This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-96SR18500 with the U. S. Department of Energy.

Proceedings of ASME PVP 2006 / ICPVT-11 Conference
Pressure Vessel Technologies for the Global Community
July 23 – 27, 2006 Hyatt Regency Vancouver, Vancouver, BC, Canada

PVP2006-ICPVT11-93109

EXTENDING PRESSURE RELIEF VALVE INSPECTION INTERVALS BY USING STATISTICAL ANALYSIS OF PROOF TEST DATA

Robert E. Gross, Principal Engineer
Westinghouse Savannah River Company
Aiken, South Carolina 29802
United States of America
803-725-0938
fax 803-725-9036
Email robert.gross@srs.gov

Stephen P. Harris, PhD
Westinghouse Savannah River Company
Savannah River National Lab
Aiken, South Carolina 29802
United States of America
803-725-5304
Email stephen.harris@srnl.doe.gov

ABSTRACT

This paper correlates as-received test results with current inspection intervals and presents conclusions based on statistical analysis. During the past three year period, over 500 used valve proof test records from a site population of 3500 safety relief valves were acquired and reviewed. Collection and analysis of spring-loaded relief valve test data continues with the goal being to increase the test intervals within guidelines, reduce costs, and maintain safety margins. Based on current inspection intervals related to proof test data, time in service appears to have a minimal effect on valve performance. Seat material and inlet size are identified as having a statistically significant impact. An increase in TP/SP of 1-3% per year was noted for soft seat, small inlet sizes. Photographs of failed valve internals and discussion of failure causes are included.

INTRODUCTION

The sole purpose of a safety relief valve is to protect life and property. Spring-loaded safety relief valves are probably the most reliable type of pressure relief device in use today.[1] The safety relief valve's construction is relatively simple and robust, and yet it has been described as a delicate instrument. Inspection and maintenance of such a critical item must be capable of arresting the known failure modes and must be cost effective. This paper presents a statistical analysis of as-received pop test results and how it is used to establish inspection intervals. A description of the spring-loaded safety relief valve inspection and test methodology is provided in American Petroleum Institute API Recommended Practice 576.[2]

NOMENCLATURE

ASME *B&PVC*– the American Society of Mechanical Engineer's Boiler and Pressure Vessel Code.

Safety Relief Valve/ Pressure Safety Valve (PSV) – a pressure relief valve actuated by inlet pressure exhibiting a rapid opening or "pop" action. Used for air, steam, liquid or gas services.

Set Pressure (SP) – the pressure at which the relief valve is expected to lift, pop or relieve system pressure. SP is indicated on an attached tag per ASME Boiler and Pressure Vessel Code UG-129 of Section VIII, Division 1 (Pressure Vessels) UV-NB stamped valves. Adjustment is made by applying pressure to a compression spring over the valve disc.

Test Pressure (TP) – The value of increasing inlet pressure which moves the disc rapidly off the nozzle (seat) causing the valve to open.

TP/SP, the ratio of Test Pressure divided by Set Pressure. A value of TP/SP=1.0 would indicate the test pressure is equal to the original set pressure.

Pop Pressure – see Test Pressure above

Proof Test Pressure – see Test Pressure above

Time in Service – Time installed is typically expressed in years. Calculated from the original test date to time of re-test (at the end of the test interval).

BACKGROUND

This site maintains approximately 3500 air, gas, liquid and steam Pressure Safety Valves (PSV) with an average 3.5 year test/replacement frequency. The test intervals are based on engineering guidelines that suggest a range of values (1-7 years) from which to choose an appropriate interval. Approved test intervals and maintenance work histories are kept in the site's computerized maintenance management system (CMMS) database.

Table 1
Data Sets Analyzed

Test results on used valves from May 2002 to April 2005	
All Data Sets Excluded	**Reason**
New valves	Desire in service performance only
Leaked and no "pop"	TP/SP is not calculable
Retests (after servicing)	Would not reflect the in service conditions.
Damaged valves	Valves damaged during removal or transport would not reflect in service conditions
Data Set #1 excluded	
High TP/SP with cause	Prevent masking of other causes of variation in valve performance
Data Set #2 excluded	
Facility 1 and 2 data High TP/SP	Valve swapping (bench stock) routinely used
Data Set #3 excluded	
Facility 1 and 2 data High TP/SP and Bench Stock	Valve swapping is routine
First Pop minus Average (<1%)	Valves were stroked prior to as-found tests

Many of the current test intervals tend to be conservative based on a perception of past valve performance and what is known of industry practices. Inspection, test, and replacement frequencies are difficult to apply consistently. From May 2002 to April 2005, Savannah River Site inspected and tested about 105 valves per month (vpm). Of that, ~20 valves per month are being serviced and returned to the field. New replacement valves, valves retested after maintenance, and valves that leaked comprise the majority of work. A continuous improvement goal was set at 75 vpm for an anticipated reduction of 30 PSV tests per month. That reduction would be gained by increasing the time between tests. Current guidelines this site follows are: Air and Gas service tested every 2-5 years, Section VIII Steam valves tested 1-3 years, Steam Pilot valves tested every 1-2 years, Refrigerant, Domestic Water Heater, and Dewar Vessel PSV tested every 5 years, Oxygen inspected every 2-4 years, Non-Code soft-seated with < ¾" inlet are tested at 1-2 years. To ensure that process and personnel safety would not be compromised, an engineering evaluation was performed to correlate inspection intervals with various valve demographics. In a previous paper the authors presented preliminary analysis of PSV reliability based on collected proof test data.[3] At the time, statistical analysis led to the conclusion that the ratio TP/SP was not a strong function of time in service for the one-to-five year time frame. The results presented in this paper support the earlier work and in addition identify demographics correlated with aging.

Table 1 delineates what data is actually included in the data sets statistically analyzed. The entire analyzed data set consisted of 419 data points. Valves that leaked and did not pop numbered 10 and those damaged during removal from a process numbered 4. Data set #1 excluded 4 valves that had TP/SP > 1.5 and through investigation were attributed a failure cause. Causes of failure included rust and debris, insect nests, galling parts, sticking due to process deposits, and spring washers corroded to the valve stem. Data set #2 excluded many valves due to a concern over replacing or swapping valves. Swapping is the practice of buying two identical valves for one process location. When the required test interval is reached, the in-service valve is removed from the process. Prior to removal, a like valve from "under the bench" that has already been tested is tagged as the replacement. The practice limits system downtime to minimum. Suspect swapped valve test data points were excluded from the larger set before performing various regressions so we could assess any statistical differences. Data set #3 was another trial in which we primarily excluded valves with external lifting levers to address the concern of stroking or actuating valves during the removal process. Many times the lifting lever is used to verify that the system is in fact de-pressurized prior to removing the PSV from a process line or vessel regardless of gauge indication. Conclusions based on data set #2 will be discussed in following sections since they were essentially consistent with those reached using data set #3.

DATA REVIEW

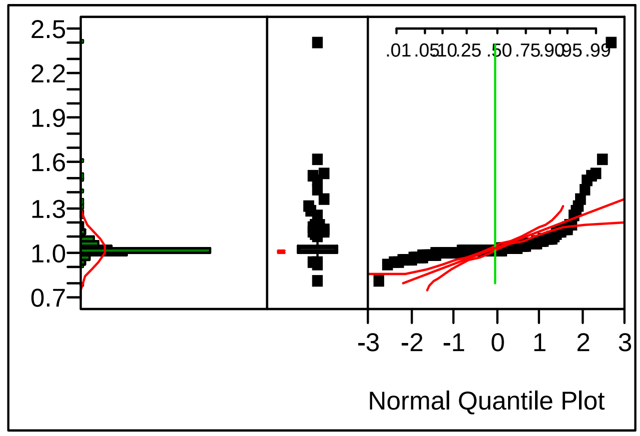
Valves from 21 different manufacturers are represented in the data set with 10 manufacturers accounting for approximately 90% of the valves tested. As mentioned earlier, several facilities on site had a policy of valve swapping from stock which may have impacted the statistical results that were based on estimates of time in service. To lower the impact of this, valves from these facilities where the practice was prevalent were removed from the data set resulting in 319 valves for the statistical analyses presented in this report (Data Set #2). In addition, the approved test interval was used as a surrogate for time in service when record of the last test date was lost.

Valve stroking is occasionally done prior to or during the removal process to verify depressurization. This essentially amounts to simulating a 1st pop. Stroking prior to valve testing leads to a downward bias in testing for a 1st pop pressure. In particular, if a valve is stroked the valve shop 1st test pressure will typically be closer to the average lift pressure of pops 2, 3 and 4. To investigate if stroking influenced the statistical results, valves for which the first pop was within 1% of the average lift (184 valves) were temporarily removed from the data set. The statistical conclusions did not change.

The distribution of the TP/SP ratios is displayed in Plot 1 where TP is the valve shop 1st test pressure and SP is the set pressure. The plot contains a vertical histogram, an outlier box plot and a normal quantile plot for the TP/SP ratios. The plot indicates that the ratios are highly skewed to the right (TP/SP>1) and not normally distributed. In fact, a log-normal distribution did not provide a substantially better fit to the TP/SP data (not displayed). The TP/SP values range between 0.79 and 2.4 with a median value of 1.01.

The large TP/SP=2.4 value displayed in Plot 1 arose from a hard seat, 1 inch inlet, gas service valve with a set pressure of 15 lbs. The ratio TP/SP stabilized to 1.0 after repeated testing. Possibly micro welding or galling of stainless disc and seat materials caused the high initial test pressure. The second largest TP/SP=1.61 was a hard seat, 1 inch inlet steam service valve with a set pressure of 90 lbs. Both its inlet and outlet were found to contain debris. The causes of the other high TP/SP down to 1.12 were unknown but the TP/SP ratio stabilized after repeated testing for every valve.

Plot 1
Distributional Plot of TP/SP Ratios for Data Set #2



The quantiles for the TP/SP ratios are displayed in Chart 1. Approximately 50% of the ratios lie between 1.0000 and 1.0400. In addition, 90% of the ratios were found to lie below 1.0909 (not displayed in Chart 1).

Chart 1
Quantiles for TP/SP Ratios for Data Set #2

Quantile		TP/SP
100.0%	maximum	2.4000
75.0%	quartile	1.0400
50.0%	median	1.0083
25.0%	quartile	1.0000
0.0%	minimum	0.7941

The average ratio displayed in Chart 2 is 1.034 with a 95% confidence interval of (1.022, 1.046). The average for the larger data set without excluding the facilities where valve swapping was prevalent is also 1.034 with a 95% confidence interval of (1.023, 1.045).

Chart 2
Moments for TP/SP for data Set #2

Statistic	TP/SP
Mean	1.034
Std Dev	0.111
Std Err Mean	0.0062
upper 95% Mean	1.046
lower 95% Mean	1.022
N	319

Approximately 45% of the tested valves were used in air service while approximately 23%, 18% and 15% were used in gas, liquid and steam services (Chart 3). Over all service conditions, 53% were hard seated while 47% were soft seated valves. However, these ratios substantially differ by service condition. For example, in steam service 94% were hard seated while 6% were soft seated.

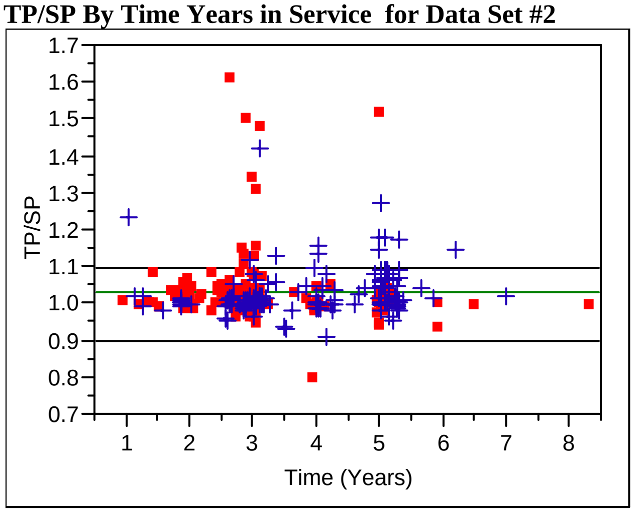
Chart 3
Contingency Analysis of Seat Material By Service

	Hard Seat	Soft Seat	Total
AIR Total % Col % Row %	**86** 26.96 50.89 60.14	**57** 17.87 38.00 39.86	**143** 44.83
GAS	**18** 5.64 10.65 24.66	**55** 17.24 36.67 75.34	**73** 22.88
LIQUID	**21** 6.58 12.43 37.50	**35** 10.97 23.33 62.50	**56** 17.55
STEAM	**44** 13.79 26.04 93.62	**3** 0.94 2.00 6.38	**47** 14.73
TOTALS	**169** 52.98	**150** 47.02	**319**

STATISTICAL ANALYSIS

The purpose of the statistical analysis was to investigate the relationship between TP/SP and time and also to determine if certain combinations of demographic conditions lead to significant aging. A plot of TP/SP by time is displayed in Plot 2 along with a fitted trend line. The slope (change in TP/SP by year) is negligible (0.06%) and in fact is not significant. However, various subsets of the data by service, seat material, pressure or manufacturer, etc. were statistically analyzed[4] to reveal if an aging trend existed over time. To explore the possibilities over 100 regressions were performed using various combinations of the population demographics.

Plot 2
TP/SP By Time Years in Service for Data Set #2



Blue cross: soft seat
Red square: hard seat

Linear Fit TP/SP = 1.032 + 0.0006Time (Years)

Summary of Fit

R-Square	0.00004
Observations	319

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	1.032	0.0191	54.1	<.0001
Time (Years)	0.0006	0.0052	0.11	0.91

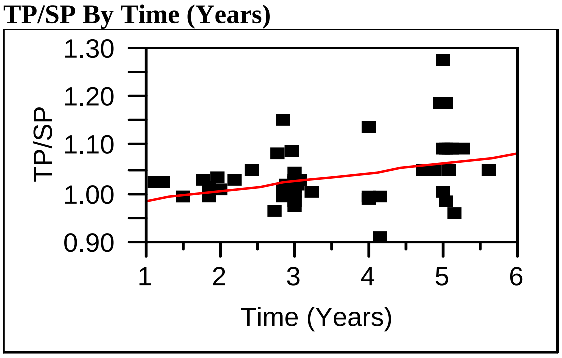
There was no change in TP/SP over time for most evaluations. However, an aging trend was revealed in Plot 3 for TP/SP vs. time for liquid service where the average gain in TP/SP is significant at about 2% per year. For example the average 100 psig liquid relief valve pop pressure would be 102 psig after one year, 104 after two and 106 psig after 3 years in service. This slope was predominately due to the influence of soft seat small inlet valves (<¾"). Even so, time in service is not a reliable predictor of valve performance since the variation in proof test values explained for liquid service is only 15% as measured by R-Square (Plot 3). A significant aging trend was not found for gas, air, or steam service.

The statistical analysis found that the aging effect for Air and Gas spring loaded pressure relief valves across all manufacturers, inlet sizes and seat materials is at most 1% per year with 95% confidence (Plot 4a). However, the amount of variation explained by time is minimal (R-Square = 2%). The greatest aging trend was found for soft seat, liquid service, small inlet valves (<¾") at 2.3%/year with minimal variation (21%) explained by time (Plot 4b). Approximately 88% of the soft seat, small inlet, liquid service, population consists of ¼" inlet valves. The aging trend in soft seated valves appears to increase after about 3 years in service indicating a hardening of the elastomeric materials that comprise the seat.

EVALUATION

Time in service generally has a minimal effect on valve performance over the 5-6 year time frame of the study. The average estimated increase in TP/SP is at most 2.3 % year, but the amount of variation explained by time is minimal (less than 21%). For the soft seated valves we would expect to see an indication of aging or hardening of the seat materials. The data in Plot 2 shows that departure from the used valve test acceptability of SP +/- 10 % remains minimal after 5 years in service except for soft seat valves. Many of the site's PSV test intervals tend to fall at the lower value within the range. Those valves should be extended to longer intervals with the proper justification. Guidelines were revised recently to allow up to 7 years between tests for Air and Gas service if protected from the weather and if the last proof test was within 10% of set pressure.

Plot 3
LIQUID
TP/SP By Time (Years)



Linear Fit
TP/SP = 0.9692849 + 0.0189633 Time (Years)

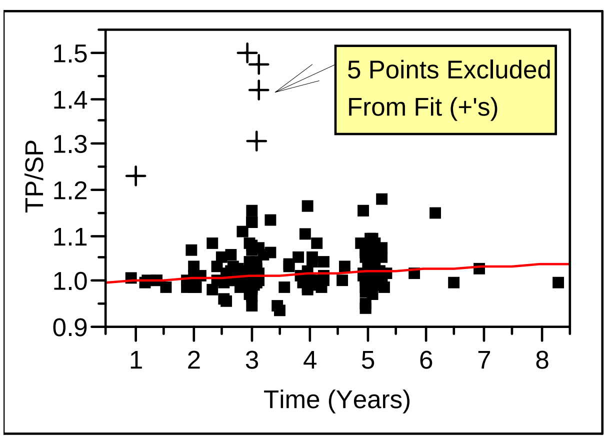
Summary of Fit

R-Square	0.152378
Observations	56

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9692849	0.021635	44.80	<.0001
Time (Years)	0.0189633	0.006086	3.12	0.0029

Plot 4a
Air and Gas Service, All inlet sizes and seat materials
TP/SP by Time (Years)



Linear Fit
TP/SP = 0.9985433 + 0.0051245 Time (Years)

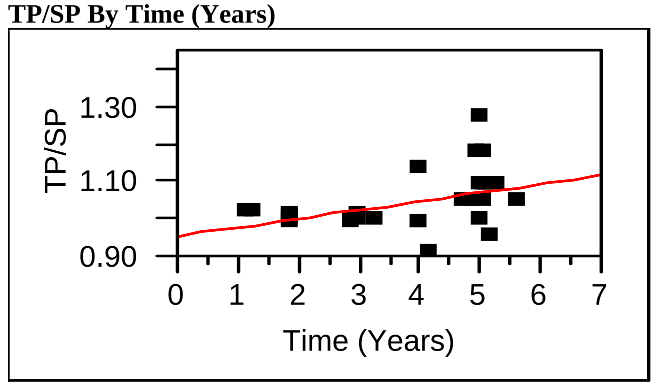
Summary of Fit

R-Square	0.023646
Observations	210

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9985433	0.008878	112.48	<.0001
Time (Years)	0.0051245	0.002283	2.24	0.0259

Plot 4b
ID= Soft Seat : LIQUID : Small Inlet < 0.75"
TP/SP By Time (Years)



Linear Fit
TP/SP = 0.9553326 + 0.0231851 Time (Years)

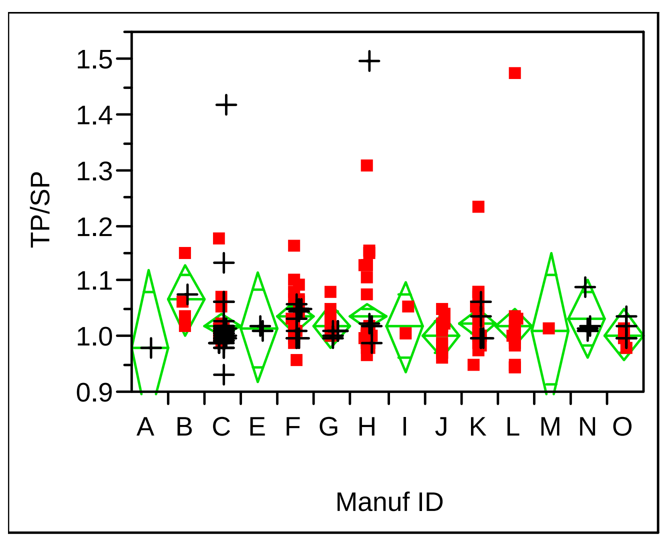
Summary of Fit

R-Square	0.207137
Observations	32

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.9553326	0.032935	29.01	<.0001
Time (Years)	0.0231851	0.008282	2.80	0.0089

Plot 5
TP/SP for Air and Gas Service By Manufacturer ID



1 Outlier Deleted: TP/SP=2.4, Mfr ID= O, Gas,1" Inlet
Air service red square
Gas service black cross

Plot 5 compares air (Red) and gas (Black) service by manufacturer. There is no statistical difference in the average TP/SP between manufacturers as displayed by the overlapping mean diamonds using the combined air and gas TP/SP ratios. Consequently it is presumed that a TP/SP value at test interval 1, 2, 3, 4 or 5 years would have the same average for any manufacturer. This addresses the concern for “early failure”, or the supposition that if a valve failed test at 3 years, it might have actually failed after one year in service.

FAILURE INVESTIGATIONS

The cooling water valve in Figure 1 was in service at the Savannah River Site. It was a 1" inlet, 1" outlet, valve with a set pressure of 90 psig operating at a temperature of 112 degrees F. The test date was 7/29/04. The lift lever is packed. Its capacity rating is 624 Lb per hour. The first, second, third and forth pops were 145 psig, 92 psig, 93 psig, and 93 psig, respectively. The valve would not re-seat leak tight after the first pop. The re-seat pressure was 60 psig and blow down was 32/33 psig. The following photograph, Fig 1 was taken in the valve shop prior to cleaning and refurbishment.

Figure 1 Bronze body, stainless disc holder, disc, spring washers and nozzle with bronze guide

The as found condition of this valve is shown in the photograph. No apparent damage or wear marks were visible. There appeared to be no corrosion or buildup on any of the sliding parts. Yet, the cause for high first pop pressure and settling back to set pressure needs to be understood. Disc holder-to-guide and spring washer-to-stem clearance are what we traditionally think of as sticking points. According to our valve shop mechanics, on the test stand this valve was leak tight up to the 1st pop pressure of 145 psig. After the first pop, the valve would not re-seat, but the next three pops were within ASME tolerance for set point of a new valve (90 psig +/- 3 %). Fig 2 is a closer view of the disc, disc holder and deposits from the cooling water system. One theory for the high proof test developed from an MIT paper was that the seat and disc may have micro-welded, diffusion bonded, or galled together.[5] Further research using scanning electron microscope and X-ray fluorescence spectroscopy (XRF) shown in Fig 3 verified the disc was made of copper-nickel and the nozzle seat made of 302 series stainless steel. No surface distortion was found that would indicate galling or metal-to-metal adhesion. The elemental composition of deposits adhering to the disc surface are listed in Table 2.

Figure 2 Disc and Disc Holder showing deposits in the seating area

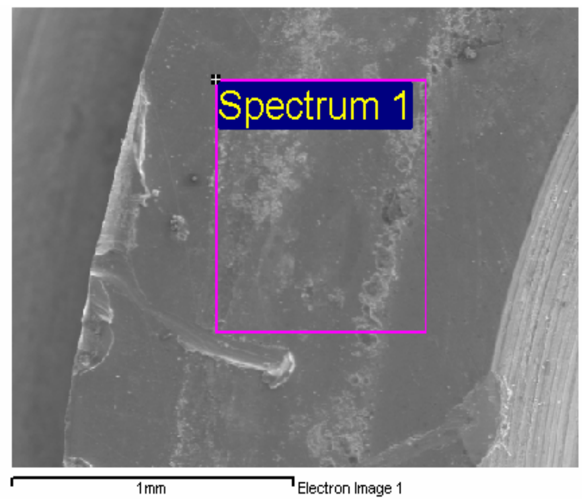


Figure 3 As-found disc prior to cleaning

Element	Weight %	Atomic%
O K	12.34	34.09
Si K	0.56	0.87
P K	0.35	0.50
S K	0.22	0.30
K K	0.36	0.40
Cr K	0.46	0.39
Mn K	0.94	0.76
Fe K	7.78	6.15
Ni K	52.03	39.16
Cu K	24.97	17.37
Totals	100.00	

Table 2. Elemental analysis of deposits on the disc

Table 2 indicates high % oxygen by weight in the surface deposits. After cleaning, the spectrum indicated 69% Nickel and 30% Copper.

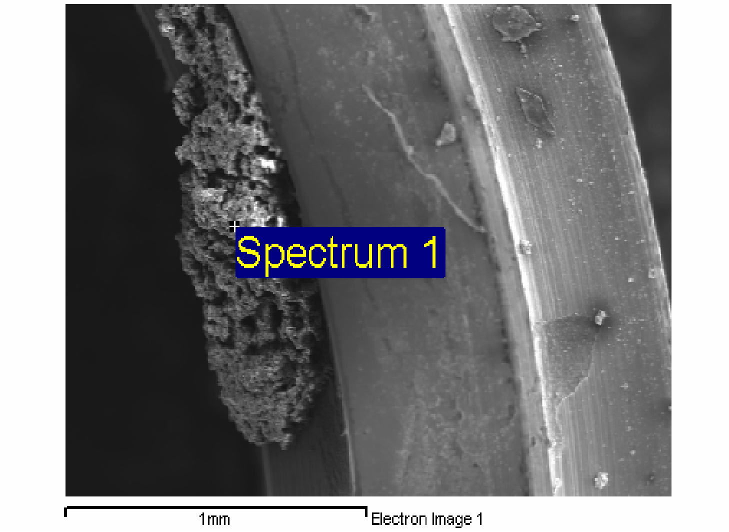


Figure 4. Valve nozzle surface prior to cleaning.

An XRF Spectrum 1 the nozzle in Fig 4 indicated the presence of oxygen, calcium, chlorine, phosphorous, silicon, titanium and iron (60%). We deduce that local oxide deposits present on the seat and disc made necessary an application of additional force to separate the two surfaces. Once the two surfaces were separated at the first pop, the adhesive force was eliminated and the valve tested three more times at the original set pressure.

Figure 6. Chill Water Service

This valve was installed in chilled water service for 10 years without retest because the 5-year test was overlooked. Corrosion buildup and broken spring were the result.

Figure 7. Steam Service
This particular 165 psig set point steam relief valve had been in service for 6 years before needing a rebuild. Every two years it was brought back to the shop and passed proof testing. At the third cycle, it proof tested at 154 psig but the seat leaked and was then repaired.

OVERALL PERFORMANCE SUMMARY

The following percentages were based on the original data set included leaking and damaged valves.

- 1.4% leaked on the test stand and would have relieved low in service
- 4.5% failed High from 110-120 % of Set Pressure
- 6.4% tested >110% but <150% of Set Pressure
- 1.9% classified as "stuck shut" TP/SP $\geq$ 1.5
- Estimated probability of relieving at less than 1.2 SP during an overpressure is 95.7%
- Overall probability of relieving at less than 1.5 SP during an overpressure event 98.1%

RECOMMENDATIONS

1. Protect valves exposed to weather by using bug screens, packed levers, rain hats, sheds, or awnings.
2. Specify high quality hard-seated valves when possible.
3. Utilize corrosion resistant materials where feasible on the discharge side, i.e., spring, washers, stem, disc, and disc holder. Even though not exposed to system fluids, corroded and frozen discharge components are a major contributor to failure statistics.
4. Address the galling potential when using stainless steel parts together e.g., Type 304 disc, disc holder, stem and nozzle.
5. Install a parallel pressure relief device, for example a rupture disc to significantly improve probability of success.

CONCLUSIONS

Approximately 11% of the valves failed to proof test within 0.9 – 1.1 x SP range. Failures were investigated and a number of them are shown in this paper and in an earlier publication.[3] The most common failure cause is corrosion of the valve materials on the outlet side. Either spring washers seized to the stem, the spring failed or foreign material became lodged at the valve inlet / outlet. This analysis found that the aging effect for Air and Gas spring loaded pressure relief valves across all manufacturers, inlet sizes and seat materials is at most 1% per year with 95% confidence. Therefore, Air and Gas PSV will be extended to 5 and 7 year retests in most cases unless past history, the location, risk analysis, or a harsh environment prohibits it. Section VIII Steam valves are being extended for up to 3 years based on the data analysis. Again, research into the individual history of the last 2 or 3 proof tests weighs heavily in the decision to extend. Non-Code soft-seated liquid reliefs with < ¾" inlet could be extended to 3 or 4 years based on the findings. With aging approximately 2% / year, an average increase of 9% +/- 2% would be predicted at the end of 4 years. Individual valves may vary substantially from the average.

ACKNOWLEDGEMENTS

George Antaki and Scott Tutak, *Savannah River Site Pressure Equipment Protection Committee*

Frank Keelty, SRS *Six Sigma Black Belt*

Shirley Hightower, *Publication Services*

REFERENCES

1. Lester Millard, "Safety Relief Valves Protecting Life and Property", Hitma Group, Published by Valve World, 2003
2. Inspection of Pressure-Relieving Devices, API Recommended Practice 576 Second Edition, December 2000, American Petroleum Institute, Copyright API.
3. R.E. Gross, "Reliability Testing of Relief Valves", ASME-PVP-VOL.477, PPV2004-2610 Design and Analysis of Pressure Vessels, Heat Exchangers, and Piping Components, July 25-29, 2004, San Diego, California.
4. SAS Institute, Inc., JMP™ Version 5 Statistics and Graphics Guide, SAS Institute, Inc., Cary NC, 2002.
5. JJ Bikerman (MIT), "Solid-To-Solid Adhesion", Fundamental Phenomena in the Materials Sciences, Vol. 2, Surface Phenomena, Eds. L.J. Bonis and H.H. Hausner. Proceedings of the Second Symposium on Fundamental Phenomena in the Materials Sciences, January 27-28, 1964, Boston, MA.