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PROBABILITY OF INITIAL FAILURE FOR SPRING OPERATED RELIEF VALVES

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ABSTRACT

We present clear and convincing evidence that, for new spring operated relief valves (SORV) that are not proof tested *by the user* shortly before installation, there is a non-trivial probability that the SORV will be installed in the fail-to-open (stuck shut) failure mode. Using the results of over 4800 new ASME Boiler and Pressure Vessel Code Section VIII SORV proof tests, we estimate the probability of initial failure (PIF) due to manufacturer/assembly anomalies, as well as PIF due to in-storage aging of SORV based on their material composition.

We indicate how PIF can be reduced by various pre-installation activities that may be undertaken by the user. We show how to compute values of PIF to be used in calculating the average probability of fail danger (PFDavg) (as required by IEC61508 and similar safety standards in order to determine a safety integrity level (SIL)) which accounts for both the SORV material composition and the pre-installation activities undertaken.

For four typical SORV of different material compositions we show how pre-installation activities influence the achievable SIL. We discuss the implication of these findings for estimating PIF for used (previously installed) SORV. We close with recommendations to further address PIF.

INTRODUCTION

SORV are safety devices used extensively in many industrial processes to reduce the risk of accidents due to overpressure events. During routine process operation, the SORV would normally be closed. Should the SORV become stuck in the closed position it would be unable to relieve process pressure in the event of an overpressure event. This failure mode, called fail-to-open (FTO) or “stuck shut”, is deemed a dangerous failure. Furthermore, this failure mode is undetectable while the SORV is installed in a process.

In order to discover the FTO failure mode, it is necessary to remove the SORV from the process and subject it to a proof test. In a proof test, the SORV is placed on a test bench and pressurized until it lifts (“pops”). The pressure at which it pops for the first time is the proof test pressure. If the ratio of proof test pressure to set pressure (the pressure at which the SORV is intended to pop) is greater than or equal to 1.5, the SORV is deemed to be in the FTO condition. Intuitively, the longer the SORV is installed in the process the greater the probability of finding it in the FTO state.

In order to assign a SIL to a SORV as required by IEC61508 [1] or a similar safety standard, it is necessary to be able to determine the failure rate of the FTO failure mode, as well as an appropriate interval for proof testing. It is common practice to model that failure rate as a constant, λ_D, either estimated by statistical analysis of proof test data [2], determined by a failure modes effects and diagnostics analysis (FMEDA) [3], or estimated from time to failure data. Further, these three quite different techniques have been used to establish that, for SORV, λ_D is on the order of 10^{-8} - 10^{-7} failures/hour or 10^{-4} - 10^{-3} failures/year [4, 5, 6].

However, a number of other important points emerged from the study reported in [4].

- Independent analysis of three different proof test data sets of significant size clearly indicated that λ_D accounted for only a small fraction of the FTO failures observed in SORV during proof testing.
- The remaining failures were attributed to “initial failures”, i.e., failures that are present from the time of installation.
- PIF was estimated to be on the order of 0.5 - 1.0%.
- PIF strongly influences PFDavg which is used to determine a SORV SIL rating and the interval for proof testing.

- Understanding the source of PIF is an important step to improving SORV safety performance.

The findings regarding PIF have been controversial. Some believe that while PIF may exist, it is not significant in *their* plants; however, they offer no concrete evidence to validate this assertion. Others believe that PIF is a real, non-trivial phenomenon that should be modeled in computing PFDavg and SIL, and further studied and addressed.

It is important to note that [4] offered *no* explanations or hypotheses regarding the underlying causes of initial failures. In private communications with the authors, some have attributed PIF to manufacturer defects, inappropriate transport, handling and storage, or human error during installation. However, again, no specific data has been put forth to support these assumptions.

One difficulty in studying PIF using proof test data is that most proof test data come from the testing of used SORV, i.e., SORV that have been installed in processes and then tested at their required proof test interval. If a FTO failure is discovered in this manner, it is often difficult or impossible to ascertain the time of failure. Thus, if one relies on proof test data from used SORV, it is difficult to show that a SORV was FTO at the time of installation. However, in a previous study [7], we did identify a few new SORV FTO in a sample of SORV data. Thus, it seemed logical to look for evidence of PIF in the proof test results of new SORV.

Therefore, for this paper, we analyzed extensive data gathered from the results of proof tests performed on new SORV, i.e., SORV that had never previously been installed in a process, in their "as received condition" prior to their very first installation in any process. Clearly, if a FTO failure exists in a new SORV and that SORV is not subjected to proof testing prior to installation, then when it is installed, an initial failure undoubtedly exists. Since many users do not proof test new valves "out of the box", if new valves are found to be failed, then initial failure is a real phenomenon.

In this paper, we provide details about the data source used for this study and summarize the data. We consider the physical causes of new SORV FTO, categorize the FTO relative to physical cause and material composition of SORV, and discuss the findings. For our data we compute point estimates and interval estimates for PIF for each FTO category. Further we show how to incorporate these various PIF estimates into the computation of PFDavg and SIL as a function of pre-installation activities undertaken by the user. While we do not claim that estimates of PIF from our data are appropriate values for PIF for all users or all types and manufacturers of SORV, we use the PIF estimates from our data to demonstrate the effects of PIF on PFDavg and SIL given various pre-installation activities including activities which fall short of proof testing but which reduce PIF. We also consider the implications that these findings have for estimating used SORV PIF. Lastly, we conclude with some recommendations.

DATA SOURCE AND SUMMARY

Source

Data for this study came from Savannah River Nuclear Solutions – US-DOE Savannah River Site (SRS). SRS conducts all of its valve tests at one dedicated test and repair facility which insures consistency of test and repair equipment, 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.

Data Summary

The data, collected during an approximate 8 year period from 2003 to February, 2011, consist of a total of 4846 new SORV proof tests performed on a variety of ASME Boiler and Pressure Vessel Code Section VIII SORV. While the SORV tested represent more than 50 different manufacturers, seven manufacturers account for 3782 (~78%) of the new SORV tests with each of the seven accounting for 330 or more tests. Of the 4846 new SORV tested, 18 (~ 0.37%) were found to be FTO. However, before concluding that this small percentage is an appropriate estimate for PIF for every SORV, we examined each FTO record to ascertain the physical cause of each failure to see if any patterns emerged in the FTO of different kinds of SORV.

PHYSICAL CAUSES OF INITIAL FAILURES

Summary of Findings

Table 1 summarizes the physical causes of failure of the 18 new SORV found in the FTO condition. We classified the FTO into two types according to their underlying physical causes. In Type I failures, the SORV arrived at SRS from the manufacture/assembly/shipping process in the FTO state. In Type II failures, the evidence strongly suggests that the SORV left the assembly process in working order but subsequently entered the FTO state probably during a period of prolonged storage, i.e., Type II failures are due to aging in storage. We further subdivide the Type II failures into Type II-A, Type II-B, and Type II-C according to the physical cause of the failure which relates to the material composition of the SORV seat and disc or SORV spring assembly.

Discussion of Findings

The seven Type I FTO include SORV from five different manufacturers. Reviewing the "as received" physical causes of failure for these SORV, it is clear that they are the result of manufacturer/assembly anomalies and that these kinds of anomalies could occur in any SORV regardless of material composition.

The three Type II-A FTO include SORV from three different manufacturers. The soft seat embedment phenomenon applies to SORV with non-metallic seats, e.g., viton, buna,

Table 1. Physical Causes of FTO for New SORV

FTO #	FTO Type	Material Composition of SORV	Physical Cause
1	I	Non-metal	Improper factory set
2	I	Non-metal	Valve not set as stamped; set high
3	I	Non-metal	Valve not set as stamped; set high
4	I	Non-metal	The set point could not be achieved in the as arrived condition. Shop had to scrag (crush to solid height) the spring before the setting could be achieved.
5	I	Neoprene	Internal binding due to presence of foreign material
6	I	Neoprene	Internal binding due presence of foreign material
7	I	Bronze body; stainless steel ball	Valve arrived without a discharge port being machined by the vendor; defect not detected by factory
8	II-A	Viton/Buna	Soft seat embedment
9	II-A	Viton/Buna	Soft seat embedment
10	II-A	Viton/Buna	Soft seat embedment
11	II-B	Stainless Steel	Micro-embedment; surface creep
12	II-B	Stainless Steel	Micro-embedment; surface creep
13	II-B	Stainless Steel	Micro-embedment; surface creep
14	II-B	Stainless Steel	Micro-embedment; surface creep
15	II-B	Stainless Steel	Micro-embedment; surface creep
16	II-B	Stainless Steel	Micro-embedment; surface creep
17	II-B	Stainless Steel	Micro-embedment; surface creep
18	II-C	Carbon Steel	Corrosion

nitrile rubber, Teflon, and neoprene. As the spring pressure presses down on the joint between the soft seated disc and the hard seated metal nozzle, over time, the harder material becomes embedded in the softer material such that the pressure needed to pop the SORV becomes significantly greater than the original set pressure. Clearly, the SORV does not need to be installed in a process for this type of failure to occur and any soft seat SORV is subject to this failure phenomenon. Once the embedment failure has been resolved during a proof test, the SORV may recover nicely and pop and reseat appropriately during the remainder of the proof test. It is also possible that the soft material "takes a set" which reduces the flexibility needed to seal or reseat the SORV after the first pop.

The seven Type II-B FTO include SORV from three different manufacturers. The physical causes of this failure model, micro-embedment and surface creep, are two separate phenomena that are very hard to differentiate without significant investment in time and nondestructive examination; however, they present the same observable failure and need not be distinguished for the purposes of addressing PIF in this type of FTO. These phenomena occur at the interface of two ductile, malleable surfaces such as stainless steel (SS). Both of these random failure mechanisms express themselves as surfaces adhering to one another such that the pressure required to separate them exceeds the original set pressure of the SORV. However, once the adhesion has been relieved by an initial pop during proof testing, the SORV tends to recover nicely and subsequent pops during the same proof test occur within an acceptable range at or near the set pressure. Our data show that any SORV having soft metal interfaces is subject to this failure phenomenon.

The micro-embedment and surface creep phenomena, along with other soft metal failure mechanisms that also present as adhesions, are described in detail in the Annex.

It should be noted that the Type II-A and II-B FTO detailed above are the result of extended storage, not improper storage. SRS data suggests these failures may develop over a period of two or more years but this is not certain. Nevertheless, SRS limits the storage interval on site without retesting to six months. Because many SORV have no indication as to the date of assembly, it is generally not possible to know how long a SORV has been in storage prior to receipt by the user.

Lastly, the single Type II-C failure clearly represents only one manufacturer. This type of failure is likely due to extended storage in inappropriate environmental conditions. It occurs when carbon steel (CS) components corrode so that the SORV will test FTO.

ESTIMATING PIF BY FTO TYPE

Table 2 summarizes the number of failures for and the total population of SORV subject to each type of failure along with both point estimates and 95% confidence interval estimates for PIF for the various failure types based on the SRS data. Note that the interval estimate is given by the Wilson score interval [8] 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. Also note that the point estimate is not the center of the interval.

Table 2. Summary of Failure Data and PIF Estimates by FTO Type

FTO Failure Type	# Failures Observed	# SORV Subject to Failure Type	Point Estimate of PIF	95% Confidence Interval Estimate of PIF
I	7	4846	0.0014	[0.0007, 0.0030]
II-A	3	2849	0.0011	[0.0004, 0.0031]
II-B	7	931	0.0075	[0.0036, 0.0154]
II-C	1	155	0.0065	[0.0011, 0.0356]

DETERMINING PIF FOR SAFETY CALCULATIONS

While Table 2 provides estimates for PIF by FTO type, it does not directly indicate the value of PIF that should be used in calculating PFDavg and SIL for a given SORV. Because SRS proof tests all SORV prior to installation, they can reasonably claim that no initial failures exist in their facility, i.e., they can set PIF equal to zero in calculating PFDavg and SIL for any SORV regardless of material composition. But what if they did not undertake pre-installation proof testing? Then, they would have to account for PIF in their safety calculations. Clearly, the value of PIF used in such calculations depends on both the material composition of the SORV and the pre-installation activities undertaken by the user.

For a soft seat, SS trim, i.e., SS seat and disc, or CS/SS mixed trim SORV that is not proof tested but is manually lifted (if this is possible) to insure any embedment, adhesion, or corrosion FTO are resolved, the user needs only account for the PIF due to manufacturer anomalies. If no pre-installation activities are undertaken, then the user must account for PIF due both to manufacturer/assembly anomalies and to material composition. For SORV of other material composition, e.g., bronze, if no proof test is performed, the user must account, at a minimum, for the PIF due to manufacturer/assembly anomalies. Other physical causes of initial FTO related to material composition may occur in these other kinds of valves but we have no examples in our database to support values of PIF beyond the manufacturer anomalies.

Table 3 summarizes the values and 95% confidence intervals for PIF estimated from the SRS data taking into account both SORV material composition and pre-installation activities. In the case of no pre-installation activities, the PIF is computed as the probability of the union of the two events manufacturer anomalies (MA) and in-storage failures (ISF) which are assumed to be independent failures. Thus the probability of the union is computed as

$$P(MA \cup ISF) = P(MA) + P(ISF) - P(MA)*P(ISF) \qquad (1)$$

The values for PIF are based on both the point estimates and the 95% confidence interval estimates for the various FTO types. Clearly, the interval estimates indicate that it is possible that PIF can be less than or greater than the point estimates.

Table 3. Point & 95% Confidence Interval Estimates for PIF by SORV Material Composition and User Pre-Installation Activities

Pre-Installation Activity	SORV Material Composition			
	Soft Seat	SS Trim	CS/SS Mixed Trim	Other
Full Proof Test	0	0	0	0
Man-ual Lift	0.0014 [0.0007, 0.0030]	0.0014 [0.0007, 0.0030]	0.0014 [0.0007, 0.0030]	0.0014 [0.0007, 0.0030]
None	0.0025 [0.0011, 0.0061]	0.0090 [0.0043, 0.0183]	0.0079 [0.0018, 0.0385]	0.0014 [0.0007, 0.0030]

EFFECTS OF PIF ON PFDavg AND SIL

In order to demonstrate the effects of PIF on PFDavg and SIL once SORV are installed, we needed values for λ_D which were representative of installed SORV of the four types of material composition considered in Table 3. To predict λ_D for the soft seat, the SS trim, and the CS/SS mixed trim SORV, we completed a FMEDA for one SORV of each type currently installed in SRS. To represent "Other" SORV which are neither soft seat, SS trim, nor CS/SS mixed trim, we choose a value in the mid-range of values for λ_D previously established [4]. Table 4 summarizes these values.

Table 4. Values for λ_D Used When Computing PFDavg in Examples

Material Composition	λ_D	
	failures/hr	failures/yr
Soft Seat	$2.7 * 10^{-8}$	$2.4 * 10^{-4}$
SS Trim	$7 * 10^{-9}$	$6 * 10^{-5}$
CS/SS Mixed Trim	$4.1 * 10^{-8}$	$3.6 * 10^{-4}$
Other	$5 * 10^{-8}$	$4 * 10^{-4}$

For each of these values of λ_D we computed PFDavg as a function of the proof test interval, TP, using the approximate equation [4]

$$PFDavg = PIF + (1-PIF) * \lambda_D * TP/2 \qquad (2)$$

For PIF we used the values as given in Table 3 for the point estimate and the limits of the interval estimate determined by the type of pre-installation activity and SORV material composition. The corresponding SIL levels are determined as given in Table 5. It should be noted that having PFDavg in a particular range at the time of proof test, TP, is a necessary but not sufficient condition to receive the corresponding SIL rating. Other conditions apply as well. Further, it is generally recognized that achieving a SIL 4 rating is, as a practical matter, either impossible or prohibitively expensive, and no end user or manufacturer has yet to attain this highest rating.

Table 5. Correspondence Between PFDavg and SIL

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

The resulting plots of PFDavg vs TP are shown in Figures 1 – 4. To assist the reader in interpreting the plots, we explain Figure 1 in detail. The other figures are similarly interpreted. The title at the top of Figure 1 indicates that it is for the soft seat value. The horizontal axis represents the time, TP, between installation of an SORV and the time of its post-installation proof test. The horizontal axis runs from 0 to 5 years because all installed SRS valves are proof tested at intervals less than or equal to 5 years with an average TP equal to 3.7 years [9]. The vertical axis represents PFDavg which is the average probability on the interval [0, TP] that, if the SORV were to be tested at TP, the SORV would be found in a state of FTO failure. Since PFDavg is used to determine an SORV SIL rating, we include on the plot the bands of PFDavg values that correspond to different SIL levels. In Figure 1, the higher horizontal dashed line at PFDavg value 0.001 represents the lower bound of SIL 2, while the lower horizontal dashed line at PFDavg value 0.0001 represents the lower bound of SIL 3. Any part of a plot of PFDavg that falls between the lower bound of SIL 2 and the lower bound of SIL 3 would indicate that, based on PFDavg, the SORV may receive a SIL 3 rating if the proof test is performed at the corresponding time, TP, that gave a PFDavg between [0.0001, 0.001). In Figure 1, the area of the plot above the lower bound for SIL 2 represents the region for SIL 2 as the lower bound of SIL 1(0.01) is above the highest point on the vertical axis.

In Figure 1, the solid line labeled PT represents the case of a pre-installation proof test with PIF equal to zero. Therefore there is only a single line for this pre-installation activity case. The solid lines labeled ML and NA represent PFDavg calculated using the appropriate point estimates for PIF given manual lift and no pre-installation activities, respectively, while the dotted lines labeled ML and NA represent PFDavg calculated using the upper and lower 95% interval bounds for PIF given manual lift and no pre-installation activities, respectively. Please note that in Figure 4 the solid and dotted lines labeled NA/ML represent both No Activity and Manual Lift because, based on currently available data, a manual lift will not reduce PIF compared to no pre-installation activity for "Other" SORV.

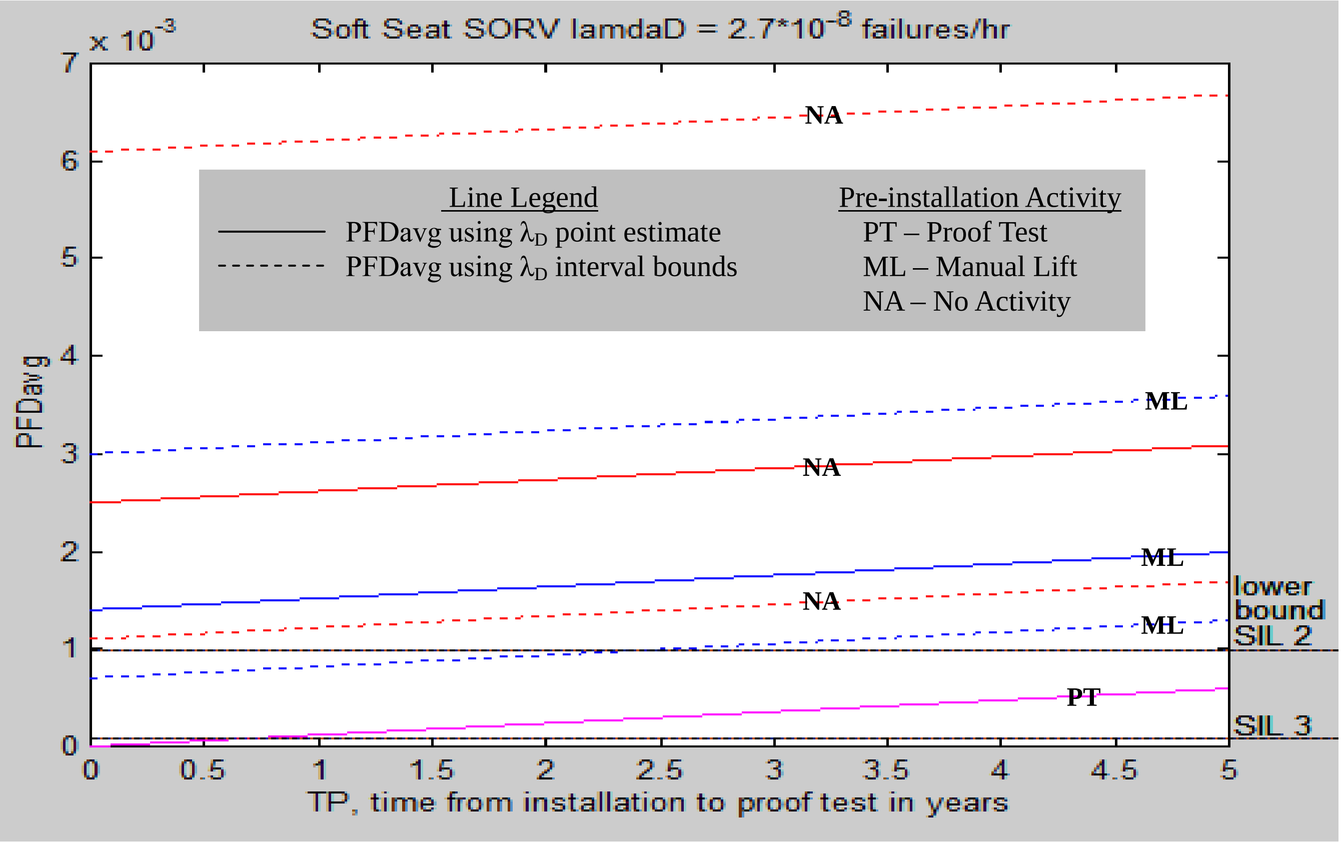

Figure 1. PFDavg vs TP for a Typical Soft Seat SORV for Various PIF Estimates and Interval Bounds Based on Pre-Installation Activities

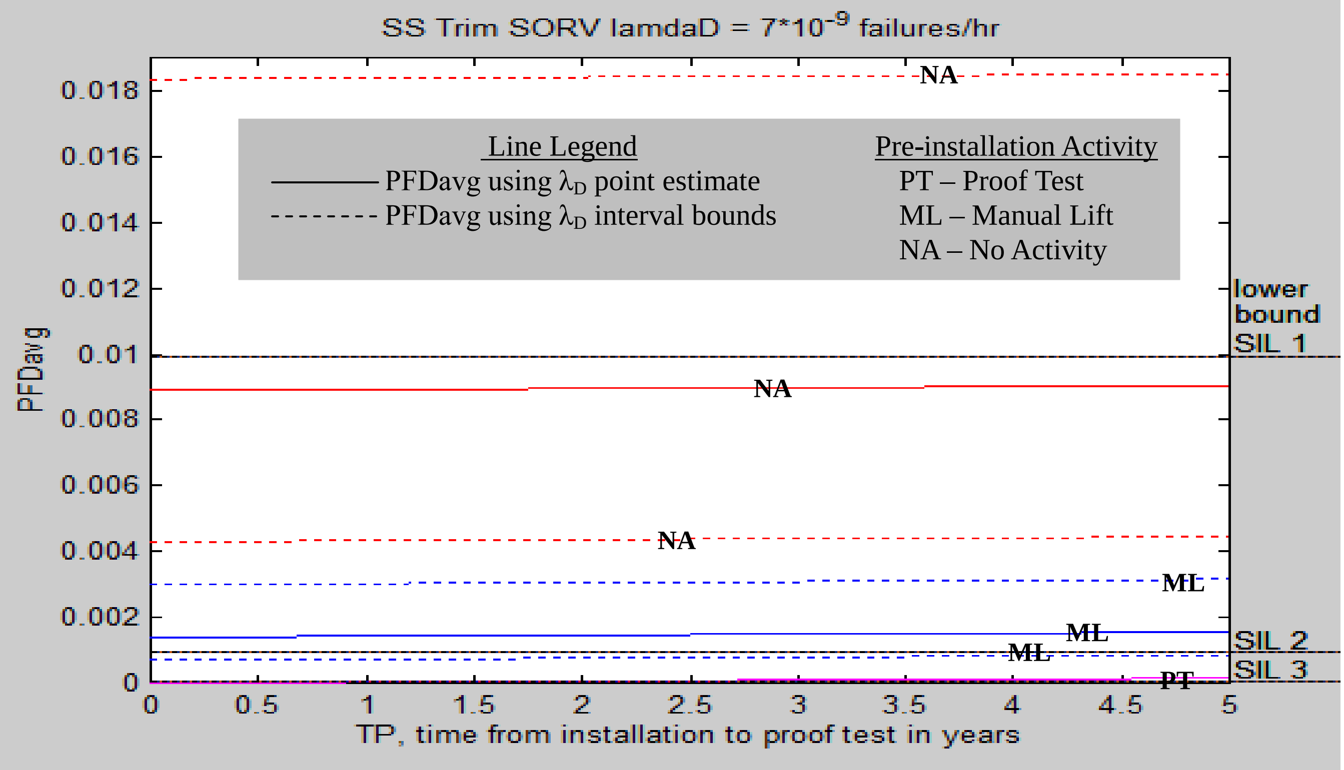

Figure 2. PFDavg vs TP for a Typical SS Trim SORV for Various PIF Estimates and Interval Bounds Based on Pre-Installation Activities

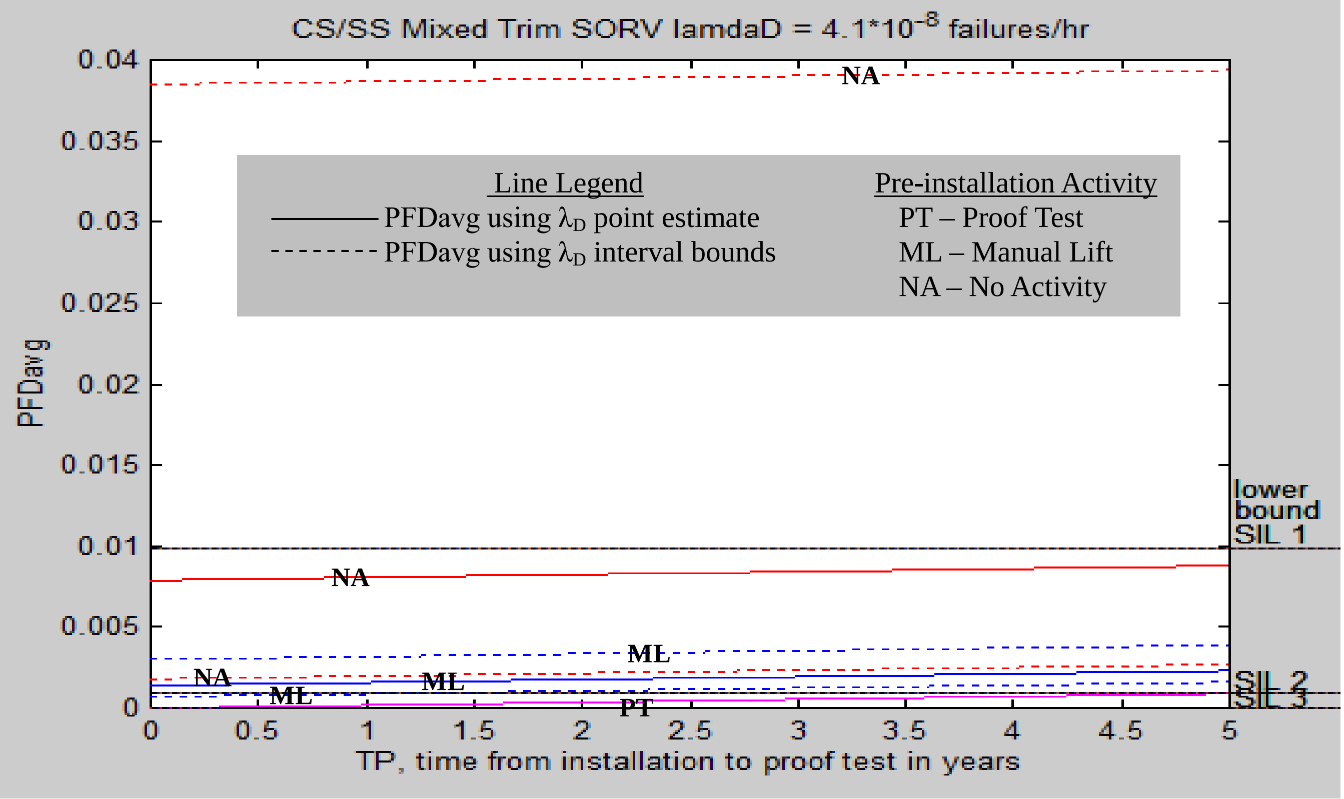

Figure 3. PFDavg vs TP for a Typical CS/SS Mixed Trim SORV for Various PIF Estimates and Interval Bounds Based on Pre-Installation Activities

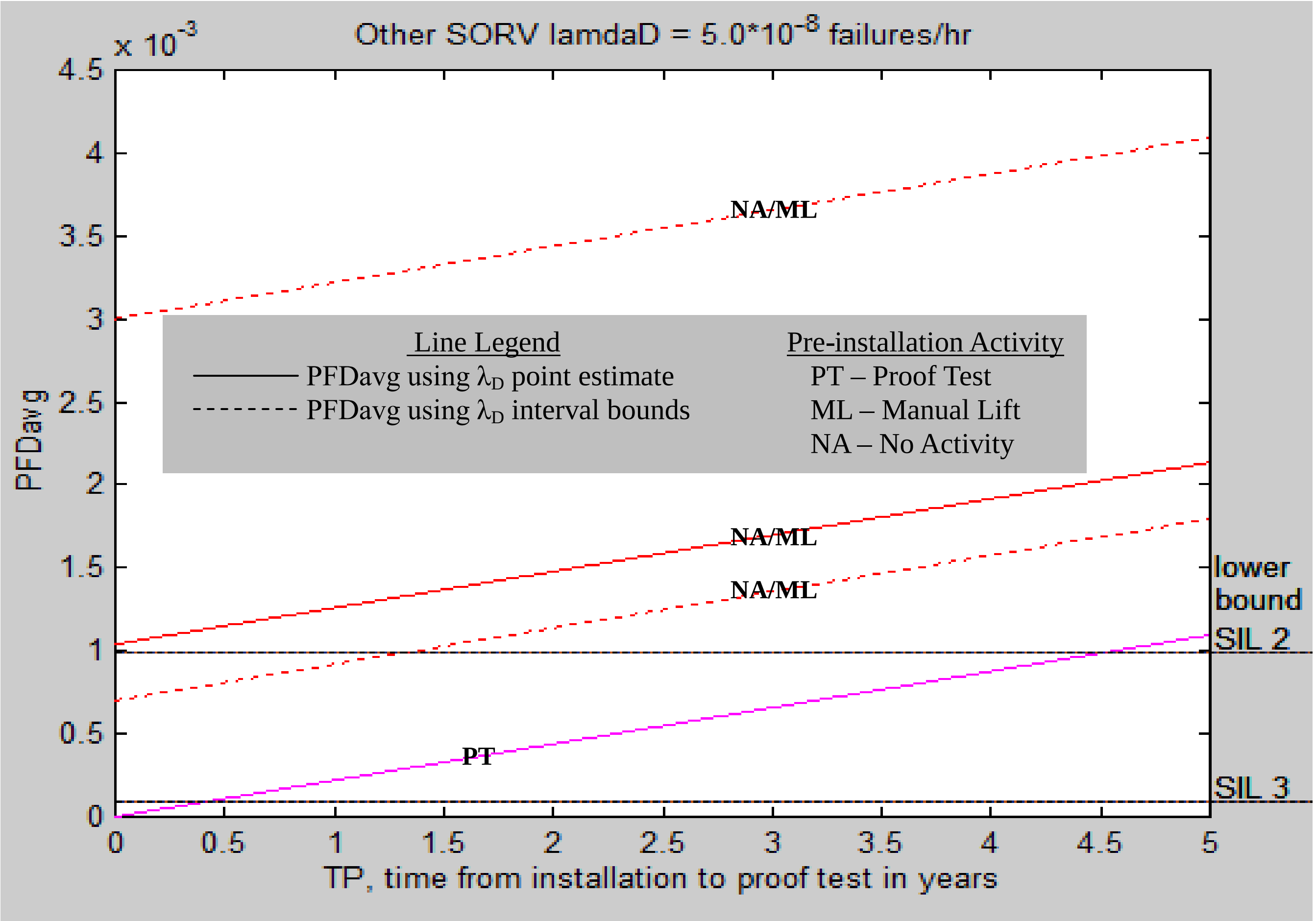

Figure 4. PFDavg vs TP for a Typical "Other" SORV for Various PIF Estimates and Interval Bounds Based on Pre-Installation Activities

Discussion of Results

As was noted above, attaining a particular range for PFDavg based on λ_D, PIF, and TP is a necessary but not sufficient condition to receive a particular SIL rating. In Figure 1 we observe that for the particular soft seat SORV illustrated, it would be necessary to perform a full proof test prior to installation in order to attain a SIL 3 rating and this rating would apply at least up to TP equals 5 years. On the other hand, a SIL 2 rating may be attained with either a manual lift (if this is possible) or no pre-installation activity with TP at least up to 5 years. We do not suggest that one may claim SIL 3 behavior in the case of the lower limit of the manual lift prior to TP about 2.25 years because one cannot guarantee being in the lower range of the interval estimate for PIF. SIL ratings may be sustained with TP greater than 5 years if it can be established that the failure rate remains constant after 5 years.

Figures 2 and 3 tell a similar story. It would be necessary to perform a full proof test on either the SS trim or the CS/SS mixed trim SORV prior to installation in order to attain a SIL 3 rating. At SIL 3, the SS SORV could have TP set at 5 years or perhaps longer if it can be shown that the constant failure rate still applies after 5 years, while the CS/SS mixed trim SORV would need a TP of about 4 years. To attain a SIL 2 rating, both SORV would need to be manually lifted prior to installation for any TP value up to 5 years. On the other hand, if no pre-installation activity was undertaken, both SORV would be limited to SIL 1 ratings with TP up to 5 years. Again, the SIL rating attained at 5 years may be sustained for a longer period if it can be established that the constant failure rate still applies.

Finally, for the "Other" representative SORV with the chosen value of λ_D, Figure 4 indicates that a full proof test prior to installation is necessary to attain a SIL 3 rating with TP no greater than 4.5 years. If no pre-installation activity is undertaken, the SIL rating would be limited to SIL 2 with TP no greater than 5 years unless it can be shown that the constant failure rate applies beyond this time.

IMPLICATIONS OF FINDINGS FOR USED SORV

Since a used SORV undergoes proof testing after it is removed from the process and before the next installation, in theory, all manufacturer/assembly anomalies should be eliminated after the first maintenance cycle. However, it is possible that an anomaly which could cause an FTO is introduced during a repair to a used SORV if the SORV is not subjected to another proof test *post* repair/reconditioning. We have no data to support a value for PIF in a used SORV due to this type of cause.

However, it is clear that used SORV of certain material compositions that are placed in extended storage after refurbishment and prior to their next installation are also subject to various failures due to aging in storage. Thus, at least some of the work presented here is directly applicable to the computation of PFDavg and SIL for used SORV.

CONCLUSIONS & RECOMMENDATIONS

- Clearly, PIF is a significant phenomenon that affects a SORV SIL rating. The American Petroleum Institute's Recommended Practices API-520 Section 12.3 and API-576 Section 6.5.2 include recommendations for pre-installation testing of all SORV within six months of installation. Those users who follow this recommendation can reasonably claim PIF equal to zero. All others need to account for a non-zero PIF in their calculations of PFDavg and should include considerations of both the material specifics of the SORV as well as the user's pre-installation activities in making these computations.
- We do not claim that the PIF values presented in this paper apply to all manufacturers or user facilities. We recommend that manufacturers use any available data to estimate PIF based on manufacturing/assembly concerns and to publish these estimates in their products' safety manuals.
- We recommend that manufacturers indicate, at a minimum, the actual month and year of a SORV's assembly directly on the assembly so that the user may gage the length of time the SORV has been in storage before the user has received it. Serial numbers do not, by themselves, allow the "born on" date to be verified in the field.
- Finally, we recommend continued research on the issue of in-storage failures. There are many unanswered questions which, if answered, would allow for PIF to be predicted as is now done for λ_D in a FMEDA. For example, what is the actual timeframe required for a soft seat embedment FTO to occur? Are all soft seat SORV equally likely to see this type of failure or do different soft seat materials produce different likelihoods of this failure mode? Does the set pressure influence the timeframe for experiencing these failures in storage? Similar questions apply to other types of SORV with in-storage failure concerns.

NOMENCLATURE

CS	carbon steel
FMEDA	failure, modes, effects and diagnostics analysis
FTO	fail-to-open
ISF	in-storage failure
MA	manufacturer anomalies
ML	manual lift
NA	no pre-installation activity
PFDavg	average probability of fail danger
PIF	probability of initial failure
PT	proof test
SIL	safety integrity level
SORV	spring operated relief valve
SS	stainless steel
SRS	Savannah River Site
TP	proof test interval for installed valves
λ_D	constant failure rate of SORV dangerous failure mode
new SORV	an SORV which has never previously been installed in a process
used SORV	an SORV which has previously been installed in a process

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ANNEX

DISCUSSION OF DUCTILE MATERIAL SURFACE BONDING PHENOMENA

APPLED SPRING PRESSURE

Because SS valves have the highest estimated PIF, we include here a description of the pressures exerted on the seat (nozzle) and disc and how they lead to the FTO observed. We also include descriptions of a variety of ductile metal phenomena that could explain why a SS seat and disc may be found FTO.

For a seat width of 0.020 inch, and using the dimensions for a one inch **F** orifice valve with a 145 psig set point, 84 Lbf is applied to the top of the disc by the spring and consequently 1800 psi is applied to the nozzle surface. To the disc, the nozzle looks like a sharp knife edge. Now if the asperity contact area is no more than 5% of the total visible area of the disc and seat, then the compressive stress becomes 84 / .047 (.05) = 36,000 psi between seat and disc. Using ~1% area [10], the stress is well over 100,000 psi. The accepted penetration (yield) strength of 304L stainless steel is as high as 95,000 lbF / square inch (~500 times the Brinnell hardness) [11]. As discussed below there will be localized plastic deformation when these surfaces are first pressed together and the bond will continue to grow stronger with contact time.

The following are possible explanations for an uncoated stainless steel disc and seat "sticking" together based on a review of available literature, experience and observations at the Savannah River Site.

COLD WELDING

In [12] it is stated that in cold welding, it is necessary that at least one (but preferably both) of the mating parts be ductile. Prior to welding, the joint surfaces are de-greased, wire-brushed, and wiped to remove oxide smudge. Cold welding is used to join small work pieces made of soft, ductile metals. It is now known that the force of adhesion following first contact can be augmented by pressing the metals tightly together, increasing the duration of contact, raising the temperature of the work pieces, or any combination of the above. Research has shown that even for very smooth metals only the high points or asperities of each surface touch the opposing piece. Perhaps as little as a few thousandths of a percent of the total surface is involved. However, these small areas of contact develop powerful molecular connections; electron microscopic investigations of contact points reveal that an actual welding of the two surfaces takes place after which it is impossible to discern the original interfaces. If the original surfaces are sufficiently smooth, attractive van der Waals forces between contact points eventually draw the two pieces completely together and eliminate even the macroscopic interface.

Some describe cold welding as a method of joining metals at room temperature by the application of pressure alone. The pressure applied causes the surface metals to flow, producing the weld. It is a solid-state bonding process in which no heat is supplied from an external source. Before a weld is made, the surfaces or parts to be joined must be wire-brushed thoroughly at a surface speed around 3000 ft/min (15 d s) to remove oxide films on the surface. In making a weld the pressure is applied over a narrow area so that the metal can flow away from the weld on both sides. It is applied either by impact or with a slow squeezing action; both methods are equally effective.

ADHESION

There are a number of different types of adhesion that might apply here including mechanical, chemical, and diffusive [13]. Mechanical adhesion involves filling the "voids and pores" of the two surfaces holding them together by interlocking (an example would be Velcro). Chemical adhesion occurs at the atomic level where surfaces form ionic, covalent or other bonds. In general surfaces need to be brought very close together and held together to maintain this type of bond. Diffusive adhesion happens at the molecular level especially where both materials are mobile and soluble in each other.

The strength of adhesion between two materials depends on which of the above mechanisms occur between the two materials, and the surface area over which the two materials contact. Materials that "wet" against each other tend to have a larger contact area than those that do not. Wetting depends on the surface energy of the materials; high surface energy means more tendencies to adhere. Stainless steels have relatively high surface energies.

BONDING

Hysteresis and diffusion bonding refer to the restructuring and re-bonding of the adhesive interface over some period of time, with the result being that the work needed to separate two surfaces is greater than the work that was gained by bringing them together. This is a phenomenon associated with diffusive bonding. The more time given for the mating surfaces to engage, the more diffusion will occur and the stronger the adhesion (bonding) will become.

According to the study of Tribology [14], [15], in practice surfaces are not perfectly smooth. Even for a highly polished surface finish of 6-8 micro inch roughness average (RA), microscopic or macroscopic asperities exist. When two ductile pieces of material are brought together, such as 300 series stainless steel, the asperities come into contact and elastically and plastically deform until the real area of contact is sufficient to carry the load. This is known as asperity bonding.

RESIDUAL STRESSES

In [16] it is stated that plastic deformation is present in any machining process. This is certainly the case with the manufacture of both disc and nozzle in the SORV. The extent of the deformed layers and the residually stressed region will depend on the depth of cut, sharpness of tool, the rate at which material is removed and the relative machinability of the material. When residual stresses are set up in the component after fabrication and proof testing above normal operating loads, the surface stress state is increased. Should the residual stresses be compressive, and then a compressive normal load is super-positioned, the stresses are additive according to [17, 18]. This is believed by a co-author of this paper to increase the tendency for plastic deformation or embedment of the SORV nozzle and disc.