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EFFECTS OF SEAT WIDTH ON DEVELOPMENT OF ADHESIONS IN STAINLESS STEEL TRIM SPRING OPERATED PRESSURE RELIEF VALVES

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ABSTRACT

Previous research has shown that stainless steel (SS) adhesions form in about half of new SS trim spring operated pressure relief valves (SOPRV). These adhesions require an additional force (beyond the spring force) to be applied by the process fluid to the disc in order for the valve to lift. This additional force may cause the SOPRV to fail its proof test (FPT) or even to fail to open (FTO) in the presence of excess process pressure. This paper expands on the previous findings to show how seat width relates statistically to whether or not these SS adhesions form and, if they do, whether or not they are of sufficient size to cause FPT or FTO.

The findings show it is statistically significant that SOPRV in the study population with seat widths greater than 0.030 inches (in.) formed adhesions more often than SOPRV with seat widths less than or equal to 0.030 in. Furthermore, for this population it is statistically significant that all FPT and FTO occurred on SOPRV with seat widths greater than or equal to 0.030 in. The ramifications of these findings to the safety performance of SS trim SOPRV are discussed.

INTRODUCTION

Many industrial processes use a SOPRV as a safety device to mitigate the hazards of a process overpressure event. The basic mechanics of a typical SOPRV are illustrated in the conceptual representation shown in Figure 1. Additional information about the SOPRV nozzle is provided in the conceptual representation shown in Figure 2. While there are many possible design variations, Figures 1 and 2, along with their respective descriptions, provide sufficient background to understand the research presented in this paper.

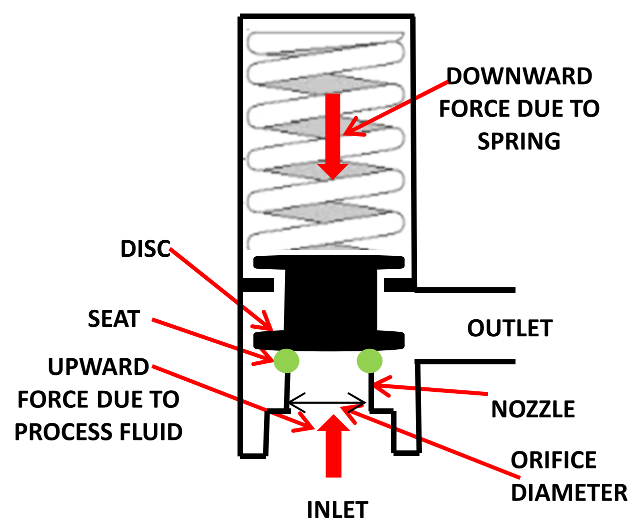

Fig. 1 Conceptual representation of a typical SOPRV

In a properly operating SOPRV a spring exerts a downward force/pressure on the disc pressing the disc against the seat. The seat base is generally the top surface of the wall of the nozzle and the seat itself is often a small raised structure of specific width on the seat base; this is described further in the narrative accompanying Figure 2. The green circles in Figure 1 are not intended to describe the shape of the seat but merely to indicate its position. The orifice diameter (area) is the diameter (area) of the circular opening formed by the nozzle bore. The spring pressure on the disc results in the formation of a fluid tight seal preventing process fluid, which reaches the nozzle through the inlet, from leaving the nozzle through the orifice and outlet. The process fluid exerts an upward force/pressure on the disc. However, since the process *pressure* is nominally about 80-90% of the spring "*set pressure*" the disc remains closed.

During normal plant operation the SOPRV is in the closed position. If the process pressure increases beyond that of the spring set pressure, the disc will be lifted, allowing process fluid to flow through the outlet and thereby relieving excess process pressure. When the process pressure returns to the closing pressure of the SOPRV, the disc once again seals the SOPRV and the process proceeds normally.

Figure 2 is a more detailed conceptual representation of the top of the nozzle and seat. First, note that at its top the nozzle flares outward so that the region where the nozzle meets the disc has a diameter larger than the diameter of the nozzle bore. Therefore, the actual force placed on the disc by the process fluid is determined by the process fluid pressure and the seat inner diameter. Also note that the seat may be positioned on the inner edge of the seat base (as shown in Figure 2), may occupy the entire seat base, or may be positioned on the outer edge of the seat base. In this latter position, the inner seat diameter increases, as does the force exerted by the process fluid on the disc.

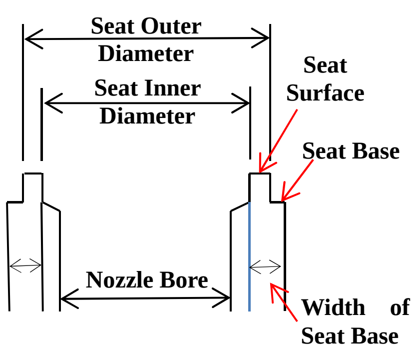

Fig. 2 Conceptual Representation of a Typical SOPRV Nozzle and Seat

The SOPRV can fail in a number of ways. If the SOPRV either slightly opens or fails to form a fluid tight seal when the process pressure is within normal ranges, the valve is said to leak. This is usually considered a safe failure, provided that the unintended pressure relief and fluid release does not itself induce a safety hazard. On the other hand, if the SOPRV does not open under conditions of excessive process pressure, the valve is said to FTO, or to be "stuck shut." This is a dangerous failure.

Previous research [1] looked at the probability of a new SOPRV being in the FTO state upon arrival, i.e., that a new valve is in a state of initial failure. It was shown that while only approximately 19% of the tested new SOPRV population had SS trim, i.e., had both a seat and disc made of stainless steel, those SS trim SOPRV accounted for 64% of all random failures discovered. In a follow up study [2], it was shown to be statistically significant that initial failures in new SS trim SOPRV were confined to valves with set pressures less than 125 pounds per square inch gauge (psig).

Yet another study [3] on new SS trim SOPRV demonstrated that measureable SS adhesive forces formed between the seat and disc in about 46% of all such SS trim SOPRV. The presence of measureable adhesive forces was evidenced by considering the difference between the pressure required for first lift and the average pressure required for the next three lifts during the same proof test. For set pressures below 500 psig, a minimum of 1 psig pressure difference between first lift and the average of the next three lifts was required to indicate the presence of adhesive forces. The rationale for this criterion is detailed in [3]. Only a small portion of these valves with evidence of adhesions developed adhesive forces that were large enough to cause the SOPRV to FTO. At a statistically significant level, the FTO condition was confined to valves with set pressures less than 150 psig AND orifice diameters less than or equal to 1 in.

Each study contained sufficient data to permit the estimation of the probability of initial failure (PIF) along with a two-sided 95% confidence interval for PIF for different subpopulations. Each made more precise the characteristics defining the subpopulation of SS trim SOPRV vulnerable to initial failures caused by the development of SS adhesions. The relatively large estimates for PIF raise concerns with respect to the safety performance of valves in the vulnerable subpopulation.

Table 1 summarizes those estimates and confidence intervals based on data from prior studies and includes the latest estimate and confidence interval based on the research reported in this paper. Note: some of the numbers of FTO do not match prior reference papers because the numbers were updated to the latest database which contains additions, deletions and corrections as discrepancies are identified. In particular, studies reported in [1] and [2] identified seven FTO's in their respective study populations. This number was reduced to four during the study reported in [3] because re-evaluation of the root cause analysis information revealed the presence of other factors that may have existed in addition to adhesions. Therefore, it could not be stated that adhesions alone caused three particular FTO's though adhesions may have been a contributing factor. The effect of this change on the conclusions of [1] and [2] is merely to update the estimated PIF and 95% confidence interval as shown in Table 1. There was no effect on any of the conclusions made based on hypothesis testing conducted in [2].

The remainder of this paper,

- describes the data source and summarizes the relevant data;
- presents the main findings and supporting statistical analysis showing that SOPRV seat width is a significant

Table 1 Summary of Findings for PIF Estimates & 95% Confidence Intervals

Characteristics of Vulnerable Subpopulation of SS Trim SOPRV [Source]	#FTO	#SOPRV	Estimated PIF	95% Confidence Interval
SS Trim SOPRV [1]	4	931	0.004	[0.005, 0.017]
Set pressure < 125 psig [2]	4	412	0.010	[0.003, 0.024]
Set pressure < 150 psig Orifice Diameter $\leq$ 1.0 in. [3]	4	509	0.008	[0.004, 0.022]
Set pressure < 150 psig Orifice Diameter $\leq$ 1.0 in. Seat Width > 0.030 in. [current paper]	4	251	0.016	[0.003, 0.030]

factor both in the formation of SS adhesions and in having new SS trim SOPRV "arrive" in a state of FPT or FTO;

- provides updated estimates for the probability that a new SS trim SOPRV will arrive in the FTO state;
- explains the results and discusses the impacts of the findings on the safety performance of SS trim SOPRV;
- closes with conclusions including suggestions for end-users who choose SS trim SOPRV as part of their protection systems.

NOMENCLATURE

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
df	degrees if freedom
FTO	fail to open
FPT	fail proof test
in.	inch(es)
lbf	pounds force
PFDavg	average probability of failure on demand
PIF	probability of initial failure
psig	pounds per square inch gauge
R	proof test ratio; first lift pressure/set pressure
RCA	root cause analysis
SRS	Savannah River Site
SIL	safety integrity level
SOPRV	spring operated pressure relief valve
SS	stainless steel
SS trim	SOPRV with a SS seat/nozzle and SS disc
T_P	proof test interval
[x, y)	interval notation; z belongs to the interval if $x \leq z < y$
λ_D	dangerous constant failure rate

DATA SOURCE

Data for this study came from Savannah River Site (SRS). As previously described in [4], SRS conducts all of its valve tests at one dedicated test and repair facility on site. This insures consistency of the test and repair facility and personnel, test procedures, management oversight, and data records. It is the policy of SRS to proof test all valves, including new (not previously installed) valves, prior to installation. The criterion for "prior to installation" is that the valve be subjected to proof testing by SRS personnel at most six months prior to installation.

A full description of the proof test procedures as practiced at SRS is provided in [5]. A brief description is provided here. When a new or used (installed and actively in service prior to testing) SOPRV is received in the valve repair shop, it is checked for evidence of external physical damage, corrosion, and deposits. The manufacturer, the model, and, if present, the serial number are recorded. Following the external visual inspection, valves are first tested in the "as-arrived" or "as-found" condition. On a test stand the test pressure is increased until the valve lifts or "pops" open. This activity is believed to closely simulate field performance. After the first lift, if possible, the test is repeated three times, and the three subsequent lift pressures are recorded along with the first lift pressure. If a SOPRV lifts above or below the American Society for Mechanical Engineers (ASME) tolerance on the valve's tagged set pressure (set point), it is disassembled, and additional parts inspection is performed. All parts are cleaned, either mechanically or chemically. In some cases, parts will be replaced, lapped to ensure a leak-tight seal, or machined if the seat and disc have experienced chemical or mechanical deformation.

The proof test ratio, R, is computed as the first lift pressure divided by the set pressure. A SOPRV is defined to have failed its proof test (FPT) if R is greater than or equal to 1.3 per ASME PCC-3-2007 [6] and American Petroleum Institute (API) RP 581 [7]. This ratio of 1.3 has also been used in other data analysis [8]. A SOPRV is defined to be FTO if R is greater than or equal to 1.5 per generally accepted industry practices and API RP 576 [9]. R greater than or equal to 1.5 is considered a good indication that the SOPRV would fail to relieve excess pressure in the field, thereby challenging the mechanical integrity of process piping and pressure vessels.

Beginning in late 2003, SRS instituted a practice of performing a root cause analysis (RCA) on any SOPRV which was deemed FTO as a result of a proof test. RCA was also performed on some SOPRV deemed FPT. The procedure for conducting a RCA is described in [4]. The purpose of a RCA is to identify the underlying cause(s) of the failure, to document them in a report for future reference so as to identify and follow trends that may emerge and to recommend possible strategies to eliminate these failures in the future.

DATA FOR THIS STUDY

The dataset for this study consists of 481 proof tests which were performed at SRS on new ASME Section VIII [10] SS trim SOPRV over an approximate 10-year period from 2003 until September of 2012. The dataset was extracted from a larger test set and was limited to those SS trim valve tests which met criteria previously identified as being statistically significant in findings of FPT and FTO in SS trim valves. Specifically, the test population [3] consists of new SS trim

SOPRV and which had set pressures less than 150 psig and orifice diameters less than or equal to 1.0 in. by API standards. This corresponds to SOPRV of orifice size H or smaller and to orifice diameters less than or equal to 1.18 in. by ASME standards. Of the 481 proof tests, 233 showed evidence of adhesion formation and the remaining 248 did not. Figure 3 shows the distribution of SOPRV with evidence of adhesions by set pressure (psig) vs orifice diameter (in.) with proof test ratio ranges distinguished both by color and shape as follows:

- [0.9, 1.2) - range of R with no FPT (and consequently no FTO);
- [1.2, 1.3) - range of R with no FPT but approaching the range of FPT. This range is also called near-FPT in [3];
- [1.3, 1.5) - range of R defined as FPT but not FTO;
- [1.5, 2.2) - range of R defined as both FPT and FTO and included the largest value of R in our study.

Note that the dataset has broad representation over orifice diameters from 0.294 to 1.000 in. and over set pressures ranging from 15 to 148 psig. Note also that SOPRV without evidence of adhesions are omitted from all plots as they add no additional information and merely increase the density of the "green X's" associated with Ratio [0.9, 1.2). There are a total of six data points in Ratio [1.2, 1.3), four in Ratio [1.3, 1.5) and four in Ratio [1.5, 2.2). If fewer points are visible for any of these ranges it is because the data points overlap.

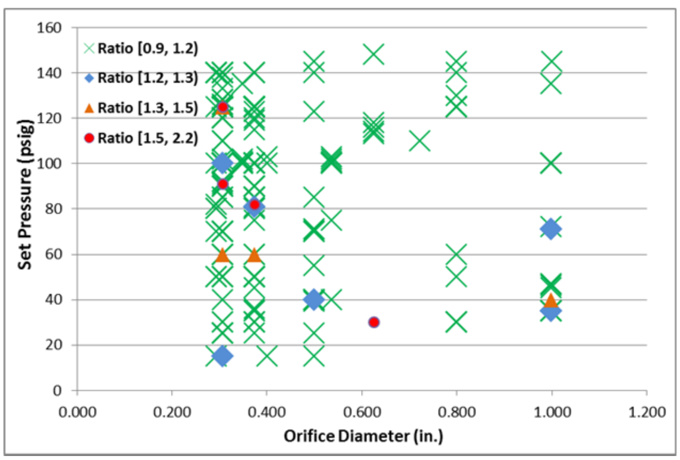

Fig. 3 Plot of Set Pressure (psig) vs Orifice Diameter (in.) with Ratio Ranges Distinguished

For every test in the study population, the following information can be identified: manufacturer and model number, test date, set pressure, proof test pressure (first lift pressure), R, SOPRV orifice diameter, seat width, and inner seat diameter as well as identifying information linking the test back to a more complete database at SRS. For all tests, it is also possible to identify the average pressure of the three lifts following first lift and the fluid service.

FINDINGS & SUPPORTING STATISTICAL ANALYSIS

Many avenues of inquiry were explored. Correlations were sought between a number of variables including the excess forces of adhesion, set pressure, seat area, seat inner diameter, spring pressure on the seat, etc. After much review and exploration of the data, the conclusions are rather simple.

Consider the plots in Figures 4 and 5 which show seat width vs orifice diameter and seat width vs set pressure, respectively. Note that proof tests resulting in ratios in the ranges [1.2, 1.3), [1.3, 1.5), and [1.5, 2.2] occur only for SOPRV with seat widths greater than 0.030 in.

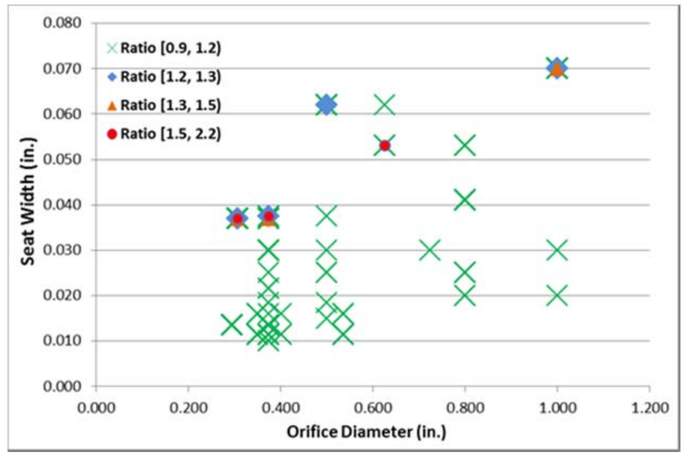

Fig. 4 Plot of Seat Width (in.) vs Orifice Diameter (in.) with Ratio Ranges Distinguished

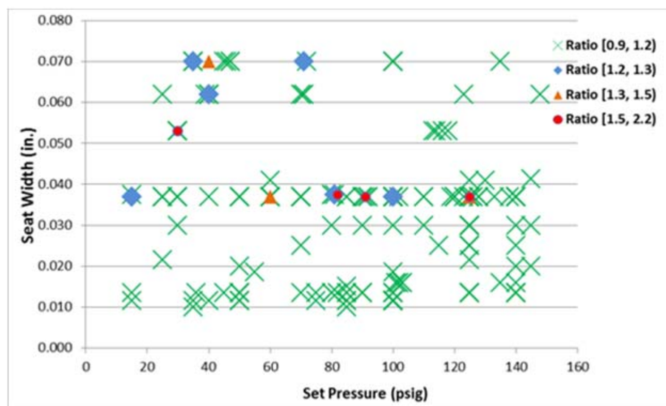

Fig. 5 Plot of Seat Width (in.) vs Set Pressure (psig) with Ratio Ranges Distinguished

Statistical tests for significance based on the data in Table 2 were made. The first null hypothesis, H_0, was that there is no statistical difference in proportions between SOPRV with seat widths less than or equal to 0.030 in. and SOPRV with seat widths greater than 0.030 in. with respect to the occurrence of proof test ratios, R, in a given range. Because the ratio range [1.2, 1.3) was defined by the authors in [3] and has no special significance with respect to ASME or API standards, a second hypothesis test was conducted based on the three ratio ranges [0.9, 1.3), [1.3, 1.5), and [1.5, 2.2) by combining the first two rows of data in Table 2. Finally, a third hypothesis test was performed on the ranges [0.9, 1.2) and [1.3, 2.2) which divide the SOPRV population into those which pass their proof test and those which do not.

Table 2 SOPRV Ratio Data Divided by Seat Width

Ratio Range	Total # SOPRV	Number SOPRV Proof Tests in Ratio Range with Seat Width	
		$\leq$ 0.030 in.	> 0.030 in.
[0.9, 1.2)	467	230	237
[1.2, 1.3)	6	0	6
[1.3, 1.5)	4	0	4
[1.5, 2.2)	4	0	4
Total	481	230	251

Table 3 summarizes the findings of these statistical tests. In each case, $\chi 2$ [11] was computed from the appropriate data and compared to the critical $\chi 2$ value for level of significance α = 0.05. H_0 is rejected if the computed $\chi 2$ equals or exceeds the critical $\chi 2$, which was determined by simulation. Using the standard $\chi 2$ tables based on the normal approximation in order to find the critical $\chi 2$ values requires certain assumptions that the data do not meet. Specifically, the standard tables should not be used "when one or more of the expected frequencies is less than 5" [11]. Due to the small number of tests in three of the four ratio ranges in each case tested some frequencies will be less than 5. Note that the critical $\chi 2$ values in Table 3 are discretized to represent whole numbers of valves with seat widths either less than or equal to 0.030 in. or greater than 0.03 in.

Table 3 Results of Testing
H_0: No Statistical Difference in Proportions Relative to Seat Width with α = 0.05

Test with respect to	Data from	Calculated χ^2	Critical χ^2	df	Conclusion
4 proportions	Table 2	13.2133	7.4529	3	Reject H_0
3 proportions	Table 2 with 1st two rows combined	7.4547	5.2115	2	Reject H_0
2 proportions	Table 2 with 1st two rows and last two row combined	7.4547	4.0666	1	Reject H_0

From Table 3 it is clear that there is a statistically significant difference in all cases and H_0 is rejected in each case. Therefore, SOPRV with seat widths greater than 0.030 in. are more prone to FPT and FTO due to adhesions than are SOPRV with seat widths less than or equal to 0.030 in.

Based on these findings it is possible to update previous estimates of the probability that a SS trim SOPRV will be found FTO. The subpopulation vulnerable to FTO due to SS adhesions is now characterized as having set pressure less than 150 psig, orifice diameter less than or equal to 1.0 in., and seat width greater than 0.030. This subpopulation has a 4/251 = 1.6% probability of arriving in an FTO state due to SS adhesions. A 95% confidence interval for this estimate is [0.0026, 0.0300]. The interval indicates that while the true value of PIF is unlikely to be exactly 0.016, there is 95% confidence that PIF lies in the computed interval. Therefore, while it is possible that PIF is as small as 0.26% it is also possible that PIF is as large as 3.00%! Note that the interval estimate is given by the Wilson score interval [12] rather than by the usual interval calculated using the normal approximation to the binomial because the proportions in these data are quite close to zero and consequently do not meet the assumptions required to use the normal approximation. Also note that the point estimate is not the center of the interval.

Based on the discovery of the statistical significance of seat width it was decided to explore whether SS adhesions are more likely to form on SOPRV with seat widths greater than 0.030 compared to those with seat widths less than or equal to 0.030. Table 4 presents the data categorized by presence or absence of evidence of measureable adhesions and by seat width.

Table 4 SOPRV Study Data by Presence or Absence of Measurable Adhesions and by Seat Width

Evidence of Adhesions	Total # SOPRV	Seat Width			
		$\leq$ 0.030 in.		> 0.030 in.	
		# SOPRV	% of 230	# SOPRV	% of 251
Yes	233	95	41.3%	138	55.0%
No	248	135	58.7%	113	45.0%
Total	481	230	100.0%	251	100.0%

The null hypothesis, H_0, is that there is no difference in the proportions of SOPRV with respect to adhesion formation between valves of different seat widths. The calculated value of χ^2 is 8.9875 and the critical value of χ^2 for this problem with 1 degree of freedom (df) is 3.841. Therefore, H_0 is rejected; there is statistically significant evidence that SS adhesions are more likely to form on SS trim SOPRV with seat widths greater than 0.030. In this case, the standard tables for χ^2 could be applied.

DISCUSSION

Explaining the Results

As detailed in [3], SS trim SOPRV with low set pressures are more vulnerable than SS trim SOPRV with high pressures to FPT (FTO) due to the formation of SS adhesions because FPT (FTO) is determined by a 30% (50%) excess of pressure above set pressure needed to achieve first lift. The lower the set pressure, the smaller the excess pressure required to meet the FPT (FTO) criterion. This may account for why the vulnerable subpopulation has set pressures less than 150 psig.

The lifting force generated by the pressure of the process fluid is smaller if the orifice diameter/seat inner diameter is smaller. Therefore, SS trim SOPRV with smaller orifice diameters have less of a chance of generating enough lifting force to overcome the adhesive force without exceeding the excess pressure limits. Hence, the vulnerable subpopulation has orifice diameters less than or equal to 1.0 in.

Now the adhesive forces created by SS adhesions are likely related to a number of factors including the surface area over which the SS seat and SS disc are in contact. The SOPRV seat is an annulus and thus the seat area is directly proportional to the seat width. Increasing the seat width increases the seat area and likely increases the corresponding adhesive force developed. Consequently, narrower seat widths likely develop smaller adhesive forces which must be overcome while wider seats develop greater adhesive forces which are more likely to cause FPT or FTO states. Thus, it is likely that the vulnerable subpopulation has seat widths greater than 0.030.

Figure 6 plots adhesive forces vs seat width. Note that for a fixed seat width, a range of adhesive forces has developed. Figure 6 show that the adhesive forces developed do not depend solely on the seat width. They may also be affected by the seat inner diameter which also impacts seat area. Furthermore, adhesions are due to a number of different microscopic processes that all have the same macroscopic presentation. This may account for the variety of adhesive forces observed for a fixed seat width. Adhesions also likely develop over time to a maximum once the SOPRV is under set pressure. This is another factor that may explain the range of adhesive forces for a given seat width. Unfortunately, it is not possible to derive the elapsed time under set pressure from the data available in the SRS database. If the assembly date were known and recorded in the database, then it would be possible to evaluate the elapsed time the seat and disc were in contact.

Safety Performance Implications for SS Trim SOPRV

This paper has focused on new SS trim SOPRV. However, in [2] it was shown that used SS trim SOPRV (valves that had been installed, were in active service, and subsequently were removed for proof testing) show statistically similar behaviors with respect to FPT and FTO failures due to SS adhesions. This makes sense. In new valves, SS adhesions form while the valve is in storage and not being lifted. When in use, for processes which rarely place excess pressure on the SOPRV, the valves are also not being lifted allowing for the same formation of SS adhesions. If the adhesions form over relatively short periods of time, then the issues regarding safety performance now described apply to both new and used SS trim SOPRV.

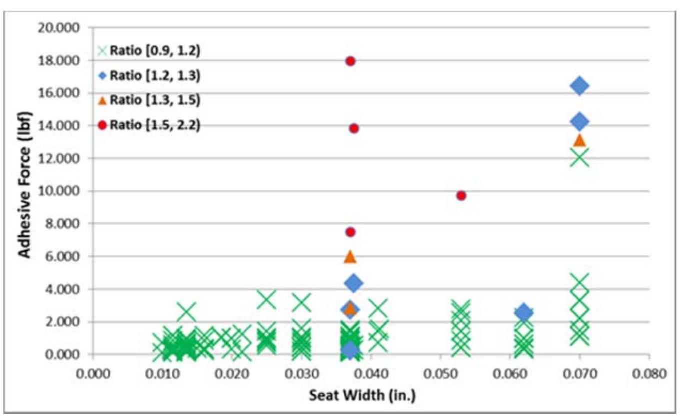

Fig. 6 Plot of Adhesive Forces (lbf) vs Seat Width (in.) With Ratio Ranges Distinguished

For low demand processes usually associated with the use of SOPRV, international safety standards [13, 14] measure safety performance by safety integrity levels (SIL) from the lowest level of SIL 1 to the highest level of SIL 4. These SIL levels are assigned based on the average probability of failure on demand (PFDavg).

Table 5 shows the correspondence between SIL levels and PFDavg where PFDavg is computed based on the dangerous constant failure rate, λ_D, of the SOPRV and on the proof test interval, T_P. PFDavg is generally well approximated by

$$\text{PFDavg} \approx \text{PIF} + (1\text{-PIF}) \times 0.5 \times \lambda_D \times T_P. \quad (1)$$

Table 5 Correspondence Between SIL and PFDavg

SIL per IEC61508[1]	PFDavg
1	$\geq 10^{-2}$ to $< 10^{-1}$
2	$\geq 10^{-3}$ to $< 10^{-2}$
3	$\geq 10^{-4}$ to $< 10^{-3}$
4	$\geq 10^{-5}$ to $< 10^{-4}$

If an end-user does not perform pre-installation testing, then about 1.6% of all SS trim SOPRV from the vulnerable subpopulation will be installed in a state of initial failure meaning the minimum value of PFDavg will be 0.016 (SIL 1) regardless of the values of λ_D and T_P. This represents a significant degradation of safety performance. Even if pre-installation proof testing is performed, PFDavg will see the impacts of the 1.6% PIF delayed in time by the time required for the SS adhesions to form. This means that even if pre-installation testing disrupts any adhesion formation present prior to installation, once installed, the SOPRV is essentially unexercised as it would be in storage and adhesions may once again form. Once the time required for the adhesions to reach a point where they cause an FTO has elapsed, the situation is the same as it would have been had the pre-installation testing not been performed but the situation is delayed in time by the time required for the adhesions to reform. At that elapsed time the PFDavg will be 0.016.

The rate of adhesion formation is not currently known. If a conservative view is taken and it is assumed that the adhesions form rather quickly (in a matter of days or weeks rather than months or years), this would imply that 1.6% of vulnerable SS trim SOPRV are in a state of failure almost immediately after installation and offer no protection for most of the time they are in service prior to proof testing.

IMPLICATIONS FOR END-USERS

For low set pressure applications (set pressures less than 150 psig), end-users choosing SS trim SOPRV with orifice diameters less than or equal to 1.0 in. need to consider the specifics of seat design. Choosing such an SOPRV with seat widths greater than 0.030 in. requires accounting for PIF in the calculation of SOPRV safety performance. However, it would be better for the end-user to be certain to choose an SS trim SOPRV with seat width less than or equal to 0.030 in.

CONCLUSIONS

This study clearly shows that the safety performance of SS trim SOPRV depends greatly on certain design parameters and the intended set pressure when in use. Specifically, SS trim SOPRV with set pressures less than 150 psig, orifice diameters less than or equal to 1.0 in., and seat widths greater than 0.030 in. have estimated values for PIF of 1.6%. This safety performance should be carefully considered when selecting SS trim SOPRV for low set pressure applications.

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