Contract No. and Disclaimer:

This manuscript has been authored by Savannah River Nuclear Solutions, LLC under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy. The United States Government retains and the publisher, by accepting this article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for United States Government purposes.

Evaluation of Spring Operated Relief Valve Maintenance Intervals and Extension of Maintenance Times using a Weibull Analysis with Modified Bayesian Updating

Stephen P. Harris, Ph.D.
Savannah River National Laboratory
Aiken, South Carolina
stephen.harris@srnl.doe.gov

Emily M. Mitchell
Emory University
Decatur, Georgia
Emitch8@emory.edu

Robert E. Gross, P.E.
Savannah River Nuclear Solutions
Aiken, South Carolina
robert.gross@srs.gov

Prepared for Presentation at
American Institute of Chemical Engineers
2011 Spring Meeting
7th Global Congress on Process Safety
Chicago, Illinois
March 13-16, 2011

UNPUBLISHED

AIChE shall not be responsible for statements or opinions contained
in papers or printed in its publications

Evaluation of Spring Operated Relief Valve Maintenance Intervals and Extension of Maintenance Times using a Weibull Analysis with Modified Bayesian Updating

Stephen P. Harris, Ph.D.
Savannah River National Laboratory
Aiken, South Carolina
stephen.harris@srnl.doe.gov

Emily M. Mitchell
Emory University
Decatur, Georgia
Emitch8@emory.edu

Robert E. Gross, P.E.
Savannah River Nuclear Solutions
Aiken, South Carolina
robert.gross@srs.gov

Keywords: API RP 581, Weibull, Bayes, Spring Operated Pressure Relief Valves

Abstract

The Savannah River Site (SRS) spring operated pressure relief valve (SORV) maintenance intervals were evaluated using an approach provided by the American Petroleum Institute (API RP 581) for risk-based inspection technology (RBI). In addition, the impact of extending the inspection schedule was evaluated using Monte Carlo Simulation (MCS). The API RP 581 approach is characterized as a Weibull analysis with modified Bayesian updating provided by SRS SORV proof testing experience.

Initial Weibull parameter estimates were updated as per SRS's historical proof test records contained in the Center for Chemical Process Safety (CCPS) Process Equipment Reliability Database (PERD). The API RP 581 methodology was used to estimate the SORV's probability of failing on demand (PFD), and the annual expected risk.

The API RP 581 methodology indicates that the current SRS maintenance plan is conservative. Cost savings may be attained in certain mild service applications that present low PFD and overall risk.

Current practices are reviewed and recommendations are made for extending inspection intervals. The paper gives an illustration of the inspection costs versus the associated risks by using API RP 581 Risk Based Inspection (RBI) Technology. A cost effective maintenance frequency balancing both financial risk and inspection cost is demonstrated.

1. Notation

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
CCPS	Center for Chemical Process Safety
MCS	Monte Carlo Simulation
MM	Million
MTBF	Mean Time Between Failures
PERD	Process Equipment Reliability Database
PM	Preventative Maintenance
Proof Test	The practice of pressurizing the inlet of a new or used 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.
PFD	Probability of failure on demand
PRV	Pressure relief valve(s)
R_p	Ratio of proof test pressure to set pressure
RBI	Risk-Based Inspection
RP	Recommended Practice
SORV	Spring operated relief valve(s)
SP	Set Pressure
SRS	Savannah River Site
TP	Test Pressure

2. Introduction

The U.S. Department of Energy's SRS SORV maintenance intervals were evaluated using an approach provided by API RP 581 [1] for RBI technology. In addition, the impact of extending the inspection schedule was evaluated using Monte Carlo Simulation (MCS). The API RP 581 approach is characterized as a Weibull analysis with modified Bayesian updating using SRS SORV proof testing experience. The approach uses the two-parameter Weibull distribution [2], which is a popular distribution for life data analysis.

Initial Weibull parameter estimates contained in the CCPS PERD were updated using the API RP 581 methodology. The methodology was also used to estimate the SORV's PFD, and the annual expected risk. For this purpose, risk is defined as the product of *Demand Rate*, *Vulnerability* (PFD as a function of time), and *Consequence*. *Demand Rate* is quantified by number of events per year, and is qualitatively the frequency of overpressurization on systems with in-service valves. *Consequence* is due to the on-demand failure of a valve, estimated in terms of US dollar costs due to human injury and restoration of the process to its original state.

Results of this study indicate that the current SRS maintenance plan is risk averse, and that cost savings may be attained in certain mild service applications that present low PFD and overall risk. Herein, current practices and recommendations for extending inspection intervals are reviewed. An illustration is provided that contrasts inspection cost versus the associated risk using API RP 581 RBI technology. Also demonstrated is a cost effective preventative maintenance (PM) frequency that balances financial risk with inspection cost.

3. Background

SORV's used in Newtonian fluid services perform an important safety function in the process industries by preventing system pressures from exceeding the maximum system design pressure. Routine pressure relief valve (PRV) inspection and testing are required because the device may fail to relieve overpressure events that can cause failure of the equipment protected by the device, leading to a loss of containment.

To comply with ASME Boiler and Pressure Vessel code [3, 4] Section VIII for unfired pressure vessels, SORV's are required to be inspected, tested and serviced on a periodic basis. These PM intervals are best optimized by studying past performance and proof test data. If insufficient data exist to provide a decision on optimum intervals, confidence may be improved by shortening the SORV's time in service. That, however, is not cost effective over the life cycle of valves. Additionally, if the primary failure mode is neither corrosion nor high stress in service, shortening time in service provides little valve performance improvement.

Consensus codes allow a company or facility to set and adjust maintenance and inspection intervals for PRV's, including the SORV. As such, methods must be developed internally to ensure that risk reduction and cost effectiveness are balanced while providing an adequate safety margin. The industry utilizes a trio of approaches to conduct inspections based on time-in-service, performance, and risk. The time-in-service method is used primarily at SRS but modified qualitatively by performance and risk. Risk, as previously defined, is difficult to quantify with data.

This paper provides an application of RBI methodology at SRS [5]. The principles and general guidelines for RBI are covered in API RP 580 [6] and API 581 provides the methodology to form a risk-based inspection plan as described herein.

4. SRS Pressure Protection Program

When a relief valve is removed from service for PM, proof testing correlates the "as found" lift pressure of the valve to its in-service "on demand" lift pressure performance. A valve whose ratio (R_p) of 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." This means that during an actual overpressure event, failure of the valve to open by 1.5 times the set pressure will challenge process piping and vessel integrity, causing failure on demand.

The confidence in the current SRS program of proof testing and inspection is considered to be highly effective in selecting parameters from API RP 581. SRS operates a local Relief Valve Repair Shop certified by the National Board of Pressure Vessel Inspectors code NB-23 [5] where maintenance forces perform inspection, testing, and repair of approximately 1,200 SORV each year as the valves are cycled in from the field. A valve is released for field installation if the actual lift pressure (proof test) is within $\pm 3\%$ of SP (for ≥ 70 psig set). If a test is outside of this range, the valve is adjusted and then retested [5].

SRS now has over 7000 certified test records in the Computerized Maintenance Management System including both new and used valve tests. "Used" is defined as a relief valve that was

installed and active in a process between inspection times. A summary of used valve data is presented in this paper.

Used valves must first pass an initial external visual inspection before proof testing. If the initial proof test is within 10% SP and the average of the next three tests are within 3% SP, then the valve has passed testing and inspection without requiring further work [5]. Any used valve whose proof testing reveals higher than 1.1 times SP is disassembled for repair. The valve is subsequently reassembled, tested, tagged and returned to the field as "like new."

Guidelines [7] are provided for disposition of each valve based on the proof test results, but the final decision to disassemble and repair is made by National Board certified technicians. Currently, the average PM interval is 3.7 years for used PRV's. Intuitively, longer intervals between maintenance and proof testing should increase the likelihood of a valve being stuck shut on demand. Prediction of a failure on demand as used in API RP 581 is when $R_p \geq 1.3$.

A key assumption of the API RBI 581 methodology is that a bench test of a PRV performed in the as-found condition from a process unit will result in a true determination of the valve's performance on demand. A good inspection program will track the history of inspection and testing of each PRV.

The API RBI 581 method allows for varying degrees of confidence in the inspection. When combined, the pre-test inspection and as-found proof test provide a Pass/Fail evaluation that is given the highest degree of confidence. Conversely, if a valve is inspected and overhauled without a pre-test, a lower confidence level is associated with the validity of inspection results.

The API RP 581 standard provides default values indicating the level of confidence that proof testing will accurately represent in-service PRV performance in an overpressure demand situation. The effectiveness associated with passing the bench test means that there is a certain probability that the valve would have properly opened on demand while in service. By default, a 90% effectiveness carries a 10% probability that the valve would have failed on demand while in service. Accordingly, these probabilities are considered conditional, and reflect the confidence that an inspection result will predict the valve's performance on demand while in service.

5. Inspection Updating using API RP 581

PRV's are classified by service severity as mild, moderate, or severe. Since severe fluid service ASME Section VIII valves are not in use at SRS, the CCPS/PERD database includes proof tests based on mild and moderate Newtonian fluid service ASME Section VIII valves. Included are proof test results of new valves before installation, and over 900 used valves tested between May 2003 and January 2010. A random sample of used in-service valves was incorporated into Inspection Updating with API RP 581, providing estimates of PFD for valves in service at SRS. The estimates were adjusted with the collection of proof test data per the API RP 581 methodology. Used valves in mild and moderate fluid services exhibited differences in proof test results that were irresolvable by frequency of failure. The severities were aggregated in given estimates.

The API RP 581 method is related to a Bayesian approach in that it uses a weighted function of current and past proof test results. When applying it to PRV's, the standard application of Bayes' Theorem resulted in PFD values that were unrealistically high. The equations were modified to include inspection effectiveness in order to produce reasonable results.

5.1. Estimating the Probability of Failure On Demand

The two parameter Weibull distribution [2, 8, 9] is used as a model for estimating PFD. In this approach, as proof test data are collected, the Weibull shape parameter β remains constant, and the characteristic life parameter η is adjusted.

The two parameter Weibull distribution for the probability of failure at t years is defined as:

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

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

The probability density function for the Weibull distribution (1) is:

$$f(t) = \left(\beta/\eta\right)\left(t/\eta\right)^{\beta-1} \exp\left[-\left(\frac{t}{\eta}\right)^{\beta}\right], \quad t \geq 0 \qquad (2)$$

η is measured in years, while β is unitless. The probability of failure by η years is 0.632 (63.2%) regardless of the shape parameter (Equation (1) with $t = \eta$). Initial values for β and η may be determined from plant-specific data if available, or starting with default values indicated in API RP 581.

5.2. Reliability

Suspensions are valves that were tested and did not fail. Reliability (R), is defined as the probability at time *t* that failure will not have occurred by that time. Suspensions affect primarily the η parameter (η increases), with generally little effect on β [8]. Because of this, API RP 581 provides for adjustment of the η parameter to increase or decrease PFD according to proof test results.

The reliability at time t is calculated by:

$$R(t) = 1 - F(t) \qquad (5)$$

For example, when $\eta = 13$ years, $\beta = 2.3$ and $t = 6$ years, $F(6) = 0.155$ from equation (1), and $R(6) = 0.845$.

5.3. Mean Time Between Failures

The mean time between failures (MTBF) is calculated for a Weibull distribution as:

$$MTBF = \eta \cdot \Gamma\left[1 + {}^{1}\!/_{\beta}\right] \qquad (3)$$

where $\Gamma(.)$ is the gamma function. Note that MTBF=η when $\beta = 1$ (the exponential distribution) since $\Gamma[2] = 1$.

The contour plot for MTBF in Figure 1 shows that Eta (η) has a major impact on MTBF, while the impact of Beta (β) is minor over the displayed range for both parameters. This offers justification for holding β constant and updating η as data are collected.

5.4. The Weibull Hazard Function

The Weibull hazard function determines the rate of failure during the characteristic life.

$$h(t) = {}^{f(t)}\!/_{R(t)} = \left({}^{\beta}\!/_{\eta}\right)\left({}^{t}\!/_{\eta}\right)^{\beta-1} \qquad (4)$$

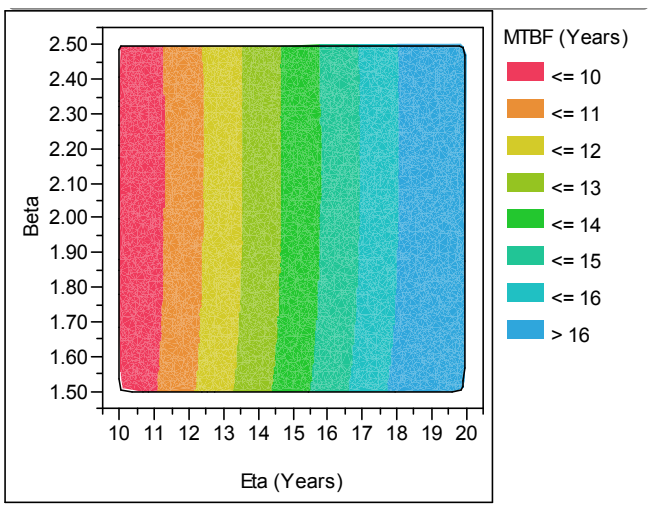


Figure 1: Contour plot of MTBF (years) assuming a two parameter Weibull distribution.

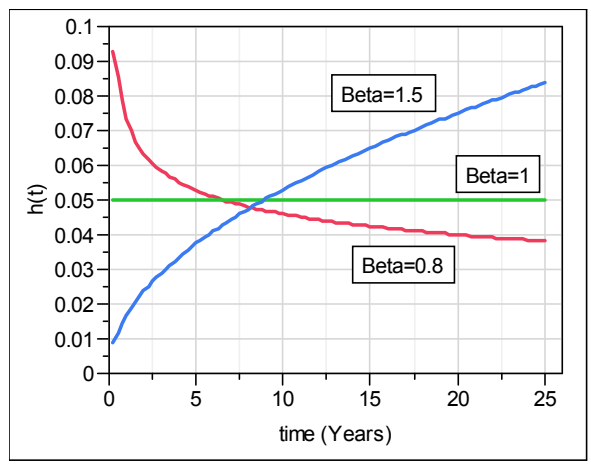


Figure 2: Hazard plot for eta=1.5 years when beta=0.8, 1, and 1.5

5.5. Conditional Probability of Failure

With the hazard plot (Figure 2), we see the following:

a) a decreasing failure rate corresponds to a burn-in period, and occurs when $0 < \beta < 1$.

b) a constant failure rate corresponds to the design life time period, when $\beta = 1$

c) an increasing failure rate corresponds to a wearing out mode, occurring when $\beta > 1$.

Initial estimates of η and β are required to start the updating process. When the PRV passes the inspection, the conditional probability of failure on demand is calculated as follows:

$$F^{cond}(t) = \left(1 - k_{pass}\right) \cdot R(t) \qquad \textit{(Passed inspection)} \qquad (6)$$

where k_{pass} is the confidence factor for the effectiveness of the proof test, specifically that the proof test determines the performance of the valve under a demand situation. As such, k_{pass} is the probability that functioning on-demand valves will pass the proof test. Typical values for highly effective pass, and for highly effective fail (k_{fail}) range from 90% to 95%.
For example, for a highly effective passed inspection at six years with 90% confidence, $(t = 6)$, and $k_{pass} = 0.90$:

$$F^{cond}(6) = \left(1 - k_{pass}\right) \cdot R(6) = \left(1 - 0.90\right) \cdot 0.845 = 0.0845$$

For a failed inspection, the conditional PFD is calculated as follows:

$$F^{cond}(t) = k_{fail} \cdot F(t) + \left(1 - k_{pass}\right) \cdot R(t) \quad \textit{(Failed inspection)} \quad (7)$$

where k_{fail} is the probability of failing on demand for valves failing the proof test. For example, with a highly effective failed proof test at $t = 6$ years, and $k_{fail} = 0.95$,

$$F^{cond}(6) = k_{fail} \cdot F(6) + \left(1 - k_{pass}\right) \cdot R(6) = 0.95 \times 0.155 + \left(1 - 0.90\right) \times 0.845 = 0.232$$

5.6. The Weighted Probability of Failure

API RP 581 weighting factors allow for variations in proof tests, giving more credit to proof tests conducted later in the characteristic life. For a highly, usually, or fairly effective proof test resulting in a pass, the weighted probability of failure can be determined by:

$$F^{wgt}(t) = F(t) - \lambda\left[F(t) - F^{cond}(t)\right]\left(\frac{t}{\eta_{\text{mod}}}\right) \quad (8)$$

where λ is the selected weighting factor and η_{mod} is the modified characteristic life. In Figure 3, the possible values for λ are 0.1, 0.2, 0.3 and 0.4 for determining the weight given to a current passed proof test. For example, with $t = 6$ years, $\lambda = 0.2$, and $\eta_{\text{mod}} = 13$ years.

$$F^{wgt}(6) = F(6) - 0.2\left[F(6) - F^{cond}(6)\right]\left(\frac{6}{13}\right) = 0.155 - 0.2\left[0.155 - 0.0845\right]\left(\frac{6}{13}\right) = 0.149$$

For a highly (also usually) effective fail proof test resulting in a failure

$$F^{wgt}(t) = F^{cond}(t) \quad (9)$$

The Weibull characteristic life is updated as:

$$\eta_{upd}(t) = \frac{t}{\left(-\ln\left[1 - F^{wgt}(t)\right]\right)^{\frac{1}{\beta}}} \tag{10}$$

where $\eta_{upd}(t)$ is the updated characteristic life. For example at $t = 6$ and $\beta = 2.3$,

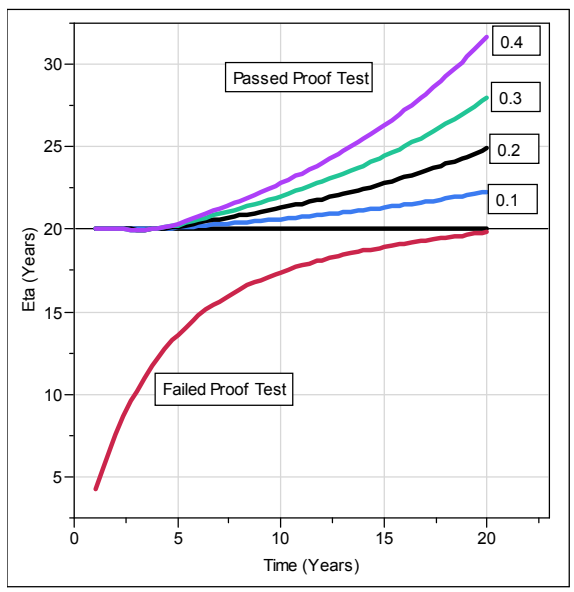
$$\eta_{upd}(6) = \frac{6}{\left(-\ln\left[1 - F^{wgt}(6)\right]\right)^{\frac{1}{\beta}}} = \frac{6}{\left(-\ln\left[1 - 0.149\right]\right)^{\frac{1}{2.3}}} = 13.27 \text{ years}$$

Figure 3 illustrates the impact of a passed or a failed proof test on updating the estimate of η_{upd}, where the initial $\eta = 20$ years, $\beta = 1.5$, and $\lambda = 0.1, 0.2, 0.3$, and 0.4. The y-axis is the updated characteristic life $\eta_{upd}(t)$.

During the updating process, the following must be true:
1) tests for valves less than one year in service are not included in the updating process
2) the characteristic life cannot decrease after a passed proof test, and
3) the characteristic life cannot increase after a failed proof test.

Figure 3: The impact of a single pass or fail proof test result on the current estimate of eta $(\eta = 20)$ for various weight factors: $\lambda = 0.1, 0.2, 0.3$ and 0.4. $(\beta = 1.5)$

Note that
1) For passed inspection at 5 years, $\eta \simeq 20$ years (essentially no change)
2) For failed inspection at 5 years $\eta \simeq 13$ years



6. Statistical Review of SRS Used Valve Proof Test Data

A plot of R_p versus time in service (in years) for 935 used valve proof tests does not display any obvious time trends (Figure 4). However, the time trend may not be apparent because the data are plotted according to the maintenance test times instead of failure times. For valves passing the proof test, it is given that they will fail at some future time. Figure 4, which represents approximately 12% of the used valve proof tests, does show that no failures $(R_p \geq 1.3)$ were recorded within the first 2.5 years in service.

The maintenance time distribution for SRS used valves is displayed in Figure 5. Approximately 25% of the SRS valves are tested in 3-year intervals, 50% by 3.1 years, 75% by 4.7 years. Approximately 1.4% of the valves were tested between 10 and 14 years in service.

The plots and statistics in Figure 6 do not show a statistically significant difference for passed and failed proof tests $\left(R_p \geq 1.3\right)$ for mean time in service for used valves. In reality, there may be an impact of time but it is hidden as a result of the censored nature of the data

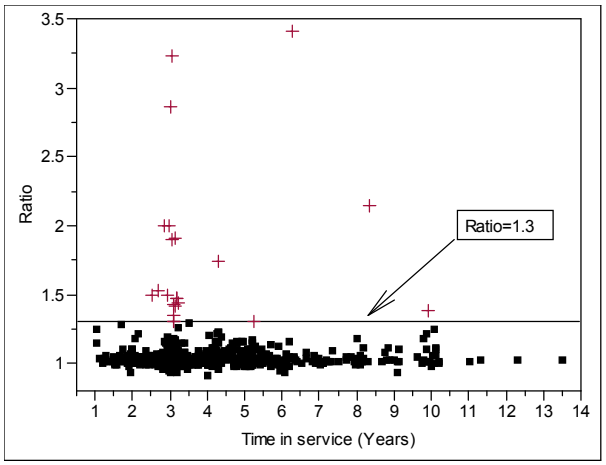


Figure 4: R_P vs. Time in service (years) for the SRS used valve proof tests.

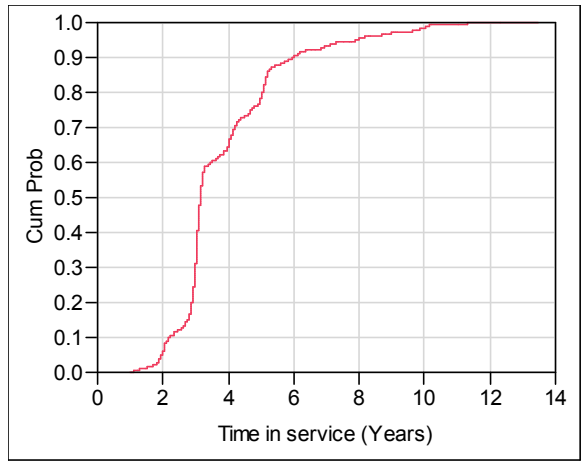
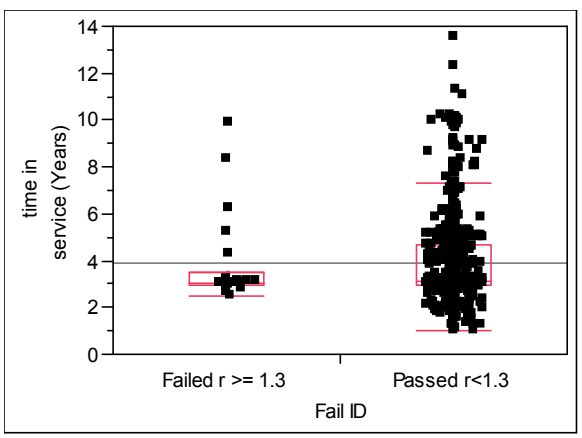


Figure 5: The cumulative maintenance time distribution for time in service for used valves



«**Figure 6**: Box and whisker plots for time in service of failed and passed SRS used valve proof tests

Means and Std Deviations for Time in Service

Level	Number	Mean	Std Dev
Failed $R_p \geq 1.3$	22	3.85	1.92
Passed $R_p < 1.3$	913	3.89	1.77

7. Initial Estimates for the Weibull Parameters

Initial PFD values were obtained based on in-service duration of the valves at the time of inspection, based on the maximum likelihood method [9]. The likelihood function is defined as:

$$L = \prod_{i=1}^{a} f(t_i) \prod_{j=1}^{b} (1 - F(T_j)) \qquad (11)$$

where there are $N = a + b$ proof tests in the database. Of the N valves tested, a have failed their proof test at time $t_i, i = 1,...,a$ based on engineering estimates of their estimated failure times. In addition, b of the valves tested have passed their proof test at time $T_j, j = 1,...,b$. The Weibull distribution function, $F(.)$ (1) is employed, along with $f(.)$, the corresponding density function (2) for failure times.

The usual technique for solving for the distribution parameters involves setting equal to zero the partial derivatives of the natural log of *L* with respect to the parameters, and then solving the resulting equations. For the current application, it is more convenient to use a contour plot for the estimates of η and β in the Weibull distribution.

A contour plot of the likelihood function (L) is presented in Figure 7. Initial estimates of η and β were obtained from the maximum region where $\beta = 2.3$ and $\eta = 20$ years.

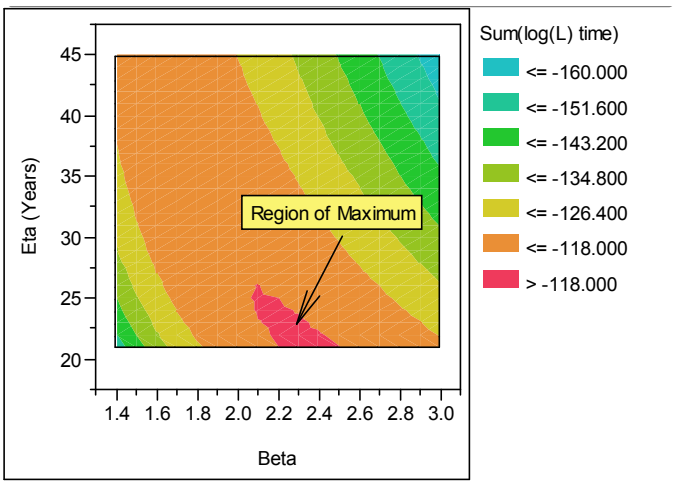


Figure 7: Contour plot of the likelihood function, L, using SRS proof test results.

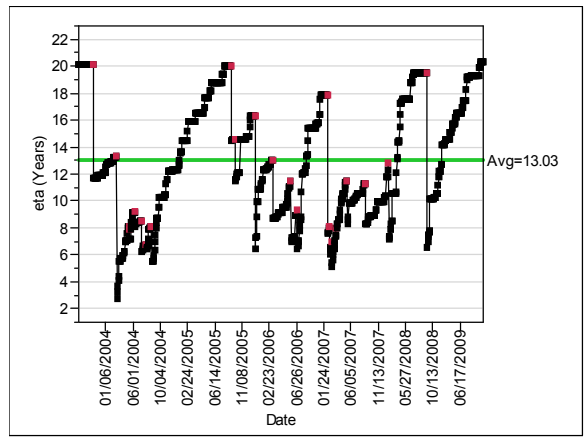


Figure 8: Updating eta based on SRS used valve proof tests

8. Application of API RP 581 and Monte Carlo Simulation Results

The API RP 581 methodology was applied to SRS used valve proof test data with the initial values of $\eta = 20$ years, and $\beta = 2.3$ for the Weibull distribution. As the first failure was realized, the drop-off in eta was dramatic (Figure 8). The plot points color coded red represent valve proof test failures at $R \geq 1.3$. The maximum eta over the time period was approximately 20 years. The eta plot in Figure 8 essentially is a scaled MTBF plot since from equation (3), $\eta \simeq (1.129) \times (MTBF)$ with $\beta = 2.3$.

Four PM plans were evaluated in the MCS: the current site-wide plan, and the current site-wide plan extended by 1, 2 and then 3 years. Each of the plots in Figure 9 contains 250 of 10,000 available data points to show the impact of API RP 581 updating. As the inspection interval is increased, η, or equivalently the MTBF, increases.

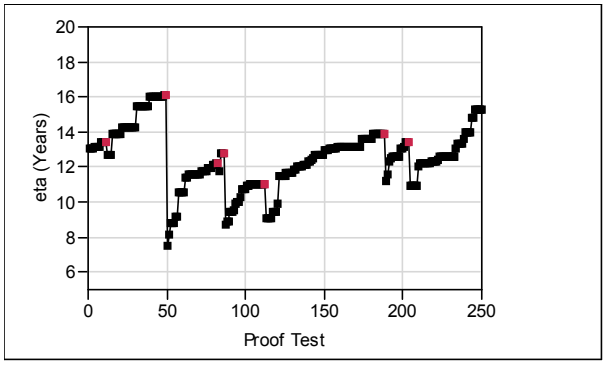
API RP 581 updating was seen to be conservative, with $\eta = 21$ years for the MCS—substantially higher than the estimated mean value of eta. Specifically, the mean value for eta for the current site-wide plan was estimated to be 13.5 years, 14.1 years for the current PM plan extended by one year, and 15.0 years for the current plan extended by two years.

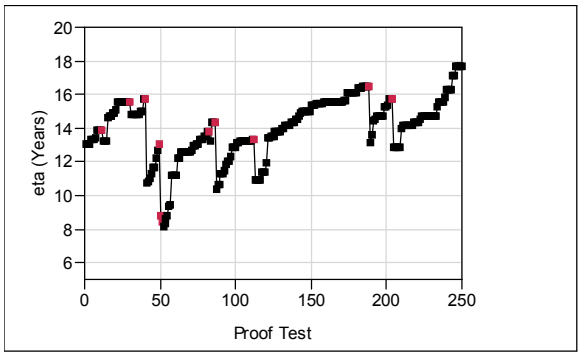
The average inspection time is 3.7 years for the current site-wide PM plan. The inspection cost per proof test is approximately $2,700. A demand frequency of 0.01/year was used in the simulation. The assumed population of in-service valves was 5,000. The expected number of demands per year was calculated as $5000 \times 0.01 = 50$. The loss distribution from over-pressurization was 1 MM, 5 MM, and 20 MM with probabilities 0.50, 0.30, and 0.20, respectively.

Annual cost of testing for the current site-wide plan is approximately 3.65 MM per year for 5,000 in-service valves, while the estimated mean risk is 5.14 MM per year (Table 1). Table 1 shows that for an inspection cost decrease of 0.78 MM, risk was increased by 2 MM for the difference between the current PM intervals and a one year increase.

Figure 9: Snapshots of a 10K Monte Carlo series of eta updating for simulated time to failure ($\beta = 2.3$, and η =21 years)

right: the current valve maintenance plan
bottom left: current plan extended 1 year
bottom right: current plan extended 2 years





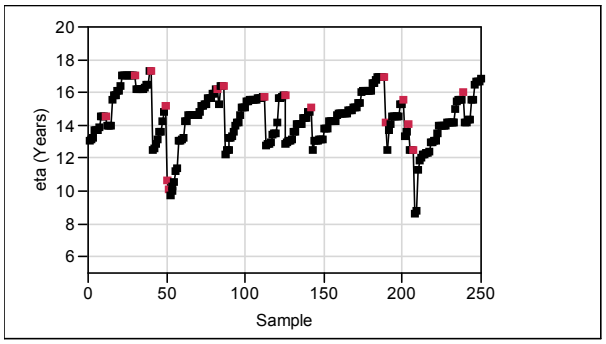


Table 1
Financial Risk of extending Preventative Maintenance Intervals

Maintenance Plan	Mean Maintenance Years	# Demands/ Year	Increase in Risk (MM $)/ Year	Total Risk (MM $)/ Year	Inspection Cost (MM $)/ Year	Total Cost (MM $)/ Year
Baseline	3.7	50	n/a	5.14	3.65	8.79
Baseline Extended 1 Year	4.7	50	2.06	7.20	2.87	10.08
Baseline Extended 2 Year	5.7	50	3.03	8.17	2.37	10.54
Baseline Extended 3 Year	6.7	50	3.41	8.55	2.01	10.57

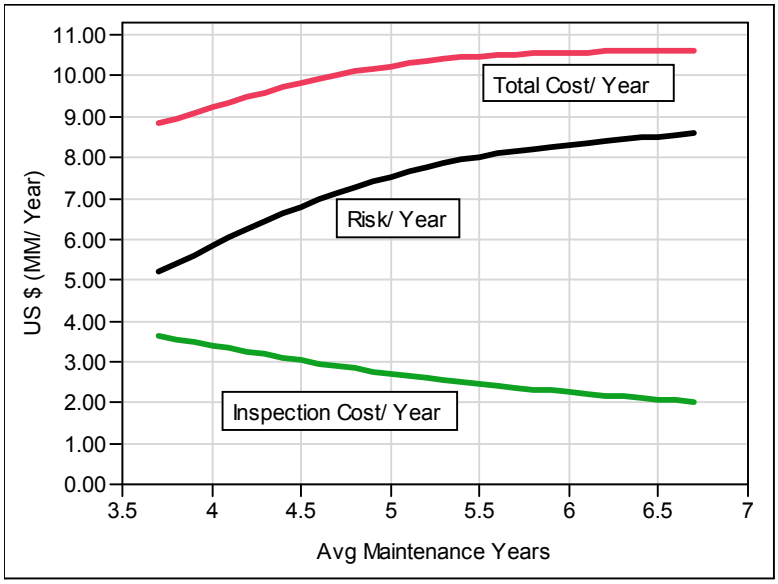


Figure 10: Risk, Inspection Cost, and Total Cost of inspection for extending maintenance intervals

A risk target is defined as the level of acceptable risk for inspection planning purposes and can be developed based on internal guidelines for risk tolerance. The level of acceptable risk can vary between companies. At SRS, current PM intervals can be extended by half a year and still fall within a target risk of $6 MM (Figure 10). The total cost (Risk + Inspection) increases $1.3 MM for extending the PM intervals up to one year. In implementation of these results, cost savings may be attained in certain mild service applications that present low PFD and overall Risk.

9. Conclusions

The API RP 581 methodology provides a nationally recognized process to analyze test data that not only considers inspection performance, but also includes the estimated demand rate and probability of failure on demand in the risk-based decision process. The methodology could be used at SRS to validate SORV PM intervals. Currently at SRS, a time-based approach is employed, and a risk-based approach is used for guidance in adjusting the intervals. Ideally, only zero risk is acceptable, however non-zero risks are a reality and must be minimized in production facilities. The API RP 581 method offers optimization of risk to inspection cost when making operating decisions.

For the past five years, the SRS Pressure Protection Program has endorsed individually-justified increases in PRV maintenance intervals based on an accumulation of passed/failed proof tests. Overall, the current program at SRS appears to conservatively reduce the risk of a valve's failure on demand. Moreover, there is only a marginal difference between the reduction in the cost of testing relative to the increased risk in extending current PM intervals up one year. Intervals in specific cases—especially mild service—could be extended by one to two years and still fall below the target risk level.

The next step at SRS is to identify sub-groups of valves, like nitrogen service valves with set pressure in the 300-1,000 psig range, for applying API RP 581 with greater precision. Refinements may be made in characterizing the demand rate and the consequences ($ loss) of an actual failure on demand while in service.

10. References

[1] API RP 581 Risk-Based Inspection Technology, Section 7 Pressured Relief Devices, American Petroleum Institute (API) Recommended Practice 581, second edition, September 2008.

[2] Abernethy, R.B. (2004). "The New Weibull Handbook", Robert B. Abernethy, North Palm Beach, Fl 33408.

[3] ASME B31.3 Pressure Piping Codes, American Society of Mechanical Engineers, New York, NY.

[4] ASME Boiler and Pressure Vessel Code (B&PV), American Society of Mechanical Engineers, New York, NY.

[5] ANSI-NB-23, National Board Inspection Code, The National Board of Boiler and Pressure Vessel Inspectors, Columbus, OH.

[6] API RP 580 Recommended Practice for Risk-Based Inspection, American Petroleum Institute, Washington, D.C.

[7] Pressure Equipment Protection Requirements, SRS Engineering Standard 15061, Rev 6, 08/01/2009, Pressure Protection Technical Committee.

[8] Nelson, W.B. (1982), "Applied Life Data Analysis", New York, John Wiley & Sons.

[9] Lawless, J.F. (1982). “Statistical Models and Methods for Lifetime Data,” Wiley, NY.

[10] Gross, Robert E., Harris, S. P., (2008) “Analysis of Safety Relief Valve Proof Test Data to Optimize Lifecycle Maintenance Costs,” Proceedings of the 2008 Annual Reliability and Maintainability Symposium (RAMS), Las Vegas, NV. January 28-31, 2008.

Acknowledgements

Research for this paper was performed by Emily M. Mitchell while on an internship in Computational Sciences at the Savannah River National Laboratory during 2010. Ms. Mitchell received her bachelor’s degree in mathematics and religious studies from the University of South Carolina and is currently pursuing a PhD in Biostatistics at Emory University.

This document was prepared in conjunction with work accomplished under the U.S. Department of Energy Contract No. DE-AC09-08SR22470. Portions of the publication were prepared and funded under an agreement with the U.S. Government. Neither the U. S. Government or its employees, nor any of its contractors, subcontractors or their employees, makes any express or implied: 1. warranty or assumes any legal liability for the accuracy, completeness, or for the use or results of such use of any information, product, or process disclosed; or 2. representation that such use or results of such use would not infringe privately owned rights; or 3. endorsement or recommendation of any specifically identified commercial product, process, or service. Any views and opinions of contributing authors expressed in this work do not necessarily state or reflect those of the United States Government, or its contractors, or subcontractors.