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Validation of Spring Operated Pressure Relief Valve Time-to-Failure and the Importance of Statistically Supported Maintenance Intervals

ABSTRACT

The Savannah River Site operates a Relief Valve Repair Shop certified by the National Board of Pressure Vessel Inspectors to NB-23, The National Board Inspection Code. Local maintenance forces perform inspection, testing, and repair of approximately 1200 spring-operated relief valves (SORV) each year as the valves are cycled in from the field.

The Site now has over 7000 certified test records in the Computerized Maintenance Management System (CMMS); a summary of that data is presented in this paper. In previous papers, several statistical techniques were used to investigate failure on demand and failure rates including a quantal response method for predicting the failure probability as a function of time in service. The non-conservative failure mode for SORV is commonly termed "stuck shut"; industry defined as the valve opening at greater than or equal to 1.5 times the cold set pressure. Actual time to failure is typically not known, only that failure occurred some time since the last proof test (censored data).

This paper attempts to validate the assumptions underlying the statistical lifetime prediction results using Monte Carlo simulation. It employs an aging model for lift pressure as a function of set pressure, valve manufacturer, and a time-related aging effect. This paper attempts to answer two questions: "what is the predicted failure rate over the chosen maintenance/ inspection interval", and "do we understand aging sufficient enough to estimate risk when basing proof test intervals on proof test results."

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Summary

The ratio (*R*) of relief valve Test Pressure to Set Pressure (TP/SP) greater than or equal to 1.5 in the as-found condition is considered by industry and API 576 to be "stuck shut." When a relief valve is removed from service for maintenance, the as-found lift pressure or "proof test" result in general correlates with the valve's performance "on demand." During an actual over pressure event failing to open by 1.5 times the set pressure will challenge process piping and vessel integrity. The Monte Carlo simulation

(MCS) in this report was based on a statistical model developed from new valve lift pressure (proof test) results. These include new valves shipped from the manufacturer and those that were rebuilt, i.e., returned to "like new" condition after having been in service. Hypothetical yearly percentage increases (1%-2%) in lift pressure were built into the statistical model for testing the analysis methods.

Introduction

The Savannah River Site (SRS) joined the Process Equipment Reliability Database (PERD) Committee 18 on pressure relief valves in 2005. Members who contribute test data in a PERD approved format are able to access available industry wide data. SRS first uploaded 4000 data points in early 2007. Consequently, PERD shared several data sets they had accumulated since 1993 with SRS. At the time, there were 9 active members of the Center for Chemical Process Safety (CCPS) within PERD.

Previous Work - SRS and PERD

The PERD data set provided an estimated Probability of Failure on Demand (PFD) of approximately 1.2 % while the estimated value for SRS data was approximately 0.7 %, see Table 1. A comparative representation of the ratio distribution is shown in Plot 1. Evaluation of differences causing the spike in SRS ratios between 1.10 and 1.20 was necessary. A review of SRS data by manufacturer determined that small, inexpensive, soft-seated style valves represented 65% of the valves in the $1.10 < R < 1.20$ range. PERD data provided similar average R for soft seat valves but the number tested is $\leq$ ½ % while soft seat for SRS comprise more than 7% in the tested population.

Table 1
Overall Proportion of Valves that Failed up to 5 years in Service
(n is the number of proof tests with $R \geq 1.5$)

Source	N	n	p (%)	95% Confidence Limits
SRS	2472	17	0.69	[0.40%, 1.10%]
PERD	6768	84	1.24	[0.99%, 1.53%]

Table 2
Summary of Proof Test Statistics for PERD vs. SRS
All Proof Test Data Combined, New and Used

Source	Number of Valves	Mean	Standard Deviation
SRS	2472	1.034	0.090
PERD	6768	1.006	0.124

Box and Whisker plots based on the ratio R for PERD and SRS data are shown in Plot 2 and the means and standard deviations are listed in Table 2. PERD recorded a significant amount of valves classified as stuck shut ($R \geq 1.5$); almost twice the rate as SRS, but their mean value is still 2% lower. SRS data indicated that the 95% confidence interval for probability of failure on demand (PFD) is 0.40% to 1.10% while the PFD for PERD is 0.99% to 1.53%. Overlap of the intervals implies that the proportion of valves that failed by source is equivalent. In Plot 2, note the close groupings of test data at approximately R=1.00; 31% of PERD Data has *R*=1.00 vs. 19% for the SRS Data. In the SRS data, we observed a failure rate of 1.3% /Year from 1 to 5 years time in service (Plot 3).

Risk Assessment

How does estimated or perceived SORV performance compare to actual proof test data results? It has been stated that an intuitive or subjective estimate of the PFD for a standby system *might double* if the standby time doubles. [1] If the PFD were actually shown to double with twice the time in service by the actual test data, then would not the estimated process safety risk increase significantly? Analysis of test data available through the CCPS-PERD, including SRS to date does not establish a statistically significant increase in the failure rate from 1 to 5 years in service. Several different authors in different publications have concluded the failure rate is fairly constant over the period.[2, 3, 4, 5] How would a Monte Carlo simulation (MCS) of the representative data using an aging model substantiate the failure rate over time - beyond 5 years? This paper investigates the consequences of standard statistical methods applied to PSV data using simulation. It explores the use of regression analysis and a quantal response method when applied to simulated data.

Data Summary

The 9 manufacturers representing about 85% of the SRS valve populations are displayed in Table 3. KFC represents the manufacturer with the most valves (nearly 20%) in the new valve population while representing only 9% of the used valve population. The top manufacturer in the used valve population is DVL representing nearly 17 % of the population. The differences in the new and used valve distributions across the different manufacturers are accounted for in the MCS.

New valves are tested before installation at SRS. A valve is released for installation at SRS if the actual lift pressure (proof test) is within ±3% of the set pressure. If a test is outside of this range, the valve is adjusted and then retested.

Table 3 - Number and Percentage (%) of New and Used valve Population for Major Manufactures

Manufacturer	N (new)	% (new)	N (used)	% (used)
CID	144	6.2%	70	7.8%
CS	330	14.1%	140	15.5%
CD	298	12.8%	54	6.0%
CRL	139	6.0%	88	9.8%
DVL	162	6.9%	152	16.9%
KFC	464	19.9%	79	8.8%
KVD	204	8.7%	67	7.4%
TNF	118	5.1%	123	13.6%
WRT	118	5.1%	0	0.0%
Total	1977	84.7%	773	85.7%

Failure Times – Survival Functions

A model is needed for the MCS to generate ratios that are realistic, include uncertainty and also the impact of specified trends. The SRS new valve data base was used for this purpose. The resulting model represents lift pressure (psig) as a function of set pressure and manufacturer. The model is expressed in the natural logarithmic space as:

$$\log_e(y_{Test\ Pressure}) = \beta_0 + \beta_1 \log_e(y_{Set\ Pressure}) + Manufacturer\ Terms + \varepsilon \qquad (1)$$

where $\log_e(y)$ is the natural logarithm of y, $y_{Test\ Pressure}$ is the Test Pressure (psig), $y_{Set\ Pressure}$ is the set pressure (psig) and ε is the random error assumed to follow a normal distribution with zero mean and constant standard deviation σ.

Using Model (1), $y_{Test\ Pressure}$ can be represented in the original metric (psig) as:

$$y_{Test\ Pressure} = e^{[\beta_0+\beta_1 \log_e(y_{Set\ Pressure})+Manufacturer\ Terms+\varepsilon]} = e^{(\beta_0+Manufacturer\ Terms)} e^{\varepsilon} y^{\beta_1}_{Set\ Pressure} \qquad (2)$$

The parameters in Model (1) were estimated using the JMP statistical software (SAS Institute, Cary, NC) in conjunction with the new valve data base. The estimates and standard errors (Plot 3) are:

$\hat{\beta}_0 = b_0 = 0.108 \pm 0.011$, $\hat{\beta}_1 = b_1 = 0.988 \pm 0.002$ and $\hat{\sigma}^2 = 0.070$. The correlation between b_0 and b_1 is $Corr(b_0, b_1) = -0.84$ and is used in the MCS.

The *Manufacturer Terms* essentially offset the intercept term β_0 in Model 1. Their estimates were included in the MCS but were not included in this report because of space requirements with there being 45 manufacturers.

Model (2) served as the basis for the MCS after known trends were built into the model. The resulting model was placed in the used valve data base so that the distribution of manufacturers in service at the SRS could be represented.

Monte Carlo Simulation (MCS)

All valves taken out of service for preventative maintenance have their service time recorded in the used valve data base. The exact impact of aging on valve performance within the PM interval (t_0, t_{PM}) where $t_0 = 0$ and t_{PM} is not known. For purposes of the MCS, it is assumed that the lift pressure could have been attained at any time t between installation and the PM maintenance time (time in service) $0 < t \le t_{PM}$. There is essentially no further aging impact in the MCS after time t and before the PM maintenance at time t_{PM}.

The time t is not known for valves in service. However, it is specified in the MCS. The aging model was taken to be linear with two cases simulated: $p = 1\%$ /year and $p = 2\%$ /year where p is the percentage increase in lift pressure per year. The aging model can be represented as:

$$y_{Test\ Pressure} = e^{(\beta_0+Manufacturer\ Terms)} e^{\varepsilon} y^{\beta_1}_{Set\ Pressure} + p \times t \times y_{Set\ Pressure} \qquad (3)$$

MCS time was taken from a uniform distribution over the interval $0 < t \le t_{PM}$, while all other terms in Model 3 were generated from a normal distribution with means, standard errors and $\hat{\sigma}^2$ taken from the regression output (Plot 4).

Regression Analysis

The MCS was based on 25 runs for each p. The regression model $R = \beta_0^{'} + \beta_1^{'} t + \varepsilon^{'}$ where the ratio $R = y_{Test\ Pressure} / y_{Set\ Pressure}$ was fit to MCS time (t) using the JMP software. Time was first taken to be the time in service and then taken to be time t at which the ratio is attained over $0 < t \le t_{PM}$. An illustration of one MCS run (of the 25) is displayed in Plot 5a for time t over $0 < t \le t_{PM}$ and in for service time in Plot 5b. The aging rate was estimated as 1.13% / year increase (Plot 5a) and as 0.58%/ year (Plot 5b). The true value was 1%/year in the MCS. Over the 25 run MCS, the average increase in *R* is 0.56%/ year (Table 4) when using Service time as the regressor with a between run standard deviation of 0.0012. Using simulated MCS time at which *R* is incurred yielded an estimate of 1.08%/ year with a between run standard deviation of 0.0014. The true MCS value was a rate of 1% /year. Next, the true MCS value was taken to be a 2% /year increase. Over the next 25 runs, the average increase in *R* is 1.06%/ year when using the Service time as the regressor with a between run standard deviation of 0.0016. Using the simulated time at which *R* is incurred yielded an estimate of 2.06%/ year with a between standard deviation of 0.0015.

Table 4
Final Simulation Results Based on 25 Replications

Simulated % Increase/ Year	Estimated % Increase/ Year Using The Service Time	Estimated % Increase/ Year Using MCS Time
1%	0.56%	1.08%
2%	1.06%	2.06%

Quantal Response Analysis

A PRV is considered as failed for the purposes of this MCS when *R* ≥1.10 to ensure an adequate number of valves for statistical analysis. During pressure testing, if a valve has failed, one only knows that its failure time was before its maintenance inspection time. Similarly, if a valve proof test was acceptable, then its failure time is beyond the maintenance inspection time. Such test data are sometimes called quantal response (QR) data. [6] Data of this type are sometimes incorrectly analyzed by taking the inspection time to be the failure time. Illustrations of PRV quantal response analysis are described by and Sheesley[2] et. al., and Bukowski. [3]

To implement a QR analysis, the data are grouped into *m* consecutive non-overlapping intervals $I_1, I_2, I_3, ... I_m$ fully covering the distribution of maintenance times and $I_i = \{t; t_i \le t < t_{i+1}\}$ for $i = 1, 2, 3, ..., m - 1$. In practice, each interval should contain at least 5 failures; their occurrences are well represented in the MCS. The fraction failed, q_i, and the average time, T_i, for the failed valves are calculated for each interval.

Once calculated, a plot is made of the points $-\log_e(1 - q_i)$ versus T_i. End of useful life could be indicated by the time when the slope substantially increases after a period of constant failure rate. [5]

The MCS was driven by Equation 3 but with time $t \ge 2$ years. Therefore the QR plot should be flat over the first 2 years and then experience a positive slope over the subsequent years. The resulting QR plots are displayed in Plot 6a and 6b for a 1%/year increase and in Plot 7a and 7b for a 2%/year increase. A plot of q_i vs. time in service (Plot 6a) does not show the full impact of the increase in the ratio as when the MCS times are used (Plot 6b). One could come to the same conclusion for a 2%/year increase as displayed in Plot 7a vs. 7b. The change in slopes in the QR function is much more obvious when the MCS times are used (Plot 6b and 7b).

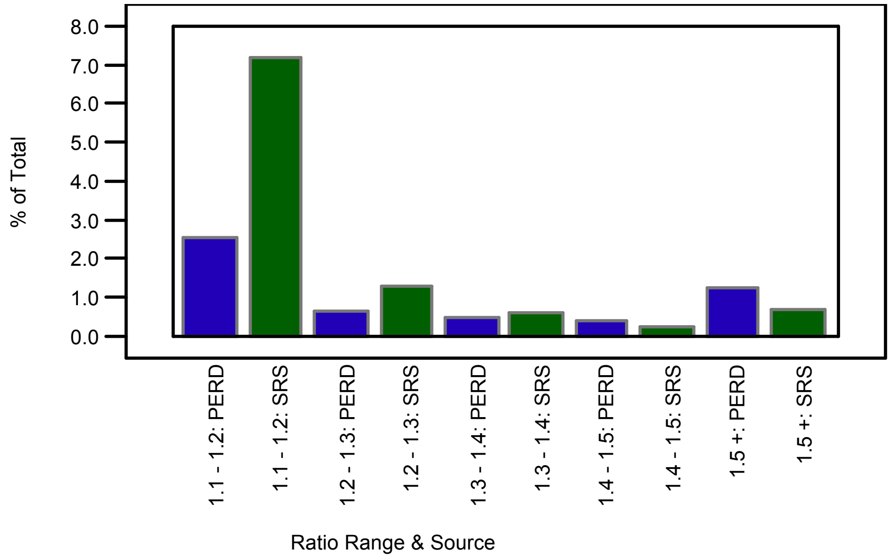
Conclusions

The primary result of the MCS was that an increased rate in the ratio (*R*) can be underestimated by a factor of approximately 2 if time in service is used in a regression analysis of the ratio (R) over time. Furthermore, quantal response (QR) analysis underestimates the impact of a 1% -2%/ year increase in the ratio and may be insensitive to the time of occurrence. Real test data obtained from increased maintenance intervals would provide additional insight into valve aging and end of useful life. At present there appears to be an abundance of proof test results and failure data out to 4 - 5 years, but few qualified data points for 6 - 10 years.

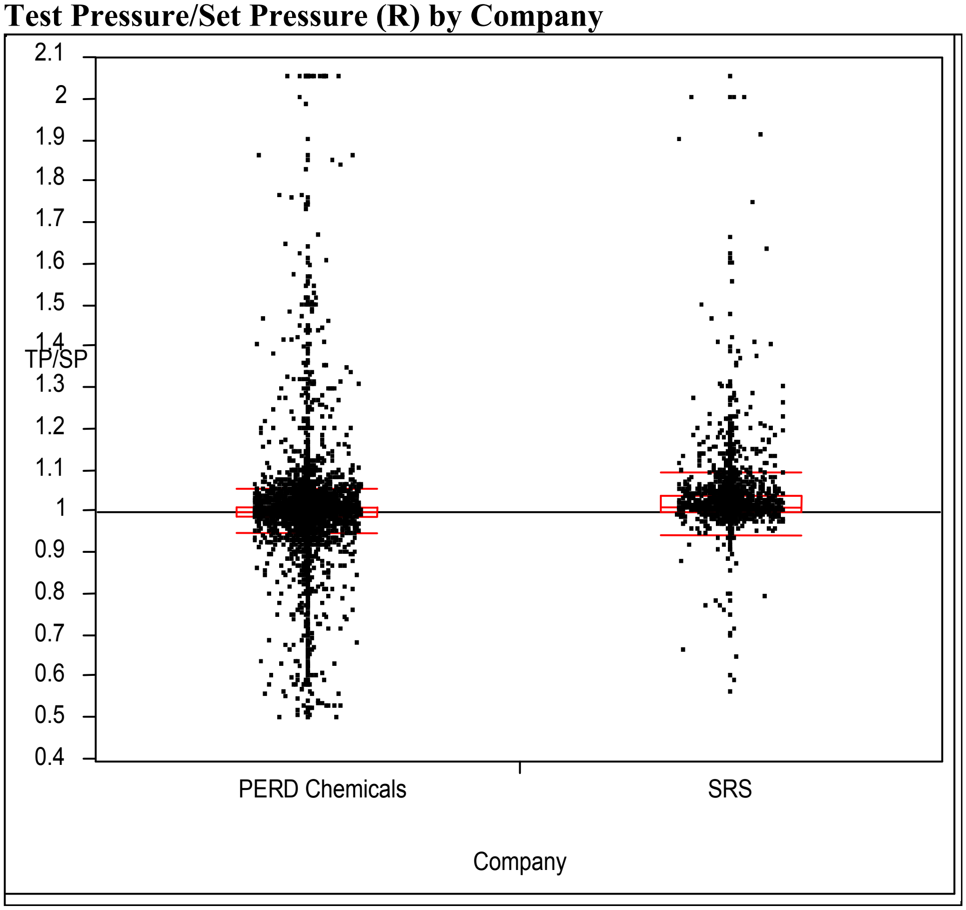
References

1. Urbanik, Stanley A. (2004), "Evaluating Relief Valve Reliability When Extending the Test and Maintenance Interval", *Process Safety Progress (Vol.23, No.3),* September 2004 pp 191-196.
2. Sheesley, J.H, Thomas, H.W. and Valenzuela, C.A. (1995) "Quantal Response Analysis of Relief Valve Test Data", *ASQ 49th Annual Quality Congress Proceedings*, pp741-748
3. Bukowski, J. V. (2007), "Results of Statistical Analysis of Pressure Relief Valve Proof Test Data Designed to Validate a Mechanical Parts Failure Database," *Exida Technical Report,* September, Sellersville, PA.
4. Gross, Robert E., Harris, Stephen P, (2006) "Extending Pressure Relief Valve Inspection Intervals by Using Statistical Analysis of Proof Test Data", *Proceedings of the ASME PVP-2006 / ICPVT – 11 Conference*, Vancouver, BC, Canada July 23-27, 2006.
5. Bukowski, J. V. and Goble, W. M., "Statistical Analysis of Pressure Relief Valve Proof Test Data: Findings and Implications," *Proceedings AIChE 4th Annual Global Conf on Process Safety*, New Orleans, LA, April, 2008.
6. Nelson, W.B. (1982), "Applied Life Data Analysis", New York, John Wiley & Sons.

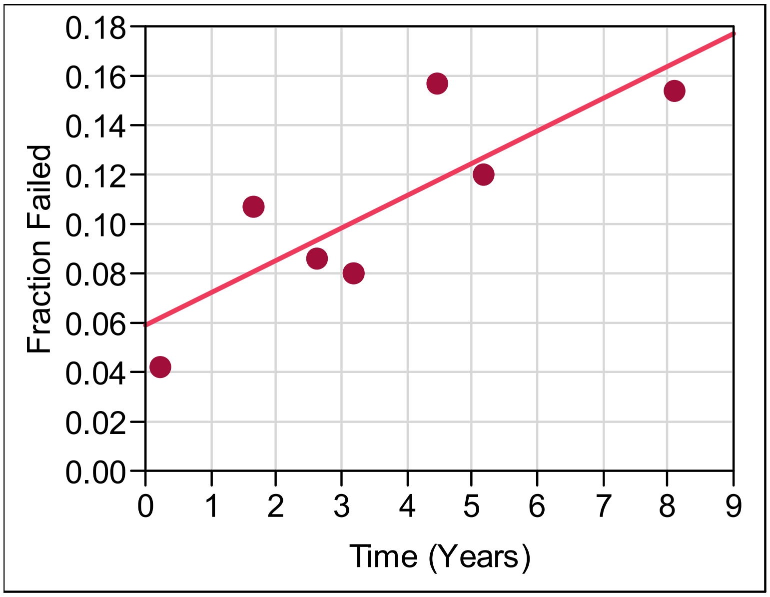
Plot 1: Pressure Relief Valve Proof Test Results at TP/SP Ratios > 1.10
Percentage of valves tested vs. Proof Test Ratios for SRS and PERD Data



Plot 2 - PERD vs. SRS PSV Data New & Used PSVs Combined
Test Pressure/Set Pressure (R) by Company



Plot 3
Fraction Failed (R>=1.10) By Time in Service (years)
SRS Used Valve Proof Test Data 1998 - 2007



Linear Fit
Fraction Failed = 0.059 + 0.0132*Time (Years)
Failure Rate=1.3%/year

Summary of Fit

RSquare	0.679
Root Mean Square Error	0.0256
Mean of Response	0.1065
Observations (or Sum Wgts)	7

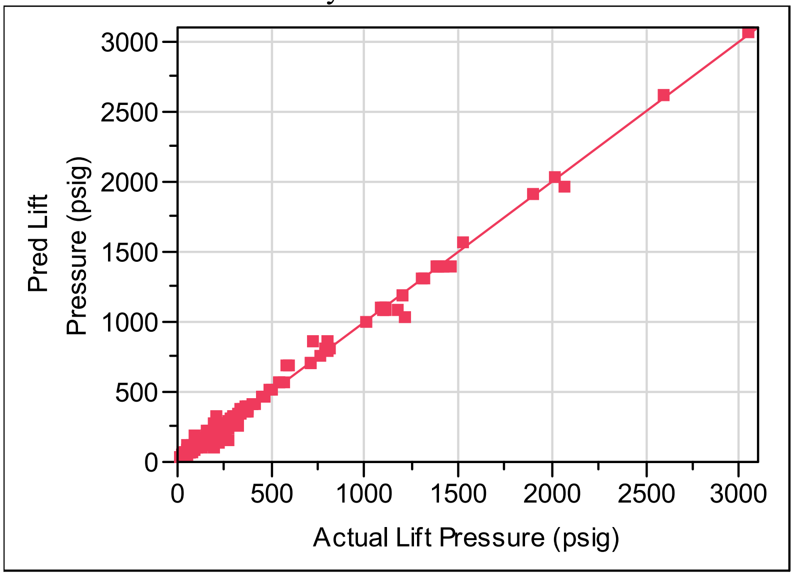
Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	1	0.0069	0.00694	10.6
Error	5	0.0033	0.00066	**Prob > F**
C. Total	6	0.0102		0.023

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.059	0.0176	3.33	0.021
Time (years)	0.0132	0.0041	3.25	0.023

Plot 4
Regression Model based on New Valve Data Set
Predicted Lift Pressure By Actual Lift Pressure



Response $\log_e$(Lift Pressure)
Summary of Fit

RSquare	0.99
Root Mean Square Error	0.07
Mean of Response	4.64
Observations	2338

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	45	1483.8	32.97	6722.4
Error	2292	11.2	0.005	Prob > F
C. Total	2337	1495.1		0.0000

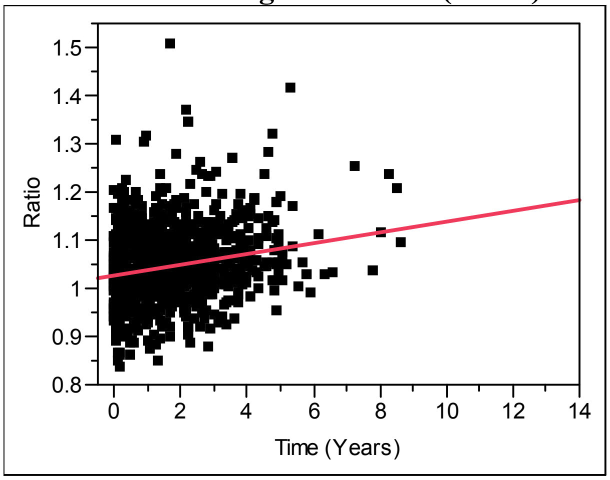
Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.108	0.0108	10.0	<.0001
$\log_e$(Set Pressure)	0.988	0.0019	508.8	0.0000
+ Manufacturer Terms				

Effect Tests

Source	Nparm	DF	Sum of Squares	F Ratio	Prob > F
ln Set	1	1	1270.0	258921.3	0.0000
Manufacturer	44	44	1.3	5.7924	<.0001

Plot 5a
Regression Estimates using One Iteration of the Simulation with 1%/ Year Deterioration Using MCS Time (Years)

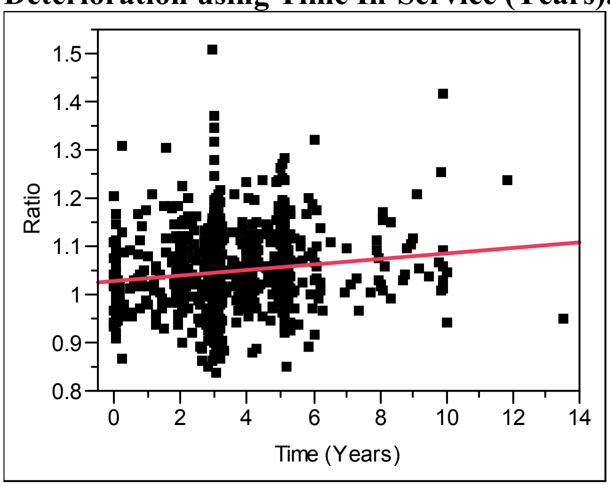


Ratio = 1.027 + 0.0113*Time (Years)

Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	1.027	0.0042	245.8	0.0000
Time (Years)	0.0113	0.0018	6.2	<.0001

Plot 5b
Regression Estimates using One Iteration of the Simulation with 1%/ Year Deterioration using Time In-Service (Years).



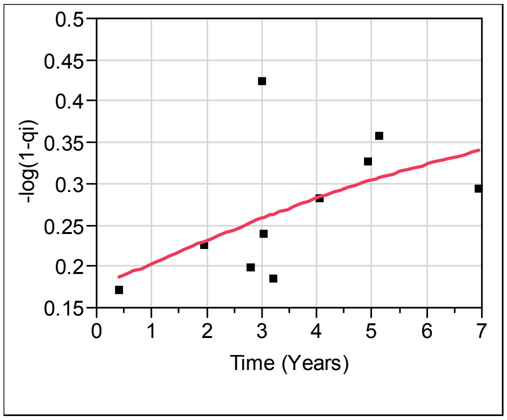
Linear Fit

Ratio = 1.026 + 0.0058*Time (Years)

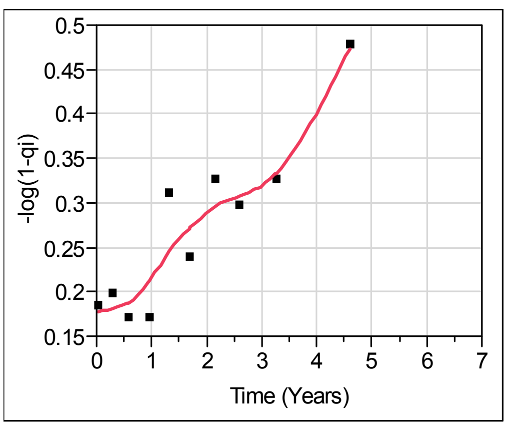
Parameter Estimates

Term	**Estimate**	**Std Error**	**t Ratio**	**Prob>|t|**
Intercept	1.026	0.0058	175.8	0.0000
Time (Years)	0.0058	0.0015	4.0	<.0001

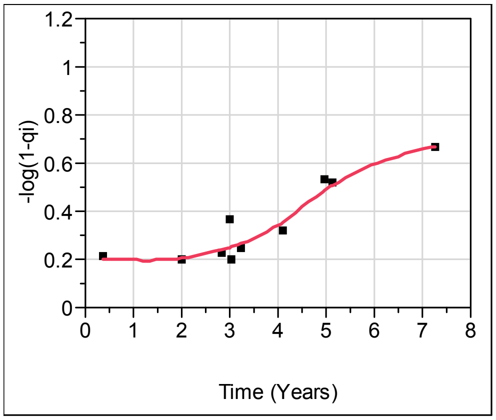
Plot 6a
Quantal response model 1%/year increase in R after 2 years using Time In-Service



Plot 6b
Quantal response model 1%/year increase in R after 2 years using MCS Time



Plot 7a
Quantal response model 2%/year increase in R after 2 years using Time In-Service



Plot 7b
Quantal response model 2%/year increase in R after 2 years Using MCS Time