Contract No:

This document was prepared in conjunction with work accomplished under Contract No. DE-AC09-08SR22470 with the U.S. Department of Energy.

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SRNL-STI-2013-00178

ASME 2013
Pressure Vessels and Piping Conference
July 14-18, 2013, Paris, France

PVP2013-97031

STATISTICAL PERFORMANCE EVALUATION OF SOFT (ELASTOMER) SEAT PRESSURE RELIEF VALVES

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ABSTRACT

Risk-based inspection methods enable estimation of the probability of failure on demand for spring-operated pressure relief valves at the United States Department of Energy's Savannah River Site in Aiken, South Carolina. This paper presents a statistical performance evaluation of soft seat spring operated pressure relief valves. These pressure relief valves are typically smaller and of lower cost than hard seat (metal to metal) pressure relief valves and can provide substantial cost savings in fluid service applications (air, gas, liquid, and steam) providing that probability of failure on demand (the probability that the pressure relief valve fails to perform its intended safety function during a potentially dangerous over pressurization) is at least as good as that for hard seat valves. The research in this paper shows that the proportion of soft seat spring operated pressure relief valves failing is the same or less than that of hard seat valves, and that for failed valves, soft seat valves typically have failure ratios of proof test pressure to set pressure less than that of hard seat valves.

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.

Risk-based inspection methods enable estimation of the probability of failure on demand (PFD: the probability that the PRV fails to perform its intended safety function during a potentially dangerous over pressurization) for spring-operated relief valves (SORVs) at SRS. Soft seat (SS) SORVs are typically smaller and of lower cost than hard seat (HS) (metal to metal) PRVs and can provide substantial cost savings in all fluid service applications (air, gas, liquid, and steam). The research in this paper shows that the proportion of SS SOPRVs failing is the same or better than that of HS valves, and that for failed valves, SS valves typically have failure ratios (R_p) lower than that of HS valves.

NOTATION

ANOM	Analysis of Means
ASME	American Society of Mechanical Engineers
β	Weibull shape parameter
α	Weibull scale parameter
CDF	Cumulative Distribution Function
$F(t)$	The probability that a SORV will fail by the time it acquires t years of operating time.
HS	Hard Seat
PFD	Probability of Failure on Demand
PM	Preventative Maintenance
Proof Test	The practice of pressurizing the inlet of a new or used PRV on a test stand. Popping pressure and seat tightness are tested, and the as-found values are compared to the stamped SP.

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PRV	Pressure Relief Valve(s) - ASME Power Test code 25-2008 definition
R_p	Ratio of proof TP to SP
RBI	Risk-Based Inspection
RP	Recommended Practice
SORV	Spring-Operated PRV(s)
SP	Set Pressure
SRS	Savannah River Site
SS	Soft Seat
TIS	Time in service
TP	Test Pressure
VRS	Valve Repair Shop

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 plainly evident. 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 four years and range from one year to five 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).

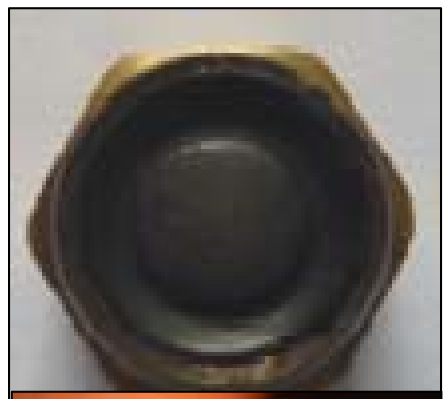
The performance of the valve is then analyzed by assessing the ratio of the *test pressure* (TP), or the "as found" lift pressure (proof test) at which the valve opened during the inspection test, over the *set pressure* (SP), the pressure at which the valve was designed to open R_p = TP/SP. If $R_p \geq 1.50$, then the valve would be considered by industry and API 576 to be "stuck shut," meaning that the valve would fail to open and 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 1.50 times the SP would challenge process piping and pressure vessel mechanical integrity.

A ratio greater than or equal to 1.30 is considered a failed test, as in ASME PCC-3-2007 [1] and API RP 581 [2]. In the data set analyzed, any valve with $R_p \geq 1.30$ is categorized as a "failed" valve. During proof testing of a valve removed from service, any valve whose proof TP is higher than 1.1 times SP is disassembled for cleaning and rebuilt. The valve is subsequently reassembled, reset to its original SP, retested, and, after passing the retest, tagged and returned to the field as "like new."

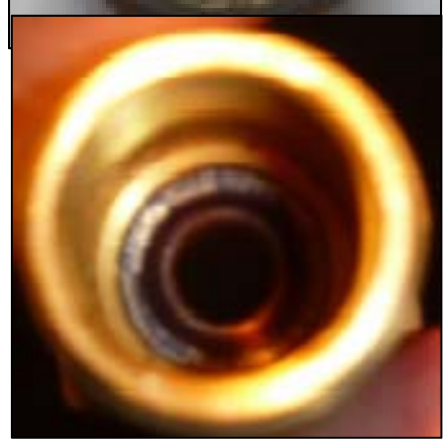
BACKGROUND ON SORVS

SS PRVs (Figures 2.1-2.3) are those valves using an elastomer to make a bubble tight seal of the process fluid. The acceptable leak criteria for HS valves is not as strict as for SS valves. SS PRVs are very often used for refrigerant and gas service (volatile organic compounds) due to limits on fugitive emissions. The type of elastomer used depends on the temperature, pressure and nature of the process fluid. Elastomer seals can be made of silicon or nitrile rubber, Teflon, Delrin, Nylon, polyethylene, polypropylene and others. Most "O" ring valves are limited to a maximum temperature of 450 degrees F depending on the elastomer selected. For higher temperature services, the HS (metal to metal) valve would be used.

Soft Seat PRV (Teflon) Figure 1.1

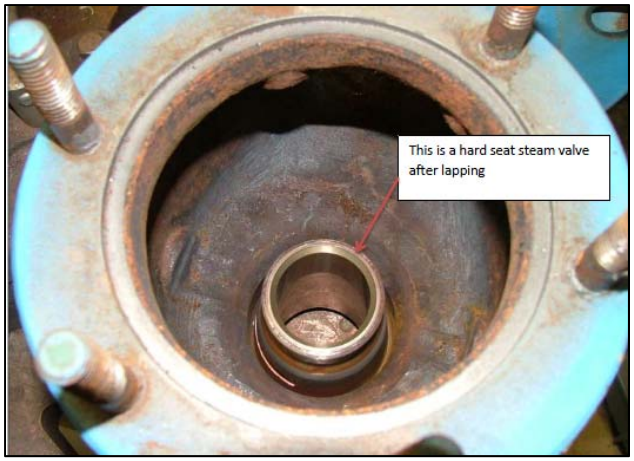


This is a graphite filled PTFE seat. The material has high compressive strength and deforms about 30-40% at higher temperatures. The compression provided by the adjustment spring provides a leak tight seal of the system fluid.



View of the metal seat /nozzle Figure 1.2

This view explains the indentation in Figure 1.1. PTFE has shown a tendency to transfer to metal surfaces following static compressive contact. Metal to substrate adhesion is sufficient to cause separation to occur in the PTFE. NASA attributes separation in the polymer to van der Waals forces. The amount of PTFE transferred depends on the load and enlargement of the real area of contact by distortion under compressive loading [3].



Hard Seat PRV Figure 2

The steam valve shown here has a metal nozzle and disc. They are both lapped to a very fine (mirror) finish, typically 6-8 microinch RA (roughness average).

Another reason to use SS valves is that they are economical in smaller sizes (1/8-1/2 inch inlet) since they can for the most part be machined from bar stock. Quite large failure flow rates relative to valve size can be achieved. SS valves may be tested in the field because they will almost always reseat after "pulling the ring". However after about three years (based on our data) without being exercised, some elastomer material will adhere to the nozzle (metal). When that adhesion happens the exercised valve will not reseat tightly and will need to be replaced.

DATA REVIEW

There were 1,631 used PRV proof tests between January 2003 and October 2012. Of the used valves tested, 963 were HS and 668 were SS PRVs. The SP ranged between 30 psi and 3300 psi with a median SP of 135 psi. Of the used valves tested, 46%, 25%, 12% and 17% were from air, gas, liquid and steam services, respectively. The R_p ratios by seat type and working fluid codes are displayed in Plot 1. The mean time in service (TIS) by working fluid type, HS and SS is displayed in Table 1. The mean TIS is a function of the site-wide preventative maintenance plan (PM) that is based on risk-based inspection (RBI) criteria. A notable difference in TIS between HS (3.73 years) and SS (2.59 years) types is evident for liquid service. The additional TIS of 1.1 years for HS valves (longer aging) could explain the slightly higher ratio of R_p = 1.063 vs. R_p = 1.024 of HS vs. SS valves in liquid service. The summary statistics are displayed in Table 2 and significance tests between HS and SS ratios by service type appear in Table 3.

STATISTICAL ANALYSIS OF SRS VALVES

- **Modeling the Tail Behavior of R_p to estimate the probability of a PRV being Stuck Shut given that it has failed the proof test: $P(R_p \geq 1.50 | R_p \geq 1.30)$**

All statistical analysis in this paper was implemented using the JMP® statistical software (Ver. 8) available from the SAS, Institute in Cary, NC.

It appears that the fraction failing the proof test is greater for HS valves than for SS valves for all service types within the used valve population (Table 4). Statistical testing reveals that the difference is significant for air and gas services, but not for liquid and steam service. These statistical results are due to the low representation of SS valves in these services (24 liquid and 30 steam SS proof tests; Table 4).

The tail behavior (larger R_p values) of the distribution of ratios is used in estimating the probability valves failing the proof test ($R_p \geq 1.30$), and estimating the probability of being valves stuck shut ($R_p \geq 1.50$) for valves that fail the proof test. This probability is referred to as a conditional probability and designated as ($R_p \geq 1.50 | R_p \geq 1.30$). Projections of the probability of failure and the conditional probability of a PRV being stuck shut are made using the Weibull distribution [4], [5]. The Weibull distribution has been used successfully in many applications as an empirical model because of its flexible shape and ability to model a wide range of failure rates. The Weibull model can be derived theoretically as a form of Extreme Value Distribution, governing the time to occurrence of the "weakest link" of many competing failure processes. This may explain why it has been so successful in applications such as capacitor, ball bearing, relay and material strength failures. The two parameter cumulative distribution function (CDF) for a Weibull distribution [4] is defined as:
$F(x) = 1 - \exp[-(x/\alpha)^{\beta}]$, $x \geq 0$ where $F(x)$ is the cumulative probability distribution for the proof test ratio R_p.

The ratios with $R_p \geq 1.30$ (N=29) were used for estimation of the Weibull parameters for HS valves. The fitted Weibull distributions for HS PRVs is displayed in Plots 2. However, $R_p \geq 1.30$ for only one SS PRV. Therefore, for SS PRVs, ratios $R_p \geq 1.17$ were used. The results of fitting the Weibull distribution to ratios $R_p \geq 1.30$ for HS PRVs and ratios $R_p \geq 1.17$ for SS PRVs. are displayed in Plot 3 and Table 5. These distributions were used to project the probability of a valve being stuck shut given that it had failed the proof test. It may be inferred that the probability of a valve being stuck shut given that it has failed proof test is greater for HS valves than that for SS valves (Table 6).

- **FREQUENCY OF FAILURE $P(R_p \geq 1.30)$**

Analysis of means procedure (ANOM) for proportions [6] plots were used to investigate the proportion failed by seat type (HS vs. SS) by working fluid type (Plots 4.1-4.4). An ANOM plot (e.g.: Plot 4.1) for proportions provides a "confidence interval type approach" that enables the determination of which, if any, of multiple groups have a proportion failed significantly different from the overall proportion failed overall groups. Any of the individual group proportions not contained within the shaded area is deemed significantly higher than the overall proportion of all groups if it lies above the upper limit. Similarly, any group proportion

that falls below the lower limit is declared significantly lower than the overall group proportion.

SS PRVs have a lower probability of failure when used in air and gas service. No statistically significant differences by seat type were found for liquid and steam services (Plots 4.3, 4.4).

SP and TIS do not appear to have an influence on the performance differences of SS vs. HS PRVs (Plots 5 and 6, respectively).

CONCLUSIONS

The probability of failure for SS valves is lower than that for HS valves in air and gas service. Furthermore, the conditional probability of a PRV being stuck shut given that it has failed the proof test is less for SS PRVs than that for HS PRVs (Table 6).

Another significant benefit verified by the test data is that HS valves can become stuck shut and hold up to nearly three times SP ($R_p \approx 3$). Not so with SS; the maximum ratio is approximately half the maximum stuck shut pressure of HS PRVs (refer to Table 2 and Plot 1). This aspect is also significant in that it is more difficult for the SS valve to hold pressures liable to challenge the mechanical integrity of equipment, piping, and vessels.

Any differences in TIS or SP do not explain the better performance of SS valves relative to HS valves. It is recommended that the use of SS valves in low risk systems be increased to improve performance.

Furthermore, the probability of a HS that failed the proof test being stuck shut is approximately 50 times that for SS valves (Table 6, 61.4% vs. 1.2%). This is definitely a significant factor of safety to consider.

The statistical analysis suggests that it may be more economical to use SS PRVs, which require replacement after three years of service, than to continue the use of HS PRVs, which are inspected and repaired every five years.

REFERENCES

[1] ASME PCC-3-2007 Inspection Planning Using Risk-Based Methods, June 30, 2008.

[2] API RP 581 Risk-Based Inspection Technology, Section 7 Pressured Relief Devices, American Petroleum Institute (API) Recommended Practice 581, 2nd ed., September 2008.

[3] Pepper, S.V., and Buckley, D.H., Adhesion and Transfer of Polytetrafluoroethylene to Metals Studied by Auger Emission Spectroscopy, NASA Lewis Research Center, Cleveland, Ohio 44135.

[4] Abernethy, R.B. (2004). "The New Weibull Handbook," Robert B. Abernethy, North Palm Beach, FL.

[5] Meeker, W.Q. and Escobar, L.A. (1998). "Statistical Models for Reliability Data," New Jersey, John Wiley & Sons.

[6] Nelson, P.R., Wludyka, P.S., and Copeland, K.A.F (2005). "The Analysis of Means" SIAM.

TABLE 1

Time in Service (years) by Working Fluid

Working Fluid	HS Avg TIS (years)	SS Avg TIS (years)
AIR	4.60	4.22
GAS	3.66	3.60
LIQUID	3.73	2.59
STEAM	3.70	3.70

TABLE 2

Ratio (R_p) Summary Statistics by Hard Seat (HS), Soft Seat (SS), and Working Fluid for Used PRVs

Level	N	Mean Ratio	Std Dev Ratio	Median Ratio	Maximum Ratio
HS/AIR	420	1.023	0.112	1.00	2.14
HS/GAS	114	1.040	0.114	1.01	1.90
HS/LIQUID	178	1.063	0.225	1.01	3.41
HS/STEAM	251	1.047	0.188	1.02	2.86
SS/AIR	327	1.031	0.051	1.02	1.31
SS/GAS	287	1.015	0.031	1.01	1.42
SS/LIQUID	24	1.024	0.050	1.01	1.20
SS/STEAM	30	1.026	0.058	1.01	1.17

TABLE 3

Welch's Test for Difference in ratios (R_p) between HS and SS PRVs assuming unequal variances

WF Code	HS Mean R	SS Mean R	Diff	F Ratio	Prob > F	Sig
AIR	1.023	1.031	-0.008	1.42	0.234	
GAS	1.040	1.015	0.025	5.44	0.021	*
LIQUID	1.063	1.024	0.039	3.91	0.050	*
STEAM	1.047	1.026	0.021	1.72	0.192	

TABLE 4

Number of Valves Failing $R_p \geq 1.30$), Stuck Shut ($R_p \geq 1.50$) and their probabilities by HS, SS, and Working Fluid for Used PRVs

Level	N	# Failed R>=1.30	# Stuck Shut R>=1.50	p (%) R>=1.30	p (%) Stuck Shut| R>=1.30
HS/AIR	420	8	6	1.90%	75.00%
HS/GAS	114	4	2	3.51%	50.00%
HS/LIQUID	178	10	6	5.62%	60.00%
HS/STEAM	251	7	4	2.79%	57.14%
SS/AIR	327	1	0	0.31%	0.00%
SS/GAS	287	0	0	0.00%	n/a
SS/LIQUID	24	0	0	0.00%	n/a
SS/STEAM	30	0	0	0.00%	n/a

TABLE 5

Estimates of Weibull Distribution Parameters probabilities by HS and SS for Used PRVs

Type	Origin	Weibull Parameter	Estimate	Lower 95%	Upper 95%
HS	Used R>=1.30	α	0.440	0.288	0.670
HS	Used R>=1.30	β	0.910	0.710	1.266
SS	Used R>=1.17	α	0.033	0.016	0.069
SS	Used R>=1.17	β	0.892	0.601	1.728

TABLE 6

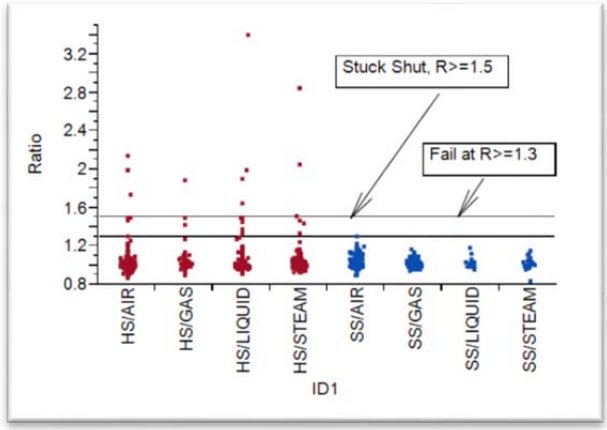
Number of Valves Failing ($R_p \geq 1.30$), Stuck Shut ($R_p \geq 1.50$) and their probabilities by HS and SS for Used PRVs

Type	N	# Failed R>=1.30	#Stuck Shut R>=1.50	p R>=1.30	p Stuck Shut| R>=1.30	Weibull p Stuck Shut| R>=1.30
HS	963	29	18	3.01%	62.1%	61.4%
SS	668	1	0	0.15%	0.00%	1.20%(*)

(*)Based on Used SS $R_p \geq 1.17$

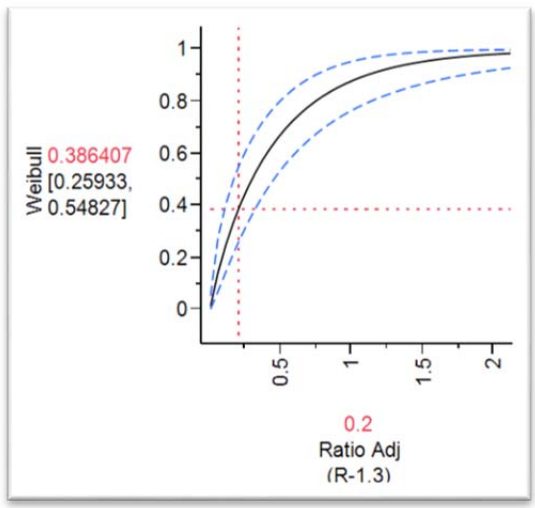
PLOT 1

Dot Plots for Ratio (R_p) by HS, SS and Working Fluid; Origin=Used



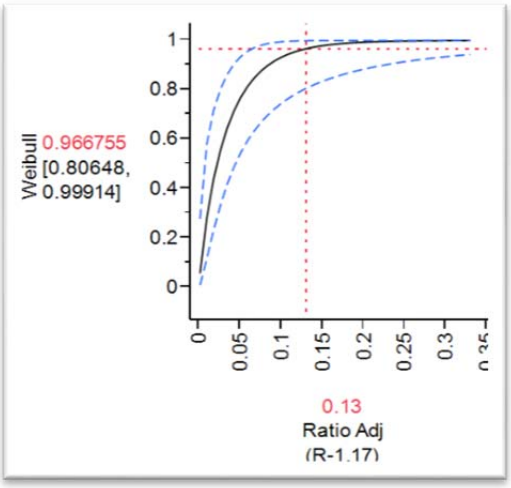
PLOT 2

P(R-1.30< 0.2|R>=1.30)=0.39, Probability of not being stuck shut for HS used valves that fail=0.39



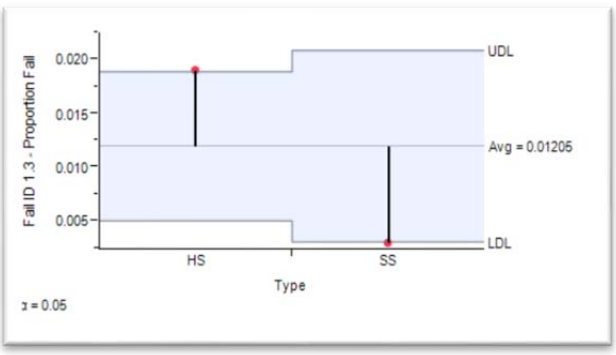
PLOT 3

Probability of not failing for HS used valves with $P(R_p \geq 1.17) = 0.9668$



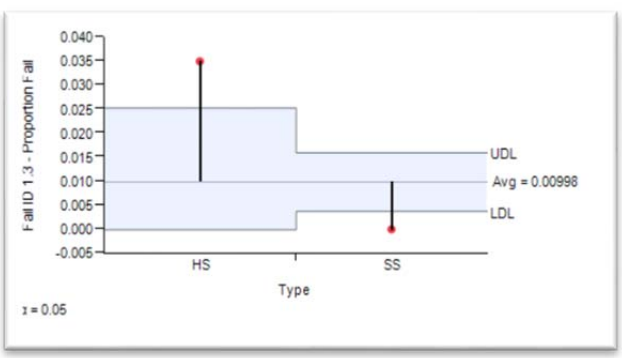
PLOT 4.1

ANOM Plot for Proportions Failing ($R_p \geq 1.30$) Air Service Used PRVs



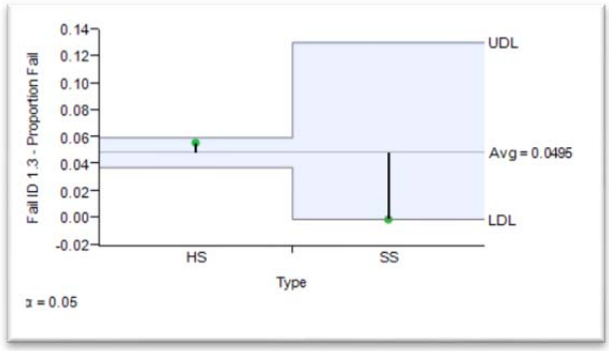
PLOT 4.2

ANOM Plot for Proportions Failing ($R_p \geq 1.30$) Gas Service Used PRVs



PLOT 4.3

ANOM Plot for Proportions Failing ($R_p \geq 1.30$) Liquid Service Used PRVs



PLOT 4.4

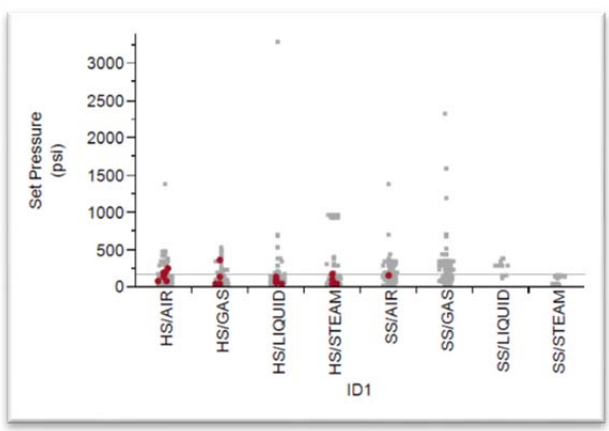
ANOM Plot for Proportions Failing ($R_p \geq 1.30$) Steam Service Used PRVs

PLOT 5

Set Pressure (psi) by Seat Material and Working Fluid for Used PRVs

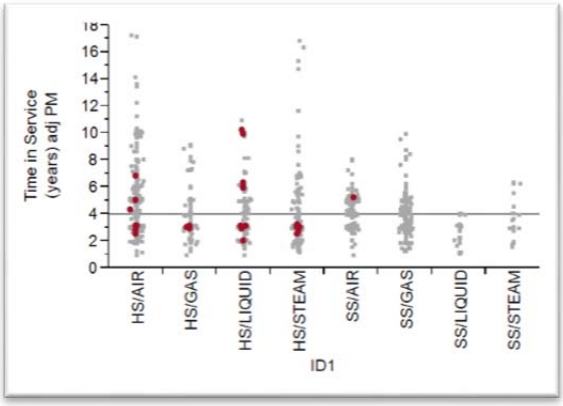
Red: Failures ($R_p \geq 1.30$)

Average Set Pressure: 174 psi



PLOT 6

Time in Service (psi) by Seat Material and Working Fluid for Used PRVs

Red: Failures (R_p >=1.30)

Average TIS: 3.99 years