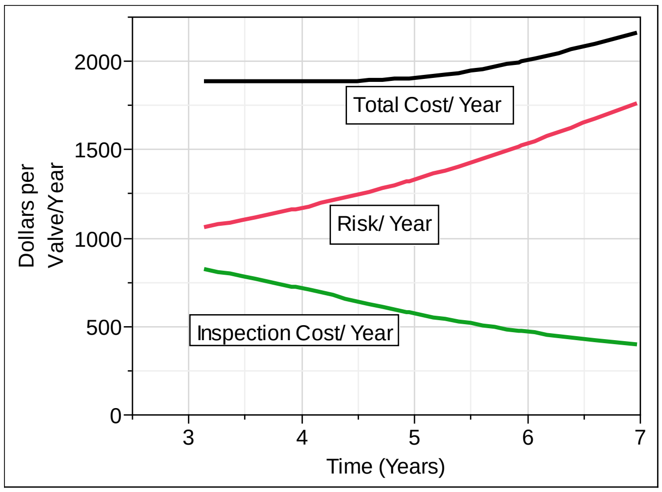


Figure 10. Risk vs. Cost by Maintenance Time (Years) for Air, Gas, and Steam Service Combined.

Table 7. Average Risk and Cost per Valve by Time (Years) Service for the Air, Gas and Steam Combined Groups.
Demand rate: 0.01/year, $k_{pass} = 0.986$, $k_{fail} = 0.886$

Time (Years)	PFD_AVG Bench	AVG_SIL Bench	PFD_AVG Field	AVG_SIL Field	Risk/Year Field (Dollars)	Inspection Cost/ Year (Dollars)	Total Cost/Year Field (Dollars)
3.15	0.0041	2.04	0.0178	1	1,066	820	1,886
3.95	0.0060	1.91	0.0194	1	1,164	730	1,894
4.95	0.0091	1.71	0.0221	1	1,324	574	1,898
5.95	0.0129	1.58	0.0254	1	1,523	474	1,997
6.95	0.0175	1.11	0.0294	1	1,764	402	2,166

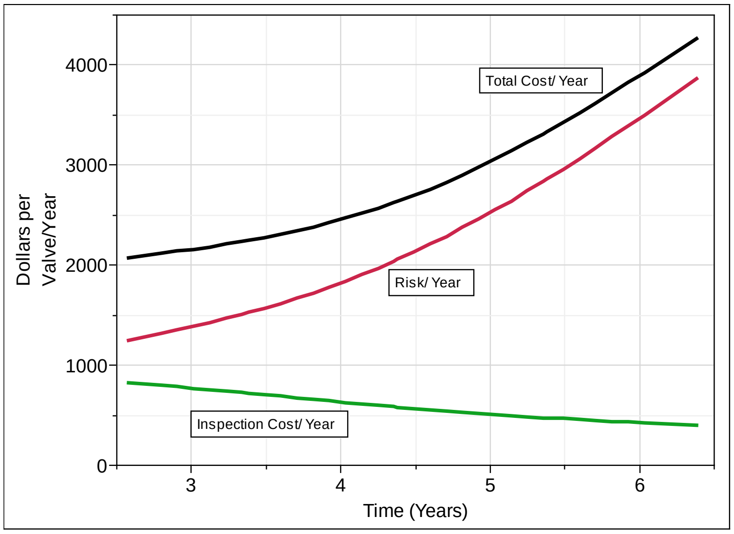


Figure 11. Risk vs. Cost by Maintenance Time (Years) for Liquid Service.

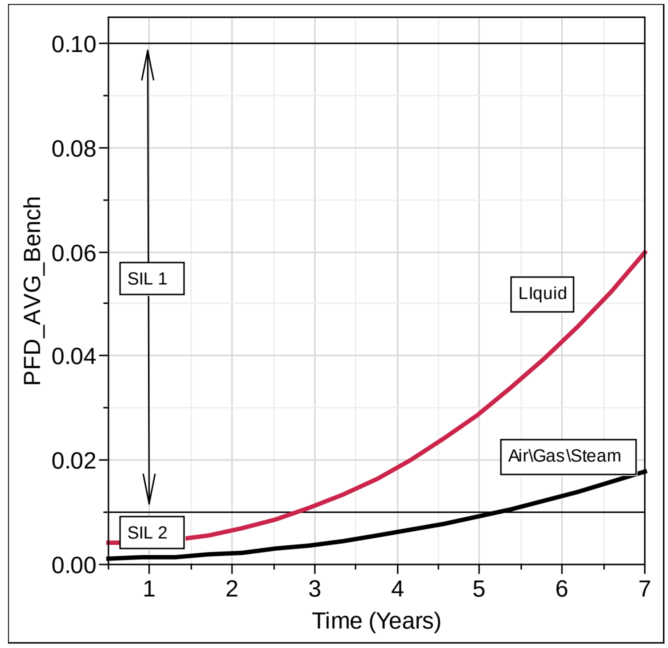
Table 8. Average Risk and Cost per Valve By Time (Years) for the Liquid Service Group.
Demand rate: 0.01/year, $k_{pass} = 0.986, k_{fail} = 0.886$

Time (Years)	PFD_AVG Bench	AVG_SIL Bench	PFD_AVG Field	AVG_SIL Field	Risk/Year Field (Dollars)	Inspection Cost/ Year (Dollars)	Total Cost/Year Field (Dollars)
2.58	0.0080	2.90	0.0211	1	1,267	820	2,087
3.38	0.0127	2.22	0.0252	1	1,514	730	2,244
4.38	0.0230	1.28	0.0342	1	2,051	574	2,625
5.38	0.0383	0.99	0.0475	1	2,852	474	3,326
6.38	0.0578	0.90	0.0646	1	3,875	402	4,277

The SIL level can be tuned by adjusting the maintenance interval. Liquid service valves with an average maintenance interval of 3.38 years have 19% (21 out of 108 valves) of its valves at SIL 1 or less. Improvements in SIL can be made by shorter maintenance intervals or more reliable valves. Approximately 13% of liquid service valves have time in service of 5 years or greater. There is uncertainty in the estimation of the bench PFD_{avg} curves that can only be remedied by additional data (Figure 12). However, one must note that once the confidence factors are used to project the bench tests results to in-service performance, attaining SIL 2 is not possible for either fluid service (Figure 13).

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 Weibull distribution for use in the risk analysis. However, grouping these data-points limits the ability to test the effect of changing the maintenance intervals for a particular fluid type.



Actual time-in-service for Liquid service valves of 3.38 years appears to be overextended.

Figure 12. PFD_{avg} and SIL Levels by Maintenance Time Based on Bench Proof Tests.

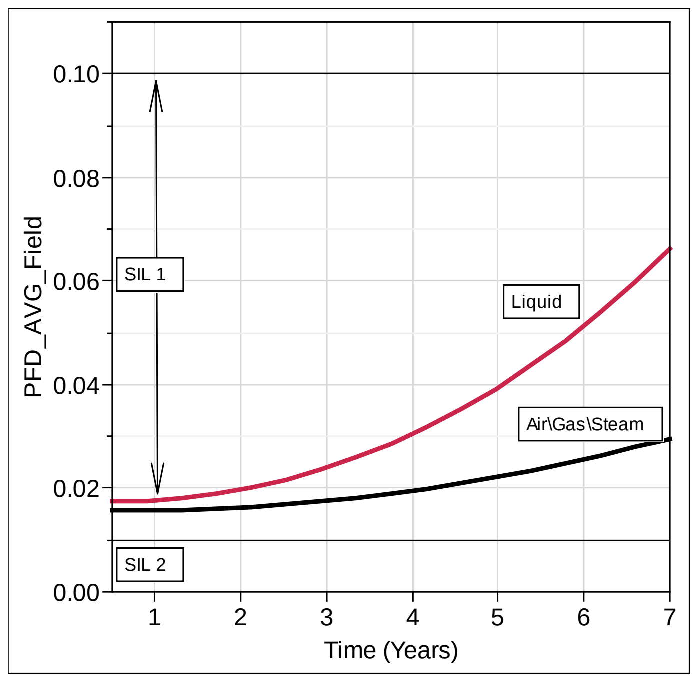


Figure 13. PFD_{avg} and SIL Levels by Maintenance Time Based on Forecasted Field Values.

Furthermore, 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. Additional data development on proof tested valves (e.g., seat material type could reveal useful subgroups of data for modeling. The methodology presented in this paper can easily be applied to these subgroups.

Confidence factors, k_{pass} and k_{fail}, as used in API RP 581 [2], are used to extend bench proof test results to in-service performance. API RP 581 [2] recommends 90% confidence for passed proof tests and 95% confidence for failed proof tests for highly effective VRS testing. Based on review of R_p, we used 98.6% for passed proof tests and 88.6% for failed proof tests due to proximity to the failure threshold $R_p = 1.30$.

A risk-based approach to adjusting maintenance intervals and safety considerations provides a more comprehensive approach than only focusing on SILs. However, much more work is necessary in implementing a risk-based approach that requires evaluating consequences for various over pressurization scenarios. SIL does take into account the dollar consequence and the demand rate to an limited extent. Assignment of SIL levels to safety systems is typically based on the potential for various severities of injury ranging from minor injuries to potential fatalities. This is good as a first step with consequence analyses pursued afterward for greater fidelity. Also, a use of SIL could be in the selection of higher reliability devices for replacement and in the design of new facilities.

Maintaining the time between field installation and proof test to correspond more closely to the set maintenance intervals would serve to improve the risk analysis and SIL results. In addition, a procedure that requires valves to be tested within a certain number of months, say 6 months, after being removed from the process would add substantially to data quality.

The method of analysis used in this paper suggests that for air, gas, and steam fluid services there may exist subsets of valves in which maintenance intervals may be extended with little impact on overall risk. Fluid service valves did not perform as well and we believe this is due to a combination of material compatibility, cleanliness of the system, and corrosiveness of the system fluid.

The average probability of failure on demand is substantially less than the maximum probability of failure on demand that occurs at the maintenance time. The average probability of probability of failure on demand is a reasonable benchmark when dealing with subsets of valves but may not be an adequate representation of any one particular valve.

failure on demand is a fraction of the maximum probability of failure on demand that occurs when the Weibull distribution is evaluated at the maintenance time. As such, the average 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 should be corroborated with additional data from the SRS program as well as data from CCPS/ PERD.

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