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INVESTIGATION OF ADHESION FORMATION IN NEW STAINLESS STEEL TRIM SPRING OPERATED PRESSURE RELIEF VALVES

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ABSTRACT

Examination of proof test data for new (not previously installed) stainless steel (SS) trim spring operated pressure relief valves (SOPRV) reveals that adhesions form between the seat and disc in about 46% of all such SOPRV. The forces needed to overcome these adhesions can be sufficiently large to cause the SOPRV to fail its proof test (FPT) prior to installation. Furthermore, a significant percentage of SOPRV which are found to FPT are also found to "fail to open" (FTO) meaning they would not relief excess pressure in the event of an overpressure event. The cases where adhesions result in FTO or FPT appear to be confined to SOPRV with diameters ≤ 1 in and set pressures < 150 psig and the FTO are estimated to occur in 0.31% to 2.00% of this subpopulation of SS trim SOPRV. The reliability and safety implications of these finding for end-users who do not perform pre-installation testing of SOPRV are discussed.

INTRODUCTION

Many industrial processes use a SOPRV as a safety device to mitigate the hazards of a process overpressure event. During normal plant operation the SOPRV is in the closed position. If the process pressure exceeds the set pressure of the SOPRV, the SOPRV will open to relieve excess pressure and close again once the process pressure has returned to normal ranges. The SOPRV can fail in one of two ways. If the SOPRV opens when the process pressure is within normal ranges, the valve is said to leak and this is a safe failure. On the other hand, if the SOPRV fails to open under conditions of excessive process pressure, the valve is said to FTO, or to be "stuck shut," and this is a dangerous failure.

Because the SOPRV is normally closed, it is not possible to observe the FTO dangerous failure mode during normal operation. Consequently, safety standards such as [1, 2] require that the SOPRV undergo periodic proof testing to determine if it is functioning correctly. In earlier research [3, 4, 5] we established that new SOPRV are subject to initial failures, i. e., that they can be FTO in their "as received" condition when they arrive from the manufacturer/distributor and that the probability of initial failure (PIF) significantly affects the SOPRV safety rating as measured by its safety integrity level (SIL). Furthermore, while some of these failures are due to manufacturing defects, a significant number are due to the development of adhesions between the seat and disc while the valve is in storage even if the storage conditions are appropriate. Also of note is the fact that SOPRV with SS trim (SOPRV with the nozzle/seat and disc made of SS) show a greater propensity for this type of failure than SOPRV with trim constructed from other materials.

Clearly, from a safety perspective, it is important to have a better understanding of this adhesion phenomenon. An extensive literature search shows research into the formation of such adhesions dating back to 1950 [6]. A number of different mechanisms to explain adhesion have been investigated and modeled. These include cold welding [7], hysteresis and diffusion bonding [8, 9] and residual stresses from the manufacturing process [10, 11, 12]. However, to date there are no definitive explanations nor predictive models of the SS adhesion formation phenomenon that leads to FTO or FPT in SS trim SOPRV. Therefore, it is not the purpose of this paper to *explain* the SS trim adhesions.

Rather, because there are no known means for preventing these adhesion formations in SS trim SOPRV, it is important that we be able to model statistically their occurrences so as to be able to calculate their effects on reliability and safety. Consequently, the purpose of this paper is to describe what we have observed regarding SS trim adhesions in a particular data set of 1000 proof tests performed on new SS trim SOPRV and to detail our investigations of the

- frequency with which SS trim SOPRV adhesions developed whether or not they caused a FTO or FPT,
- magnitudes of the forces that must be overcome to disrupt the adhesions,
- SOPRV characteristics most likely associated with the development of adhesions in this data set,
- probabilities that these adhesions lead to FTO or FPT,
- impacts on reliability and safety of these findings especially for end-users who do not perform pre-installation proof testing.

NOMENCLATURE

API	American Petroleum Institute
ASME	American Society of Mechanical Engineers
FTO	fail to open
FPT	fail proof test
H_0	the null hypothesis of a statistical 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
SS+	SOPRV with SS trim but with some non-SS materials incorporated into the remainder of the structure
SS ONLY	SOPRV constructed entirely of SS
T_P	length of time intervals between periodic proof testing
wrt	with respect to
[x,y)	range notation: square brackets include the endpoint whereas parentheses exclude the endpoint
Δf	Δp times area of SOPRV orifice
Δp	difference between proof pop and average of next three pops after proof pop
λ_D	dangerous failure rate of an SOPRV
χ^2	calculated parameter used in statistical testing of equality of proportions

DATA SOURCE

Data for this study came from Savannah River Site (SRS). As previously described in [3], 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 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 [13]. A brief description is provided here. When a new or used valve 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. Test pressure is increased on the test stand until the valve lifts or “pops” open. This activity is believed to closely simulate field performance. 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.

Beginning in late 2003, SRS instituted a practice of performing a root cause analysis (RCA) on any valve which was deemed FTO as a result of a proof test. The procedure for conducting a RCA is described in [3]. 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

Rationale for Using New SS Trim SOPRV Proof Tests

Although we previously demonstrated [5] that SS trim SOPRV FTO due to adhesion occur in the same proportion in new and used valves, we have chosen to confine this study only to proof test data obtained from testing new SS trim SOPRV. We did this in order to limit the number of factors that could be involved in the formation of adhesions discovered.

With both new and used valves we must consider factors such as differences between manufacturers, whether the valve is constructed entirely of SS or if it contains some non-SS components, SOPRV size and the pressure with which the disc is held against the seat via the force applied by the spring. A new valve is normally stored indoors, has its seat and disc exposed only to ambient air and is under full spring set pressure while in storage. On the other hand, a used valve may have seen service outdoors or its indoor service may have been in a harsh environment, it may have been subject to vibration, its seat and disc may have been exposed to any of a wide variety of working fluids, and, due to the back pressure of the process fluid on the disc, the pressure holding the disc to the seat may have varied considerably over time and was probably substantial less than the spring set pressure. Thus, new SS trim SOPRV have fewer factors to consider than do used SS trim SOPRV.

Furthermore, it is essential that we be able to identify with reasonable certainty those valve tests which demonstrate the existence of adhesion forces at the time of first proof test. We can identify adhesion forces by comparing the proof test pressure to the average pressure of the next three pops during the proof test. Adhesions typically manifest themselves with a higher proof test pressure followed by three consistently lower pop pressures. Now the pressure difference between the proof pop and the computed average of the next three pops could be due to adhesion or possibly to some other cause. When we are dealing with new valves it is relatively easy to eliminate other causes. When dealing with used valves it is more difficult to identify when the pressure difference is due to adhesion or to another cause such as corrosion of a non-SS part.

Summary of SOPRV Population and Data Available

The population for this study consists of 1000 new (not previously installed) ASME Boiler and Pressure Vessel Code Section VIII [14] SOPRV with SS trim. The proof testing of these new SOPRV took place over an approximate 10 year period from 2003 until September of 2012. The population encompasses many different characteristics which might be relevant to the formation of SS adhesions. The characteristics most relevant to this study are summarized in Table 1; they are divided by SOPRV subpopulations which are described by the materials used in the valve construction. Specifically, a SOPRV with SS trim may include one or more non-SS components in its construction. We refer to this subpopulation as SS+ SOPRV. We refer to the subpopulation of SOPRV that are constructed entirely of SS as SS ONLY SOPRV.

TABLE 1 SUMMARY OF POPULATION CHARACTERISTICS OF SOPRV IN THIS STUDY

Population Characteristics	Total Population	Subpopulations	
		SS +	SS ONLY
#Manufacturers[1] Represented	8	6	6
# SOPRV	1000	616	384
Set Pressure Range (psig)	15-6300	15-1300	15-6300
Orifice[2] Diameter (in)	0.047-3.750	0.25-3.750	0.047-1.000

[1] Readers comparing this work to [5] may note that in [5] we identified 10 manufacturers. In this work we combined manufacturer names if they produced any valves under separate names but the same model numbers. This accounts for the difference.

[2] The orifice is the nozzle opening where the nozzle meets the disc. The seat is formed by the wall of the nozzle. The disc is held to the seat by the force of the spring on the disc plus any force of adhesion which develops between the seat and the disc.

The information available about each SOPRV proof test includes:

- Manufacturer/model
- Set pressure
- Proof test pressure
- Average pressure measured on next three pops after proof

Determining If Proof Test Indicates Adhesion Formation and Whether a FTO or FPT Occurred

We used the manufacturer and model to determine material construction and SOPRV orifice diameter. We compute Δp equal to the difference between the proof pop pressure and the average pressure measured on the next three pops after proof pop.

We designated a proof test to be evidence of adhesion based on the value of Δp as follows. Proof test pressures and the pressures associated with the next 3 pops after proof pop are recorded only to the nearest integer value. Thus, if the proof pop measured 100.5 psig it would be recorded as 101 psig. If the next three pops measured 100.4, 100.5 and 100.4 psig, they would be recorded as 100, 101, 100 psig, respectively with a computed average of 100.333. Thus, Δp would be 0.667 but very likely, this would not represent a true pressure differential. Thus, we did not count as evidence of adhesion formation any Δp less than 1 psig. Now is 1 psig sufficient to indicate evidence of adhesion formation?

Based on the accuracy with which equipment at SRS can measure pressures we deemed a minimum Δp of 1 psig to be evidence of adhesion formation on SOPRV with set pressures up to 500 psig. For set pressures in the range of 1000 psig, the criterion for evidence was a minimum Δp of 2 psig, and so forth. For each SOPRV proof test designated as evidence of adhesion formation, we computed Δf equal to Δp times the orifice area. We computed the proof test ratio, R, equal to proof pop pressure/set pressure.

Much of our later data analysis relies on Δf more so than on Δp because two valves with the same Δp but with different orifice diameters will have developed different forces of adhesion and we needed to be able to make this distinction. Finally, we used R to determine if a SOPRV was in a state of FPT or FTO. We define a SOPRV to be FPT if $R \geq 1.3$ per ASME PCC-3-2007 [15] and American Petroleum Institute (API) RP 581 [16]. We define a SOPRV to be FTO if $R \geq 1.5$ per generally accepted industry practices and API RP 576 [17]. $R \geq 1.5$ 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. In our plots, we code R both by shape and color differently for the following ranges as defined for this study:

- [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;
- [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.

Table 2 summarizes population and subpopulation information. This summary takes into account whether or not there was evidence of adhesion formation and what the R associated with each proof test was for each SOPRV.

TABLE 2 SUMMARY OF EVIDENCE OF ADHESION FORMATION AND RATIO OF EACH PROOF TEST

Population Characteristics	Total Population	Subpopulations	
		SS+	SS ONLY
# SOPRV	1000	616	384
# with evidence of adhesions	462	299	159
% evidence wrt total population	46.2%	29.9%	15.9%
% evidence wrt subpopulation size	--	48.5%	41.4%
#Ratio [1.2, 1.3)	9	9	0
#Ratio [1.3, 1.5)	4	3	1
#Ratio [1.5, 2.2)	4	4	0

PLOTTING and EXPLORING THE DATA

With so many factors represented, we decided first to plot, in various ways, all of the SOPRV that evidenced the formation of adhesions. We plotted SS+ SOPRV separately from SS ONLY SOPRV as we found that most of the SS+ subpopulation had lower set pressures while most of the SS ONLY subpopulation had higher set pressures.

Figures 1a, 1b, and 2 all show plots of Δf (lbf) vs SOPRV diameter (in). Figure 1a is for SS+ SOPRV. Figure 1b is an enlargement of Figure 1a for diameter sizes up to and including 1 in. Figure 2 shows the same information for SS ONLY SOPRV. Note that in Figure 2 there is only one marker in the Ratio range [1.3, 1.5). The other markers are all X's. Darker regions represent greater density of X's**.**

Several features are evident in the three plots. First, it is immediately apparent that adhesions form over all[3] valve diameters for both SS ONLY and SS+ SOPRV. Focusing on Δf we note that, with the exception of one large force of about 44.2 lbf which formed on one of the largest diameter valves (3.750 in), all of the adhesive forces are under 12 lbf and most are under 2 lbf. Furthermore, some of the smaller adhesion forces (less than 2 lbf) result in FPT while some larger forces (including the largest Δf) are associated with valves that functioned appropriately. All of the 8 instances of FPT (of which 4 are also FTO) and 9 instances of near-FPT occur in SOPRV of diameter ≤ 1 in.

[3] Actually, there were exactly two SS+ SOPRV of diameter 2.850 in. in the entire population and neither or these showed evidence of adhesion. But the sample size of two is too small to assert that adhesions do not form over all valve diameters.

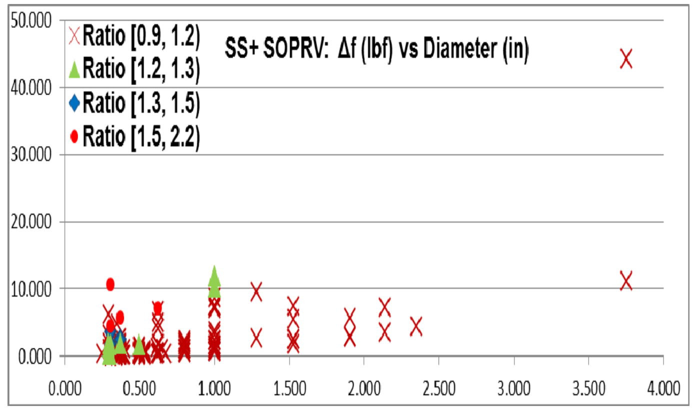

FIGURE 1A. PLOT SS+ SOPRV: ΔF (LBF) VS DIAMETER (IN) WITH RATIO RANGES DISTINGUISHED

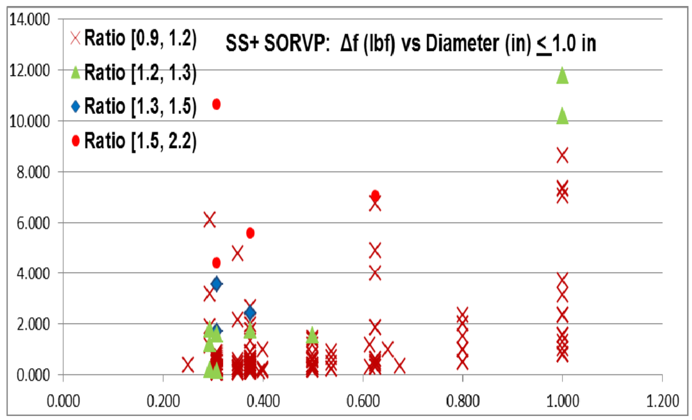

FIGURE 1B. PLOT SS+ SORVP: ΔF (LBF) VS DIAMETER ≤ 1 .0 IN (ENLARGEMENT OF PORTION OF FIGURE 1A)

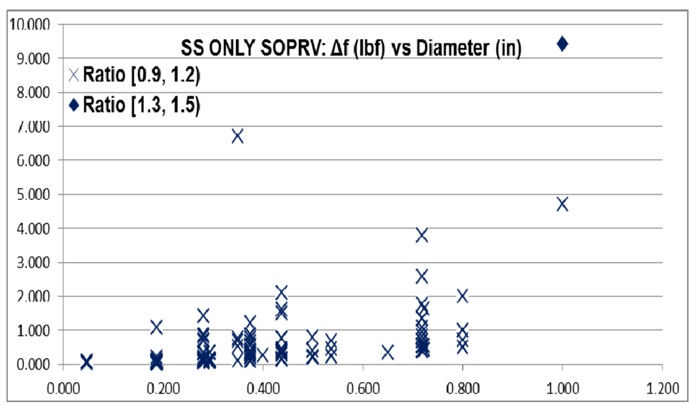

FIGURE 2. PLOT SS ONLY SOPRV : ΔF (LBF) VS DIAMETER (IN) WITH RATIO RANGES DISTINGUISHED

Figures 3a and 3b show plots of Δf (lbf) vs SS+ SOPRV set pressure (psig) for pressure ranges < 150 psig and ≥ 150 psig, respectively. Dividing the plots over the two different ranges of pressures allows for greater detail to be observed in the lower pressure range. Comparable plots for SS ONLY SOPRV are shown in Figures 4a, 4b, and 4c divided over three different pressure ranges.

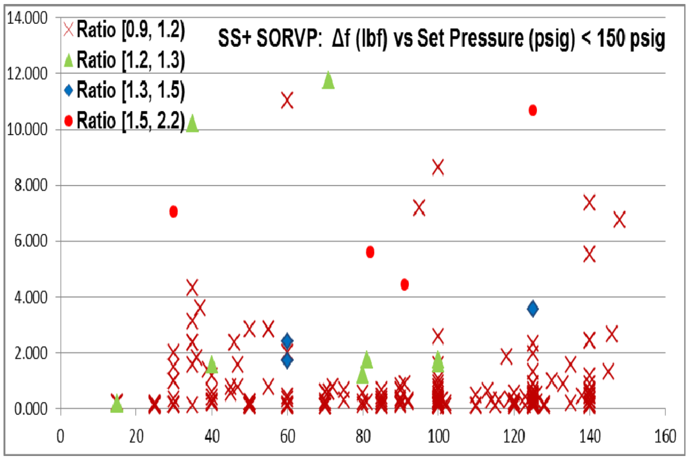

FIGURE 3A. PLOT SS+SORVP: ΔF (LBF) VS SET PRESSURE < 150 PSIG WITH RATIO RANGES DISTINGUISHED

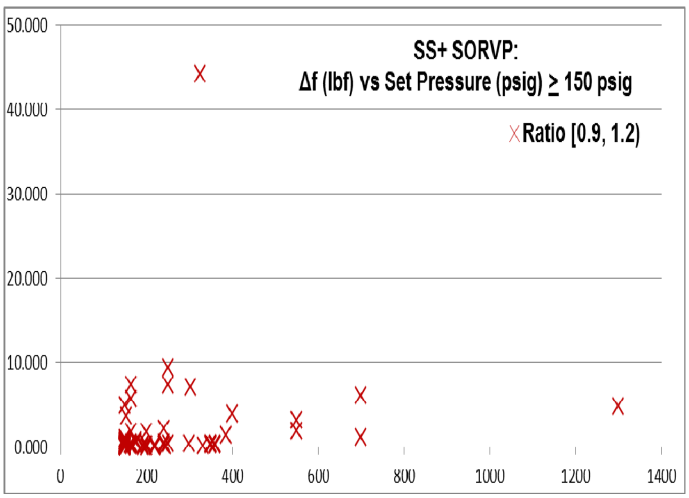

FIGURE 3B. PLOT SS+SORVP: ΔF (LBF) VS SET PRESSURE ≥ 150 PSIG WITH RATIO RANGES DISTINGUISHED

Several features are evident in the five plots. First, it is immediately apparent that adhesions form over all[4] set pressures for both SS ONLY and SS+ SOPRV. For SS+ SOPRV the maximum set pressure is only 1400 psig whereas for SS ONLY SOPRV the set pressure range is much more extensive with a maximum set pressure of 6300 psig. All of the instances of FPT and near-FPT occur in valves with set pressures < 150 psig.

In Figures 3a and 3b note that, the vast majority of SS+ SOPRV that show evidence of adhesion formation have set pressures < 150 psig. In fact, of the 299 SS+ SOPRV that show evidence of adhesion, 209 (69.9%) have set pressures less than 150 psig. Figures 4a, 4b, and 4c illustrate that the opposite is true of SS ONLY SOPRV. Of the 159 SS ONLY

[4] Actually, there are exactly two SOPRV with set pressure of 790 psig. One showed no evidence of adhesion. One had a Δf of 1 psig but was classified as "no evidence" because the set pressure exceeded 500 psig. But the sample size of two is too small to assert that adhesions do not form over all valve set pressures.

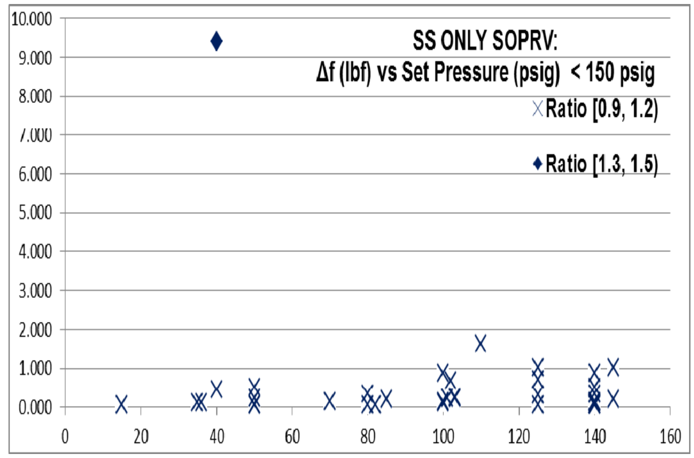

FIGURE 4A. PLOT SS ONLY SOPRV: ΔF (LBF) VS SET PRESSURE (PSIG) < 150 PSIG WITH RATIO RANGES DISTINGUISHED

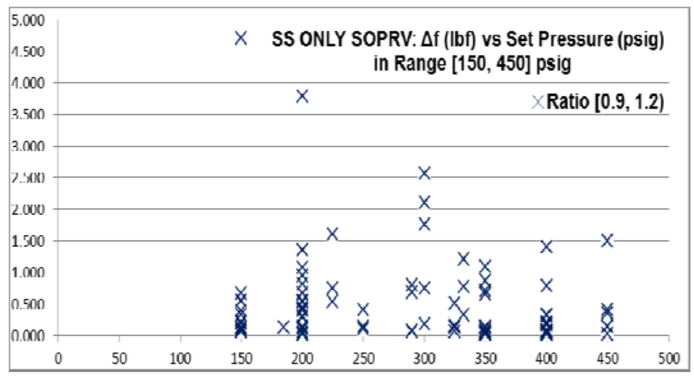

FIGURE 4B. PLOT SS ONLY SOPRV: ΔF (LBF) VS SET PRESSURE (PSIG) IN RANGE [150, 450] PSIG

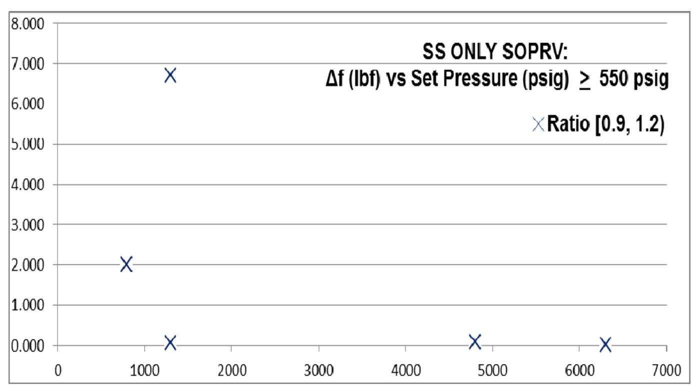

FIGURE 4C. PLOT SS ONLY SOPRV: ΔF (LBF) VS SET PRESSURE (PSIG) ≥ 550 PSIG

SOPRV that show evidence of adhesion, 35 (22.0%) have set pressures < 150 psig. Of course we need to consider also the relative distributions of set pressures for SOPRV that do not show evidence of adhesions. But when these are included and percentages computed relative to the total size of each subpopulation, 75.28% of all SS+ SOPRV and 25.8 % of all SS ONLY SOPRV have set pressures < 150 psig. Thus as a broad generalization, SS+ SOPRV tend to have lower set pressures while SS ONLY SOPRV tend to have higher set pressures.

This observation helps to understand why there is only a single FPT among the SS ONLY SOPRV while there are 7 FPT among the SS+ SOPRV with 4 of these being FTO.

Furthermore, note in Figure 3a that the Δf that develop in SS+ SOPRV with low set pressure (< 150 psig) varies substantially from less than 2 lbf to about 12 lbf. In this subpopulation, 30 of 222 valves (13.5%) develop Δf ≥ 2 lbf. In Figure 4a the Δf which develop in SS ONLY SOPRV with set pressure < 150 psig exceeds 2 lbf for only 1 valve out of 35 (2.9%). Similarly, in Figures 3b, 4b, and 4c, in set pressure ranges ≥ 150 psig, SS+ SOPRV show a greater variation in magnitude of Δf developed while SS ONLY SOPRV seldom develop Δf of more than 2 lbf. For set pressures ≥ 150 psig, 13 of 77 (16.9%) SS+ SOPRV develop adhesions with Δf ≥ 2 lbf while only 6 of 124 (4.8%) SS ONLY SOPRV similarly develop Δf ≥ 2 lbf.

The last combinations of plots explored are plots of set pressure vs diameter. Figure 5a shows a plot of SS+ SOPRV set pressure (psig) vs diameter (in) and highlights the scarcity of data for SS+ SOPRV with diameters > 1.0 in. Figures 5b and 5c expand the scales for the data in Figure 5a for SS+ SOPRV diameter ≤ 1.0 in. In Figure 5b we see clearly that all FPT and near-FPT are confined within the parameters diameter ≤ 1.0 in and set pressure < 150 psig.

Figures 6a and 6b plot SS ONLY SOPVR set pressure (psig) vs diameter (in) divided between set pressures < 150 psig and ≥ 150 psig. All SS ONLY SOPRV in this study have diameters ≤ 1.0 in. Again the single FPT in this subpopulation is confined within the parameters diameter ≤ 1.0 in and set pressure < 150 psig.

SUMMARY OF DATA

Based on the information we have gleaned from our many plots, we have summarized the study data in Tables 3 and 4. Table 3 summarizes information for SOPRV of diameter ≤ 1 in and Table 4 summarizes the same information for SOPRV of diameter > 1 in.

DATA ANALYSIS

It may be tempting to look at the summarized data and, noticing that all eight FPT, including four FTO, occur in valves produced by Manufacturer AA, conclude that the problem is with Manufacturer AA. However, this would be premature. We also need to consider that Manufacturer AA is, by far, the single largest contributor to SOPRV in this data region (diameter ≤ 1 in and set pressure < 150 psig) of Table 3. We need to understand whether this distribution of FPT/FTO among the seven[5] represented manufacturers truly represents a difference attributable to Manufacturer AA relative to the others or whether this distribution of FPT could have occurred

[5] Note that Manufacturer DD is not represented in any data with set pressure < 150 psig.

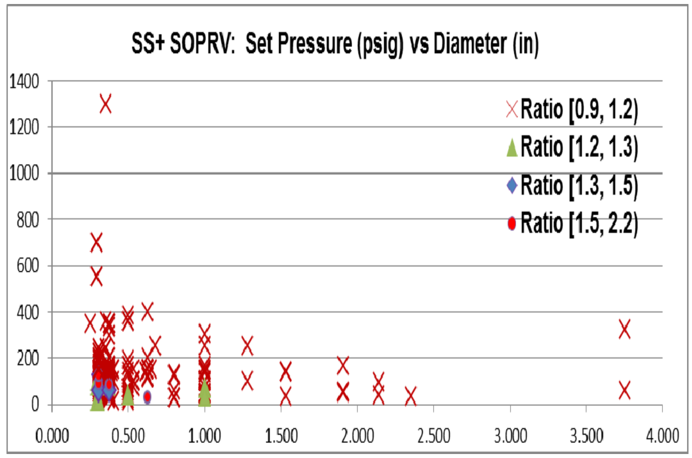

FIGURE 5A. PLOT SS+ SOPRV: SET PRESSURE (PSIG) VS DIAMETER (IN) WITH RATIO RANGES DISTINGUISHED

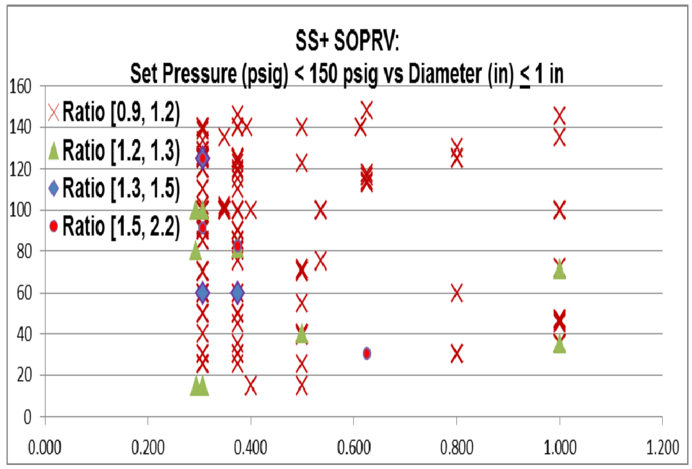

FIGURE 5B. PLOT SS+ SOPRV: SET PRESSURE (PSIG) < 150 PSIG VS DIAMETER (IN) ≤ 1 IN (ENLARGEMENT OF PORTION OF FIG. 5A)

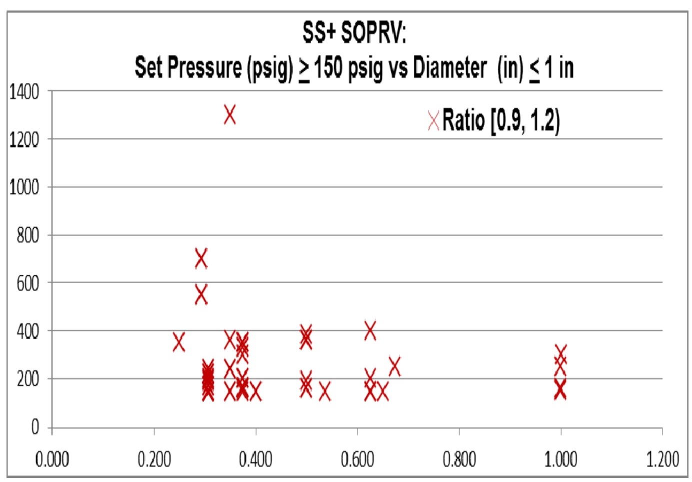

FIGURE 5C. PLOT SS+ SOPRV:SET PRESSURE (PSIG) ≥ 150 PSIG VS DIAMETER (IN) ≤ 1 IN (ENLARGEMENT OF PORTION OF FIG. 5A)

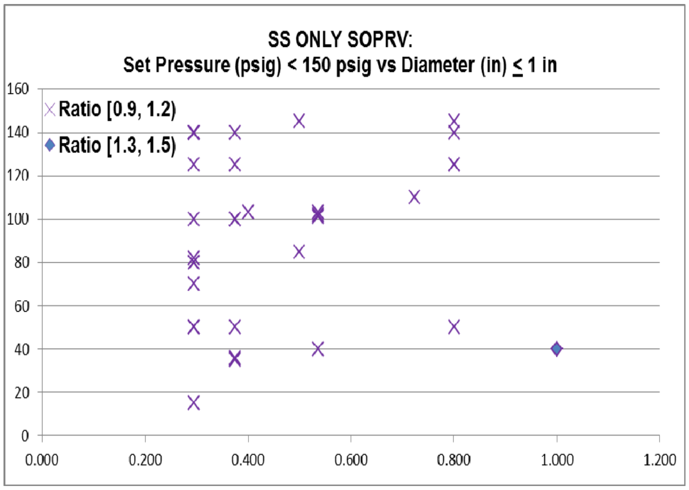

FIGURE 6A. PLOT SS ONLY SOPRV: SET PRESSURE (PSIG) < 150 PSIG VS DIAMETER (IN) ≤ 1 IN WITH RATIO RANGES DISTINGUISHED

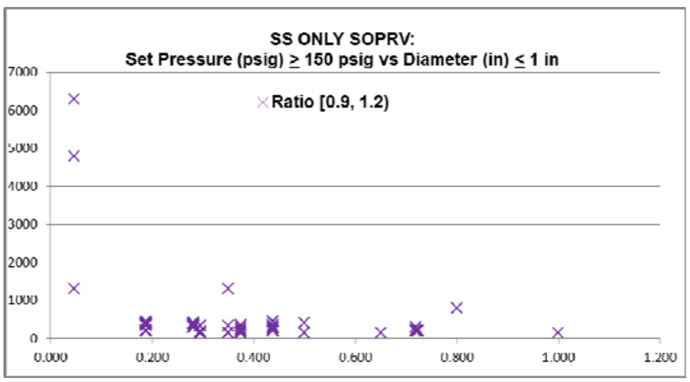

FIGURE 6B. PLOT SS ONLY SOPRV: SET PRESSURE (PSIG) ≥ 150 PSIG VS DIAMETER (IN) ≤ 1 IN

purely by chance. In fact, in general, it is useful to ask if there are statistically significant difference among manufacturers in each of the four data regions summarized in Tables 3 and 4.

Are There Differences in Adhesion Formation and Adhesion FPT Among Manufacturers?

In the case with SOPRV diameter ≤ 1 AND set pressure < 150 psig, the null hypothesis, H_0, tests difference in proportions over three possible outcomes, viz., H_0 is: the proportions of SOPRV without adhesions, with adhesions but no FPT, and with adhesions and FPT is the same for all manufacturers. In the remaining cases (combinations of diameter and set pressure), H_0 tests differences in proportions over two possible outcomes, viz., H_0 is: the proportions of SOPRV without adhesions and with adhesions are the same for all manufacturers. Table 5 summarizes the findings of these statistical tests. In each case, χ^2 [18] was computed from the appropriate data and compared to the critical χ^2 value for level of significance $\alpha = 0.05$. H_0 is rejected if the computed χ^2 exceeds the critical χ^2 which was determined by simulation. Using the standard χ^2 tables based on the normal approxima-

TABLE 3 SUMMARY OF DATA FOR SOPRV WITH ORIFICE DIAMETER ≤ 1 IN

Manufacturer Code	# SOPRV	SOPRV ORIFICE DIAMETER ≤ 1 in					
		Set Pressure < 150 psig			Set Pressure ≥ 150 psig		
		total #	# w/ adhesions		total #	# w/ adhesions	
			Not FPT	FPT/ FTO		Not FPT	FPT
AA	330	239	126	8/4	91	46	0
BB	183	108	48	0	75	33	0
CC	169	116	39	0	53	26	0
DD	181	0	0	0	181	82	0
EE	54	35	17	0	19	7	0
FF	7	3	2	0	4	4	0
GG	5	5	2	0	0	0	0
HH	3	3	2	0	0	0	0
Total	932	509	236	8/4	423	198	0

TABLE 4 SUMMARY OF DATA FOR SOPRV WITH ORIFICE DIAMETER > 1 IN

Manufacturer Code	# SOPRV	SOPRV ORIFICE DIAMETER > 1 in					
		Set Pressure < 150 psig			Set Pressure ≥ 150 psig		
		total #	# w/ adhesions		total #	# w/ adhesions	
			Not FPT	FPT		Not FPT	FPT
AA	15	9	3	0	6	2	0
BB	17	17	8	0	0	0	0
CC	33	24	2	0	9	1	0
DD	0	0	0	0	0	0	0
EE	3	3	0	0	0	0	0
FF	0	0	0	0	0	0	0
GG	0	0	0	0	0	0	0
HH	0	0	0	0	0	0	0
Total	68	53	13	0	15	3	0

TABLE 5 RESULTS OF TESTING H_0: NO STATISTICAL DIFFERENCE IN PROPORTIONS AMONGST MANUFACTURERS WITH A = 0.05

Test on	Calculated χ^2	Critical χ^2	Conclusion Re: H_0
Diameter ≤ 1 in Pressure < 150 psig	24.204	21.518	REJECT H_0
Diameter ≤ 1 in Pressure ≥ 150 psig	6.325	10.730	Do not reject H_0
Diameter > 1 in Pressure < 150 psig	9.414	5.889	REJECT H_0
Diameter > 1 in Pressure ≥150 psig	1.111	2.500	Do not reject H_0

tion in order to find the critical χ^2 values requires certain assumptions that our data do not meet. Specifically, the standard tables should not be used "when one or more of the expected frequencies is less than 5" [18]. Due to the small numbers of SOPRV with adhesions but no FPT for a number of manufacturers we have several cases where the expected frequencies will be less than 5.

In Table 5, for Diameter ≤ 1 in and Pressure < 150 psig, it should be noted that the critical χ^2 value is large because this H_0 involves a test of proportions with three possible outcomes over seven manufacturers. Therefore if we were able to use the standard χ^2 tables we would find the critical value based on 12 degrees of freedom (because 12 equals (3-1) outcomes times (7-1) manufacturers) which, for $\alpha = 0.05$, would be 21.026 – just slightly smaller than our simulated value.

Also, in Table 5 it may be noted that the critical χ^2 values for the third and fourth cases differ significantly from the standard χ^2 table values (5.889 vs. 7.814 and 2.500 vs. 3.841, respectively). The explanation is simple and is illustrated using the fourth case. In the case with SOPRV Diameter > 1 in and Pressure ≥ 150 psig there are only two manufacturers represented and only three instances of adhesions. There are only four possible ways that three adhesions can occur between the two manufacturers. Representing the number of adhesions for the two manufacturers by the pair (a, b) where a + b must equal 3, we can enumerate the possible pairs as (0, 3), (1, 2), (2, 1), and (3, 0). Thus there are only four possible computed values for χ^2, viz., 2.500, 0.069, 1.111, and 5.625 for the respective pairs. Now it is easily shown that the 95% point in the discrete distribution of computed χ2 values occurs for the value of χ^2 equal to 2.500. Because of the small sample size, the probability distribution is not well approximated by a continuum and thus, the critical χ^2 differs significantly from that of the standard χ^2 tables. The difference between the simulated critical χ^2 and standard χ^2 value for the third case is similarly explained.

In the two data regions with set pressure ≥ 150 psig, we cannot reject H_0 meaning that there is no statistically significant differences amongst the represented manufacturers with respect to adhesion formation at these higher set pressures. However, in the two data regions with SOPRV set pressure < 150, we reject H_0 meaning that there is a statistically significant difference amongst the represented manufacturers with respect to adhesion formation in the lower set pressures.

Although our statistical tests tend to support the earlier conjecture that indeed Manufacturer AA is the problem in FTO or FPT development, we cannot be sure that it is Manufacturer AA per se that is the problem. It is conceivable that some particular design characteristic is the underlying cause and that it happens to occur in our particular population in SOPRV from Manufacturer AA. If this characteristic is also present in another manufacturer's design but only in models not represented in our population, we would not see it in our data set. However, we might find similar patterns of adhesion and FPT/FTO formation in that other manufacturer's SOPRV if models with similar designs to those with FTO or FPT in our study were present in our population.

Similarly, we might find statistical differences between SS+ and SS ONLY SOPRV despite the fact that the materials are the same in each SOPRV at the surface where the adhesions form. However, it seems unlikely that adhesions would form differently on identical materials due to the use of different materials elsewhere in the SOPRV construction. Such statistical differences, if present, are more likely due to design differences than to differences in material construction not involving nozzle/seat and disc.

At this stage of our investigation, we will limit our interpretation of the data to the following: Based on the data for SOPRV in Table 3, we can say that adhesions form on about half (47.4%) of all SS trim SOPRV with diameter ≤ 1 in. Whether these adhesions develop into FTO or FPT seems to be a function of SOPRV set pressure with FTO or FPT formation limited to SOPRV with set pressures < 150 psig and may also be a function of other valve characteristics yet undiscovered.

DISCUSSION

In previous research [5] we noted that all FTO were found in SOPRV with set pressures < 125 psig but could offer no explanation for this phenomenon. At that time we did not have information about the diameters of each SOPRV. With the addition of diameter information and information about the Δf that develop when adhesions occur, the explanation for FTO occurrence at lower set pressures is relatively simple.

A SOPRV is FTO due to adhesion if the Δp required to disrupt the adhesion is ≥ 50% of the SOPRV set pressure. The smaller in diameter the SOPRV is, the smaller the orifice area and hence the larger the pressure needed to disrupt the Δf of the adhesion. So for a given SOPRV with an adhesion force of Δf, the lower the set pressure, the more likely Δp equals or exceeds 50% of the set pressure.

The same explanation can be given for the occurrence of FPT which all were discovered in SOPRV with set pressures < 150 psig. The only difference is that for FPT the Δp must equal or exceed 30% of the set pressure.

Based on the data for the SS trim SOPRV population in this paper, and conservatively assuming that adhesions may develop into FTO or FPT for any manufacturer, we can calculate both a point estimate (4/509 = 0.0079) and the 95% confidence interval ([0.0031, 0.0200][6]) for the probability that a new SS trim SOPRV with diameter ≤ 1 in and set pressures < 150 psig will be FTO due to adhesion. This probability is the probability of initial failure or PIF. At the mid-point of this 95% confidence interval PIF is 1.15%!

[6] Note that the interval estimate is given by the Wilson score interval [19] 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.

IMPLICATIONS OF FINDINGS FOR RELABILITY & SAFETY OF SS TRIM SOPRV

IEC safety standards [1, 2] assign a SIL to an individual piece of safety equipment not to a population of the same or similar equipment. The SIL level is determined by the average probability of failure on demand (PFDavg), i.e., average probability of FTO, which is based on the assumed constant useful life failure rate, λ_D, of the equipment and the length of time, T_P, between periodic proof test cycles. PFDavg is *usually* well approximated by

$$PFDavg \approx PIF + (1-PIF) * 0.5 * \lambda_D * T_P. \quad (1)$$

Table 6 gives the conversion between PFDavg and SIL levels.

Table 9
Correspondence Between PFDavg and SIL

SIL per IEC61508[1]	PFDavg
1	$[10^{-2}, 10^{-1})$
2	$[10^{-3}, 10^{-2})$
3	$[10^{-4}, 10^{-3})$
4	$[10^{-5}, 10^{-4})$

Based on (Eq. 1), the minimum value of PFDavg is PIF. Because of the development of adhesion FTO in new SS trim SOPRV for diameters $\leq$ 1 in and set pressures < 150 psig, and based on the 95% confidence interval for PIF, we see that these SOPRV cannot receive a SIL rating of better than SIL 2 based on the lower confidence interval limit of 0.0031 and cannot receive a SIL rating of better than SIL 1 based on the upper confidence interval limit of 0.0200 unless they are proof tested prior to installation.

Furthermore, though not previously discussed, in determining whether a SOPRV had evidence of adhesion formation, we also identified SOPRV with $\Delta p \geq 50\%$ set pressure due to manufacturing defects. Manufacturing defects are reasonably assumed to occur in any SS trim SOPRV, not just those of particular orifice diameter or set pressure. Based on identification of a total of 1 FTO due to manufacturer defect (out of a total population of 1000), the 95% confidence interval of PIF due to manufacturer defect is [0.0002, 0.0056][7]. If manufacturing defects are not eliminated by pre-installation proof testing, then for any new SOPRV this source of PIF must also be accounted for.

SUMMARY OF FINDINGS & CONCLUSIONS

Adhesions form between the seat and disc in about 46% of all new SS trim SOPRV. Whether these adhesions develop into FTO or FPT appears to depend on the size of the SOPRV, as measured by its orifice diameter, and its set pressure. The forces of adhesion that develop tend to be small (< 2 lbf) but a number of larger Δf have been observed. However, the size of the Δf does not correlate to the formation of FTO or FPT. Some small Δf lead to FTO or FPT while some larger Δf do not. The most important factors identified to date associated with the development of FTO or FPT due to adhesion are SOPRV diameter in the range $\leq$ 1 in and set pressure in the range < 150 psig.

For new SS trim SOPRV with diameters $\leq$ 1 in and set pressures < 150 psig, end users who do not perform pre-installation testing need to account for the PIF associated with FTO due to both adhesions and manufacturers' defects. Our data support this combined PIF being in the range [0.0037, 0.0215][7]. This is calculated by adding the point estimates for each failure source (0.0079 for adhesion FTO and 0.0010 for manufacturer defect FTO) to give a point estimate of 0.0089 and then computing the 95% confidence interval as the Wilson score interval based on 509 data samples. Adding the two point estimates assumes that the sources of FTO are mutually exclusive. We have no particular evidence to either support or refute this assumption. However, as the assumption is conservative from a safety perspective we submit that it is reasonable.

For new SS trim SOPRV with diameters > 1 in or set pressures $\geq$ 150 psig, end users who do not perform pre-installation testing need to account for the PIF associated with FTO due only to manufacturers' defects. As previously noted, the point estimate of this source of PIF is 0.0010 and the 95% confidence interval is [0.0002, 0.0056][7].

The research reported here is part of an on-going study of SOPRV safety and reliability. We next plan to examine the adhesion phenomenon with respect to its relation to contact area between the seat and disc and, if appropriate data is available, with respect to the amount of time the seat and disc are under spring pressure.

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REFERENCES

1. IEC 61508, Functional safety of electrical/electronic/ programmable electronic safety-related systems, Geneva, Switzerland, 2010.
2. ANSI/ISA SP84.00.02 – 2004 (IEC 61511 Mod.), Application of Safety Instrumented Systems for the Process Industries, Raleigh, NC, ISA, 2004.
3. Bukowski, J. V. and Gross, R. E., "Results of Root Cause Analyses of Spring Operated Pressure Relief Valve Failures," *Proceedings of the AIChE 6th Global Congress on Process Safety, 12th Process Plant Safety Symposium*, San Antonio, TX, March 2010.
4. Bukowski, J. V., Gross, R. E. and Goble, W. M., "Probability of Initial Failure for Spring Operated Relief Valves," *Proceedings of the ASME 2011 Pressure Vessels and Piping Division Conference*, Baltimore, MD, July 2011.
5. Bukowski, J. V., Gross, R. E., and Goble, W. M., "The Adhesion Failure Mode in Stainless Steel Trim Spring Operated Pressure Relief Valves, *Proceedings of the ASME 2012 Pressure Vessels and Piping Division Conference*, Toronto, Canada, July 2012.

[7] Note that the interval estimate is given by the Wilson score interval. See footnote 6 above for additional details

6. McFarlane, J. S. and Tabor, D., "Adhesion of solids and the effect of surface films," *Proceedings of the Royal Society of London* Series A, 202, 224-24, 1950.
7. "Cold Welding, Advanced Automation for Space Missions," Publication number NASA CP-2255, *Proceedings of the 1980 NASA/ASEE Summer Study*, November 1982.
8. Braun, O. M. and Naumovets, A. G., Nanotribology: microscopic mechanisms of force, Institute of Physics, National Academy of Sciences of Ukraine, Surface Science Reports 60, 2006**.**
9. Bhushan, B., Modern Tribology Handbook, Volume 1, Ohio State University, Columbus, OH USA, 2001, CRC Press.
10. Hearn, E. J., *Mechanics of Materials 2, An introduction to the mechanics of elastic and plastic deformation of solids and structural materials*, University of Warwick, United Kingdom, 3rd edition, Elsevier, 1997.
11. Smith, D. J., "The influence of prior loading on structural integrity," *Comprehensive Structural Integrity*, *Volume 7,* University of Bristol, UK, 2003.
12. Smith, D. J., "The Influence of Prior Loading on Structural Integrity", *Comprehensive Structural Integrity Volume 1, Structural Integrity Assessment – Examples and Case Studies*, University of Bristol, UK, Elsevier, 2006.
13. Gross, R., "Reliability Testing of Pressure Relief Valves," Design and Analysis of Pressure Vessels, Heat Exchangers, and Piping Components – 2004, PVP-Vol 477, Paper # PVP2004-2610, San Diego, CA, July 2004.
14. *ASME Boiler and Pressure Vessel Code, Section VIII Division 1, UG-126 Pressure Relief Valves to UG-129 Marking*, ASME International, New York, NY, 2010.
15. ASME PCC-3-2007 Inspection Planning Using Risk-Based Methods, June 30, 2008.
16. API RP 581 Risk-Based Inspection Technology, Section 7 Pressured Relief Devices, American Petroleum Institute (API) Recommended Practice 581, 2nd Ed., September 2008.
17. API RP 576 Inspection of Pressure Relieving Devices, American Petroleum Institute (API) Recommended Practice 581, 3rd ed., November 2009.
18. Johnson, R. A., *Miller & Freund's Probability and Statistics for Engineers*, 6th Ed., Prentice Hall, Inc., Upper Saddle River, NJ, 2000.
19. "Binomial Proportion Confidence Interval." *Wikipedia, the Free Encyclopedia*. Web. 10 Mar. 2013. <http://en.wikipedia.org/wiki/Binomial_proportion_confidence_interval>.