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# THE EFFECTS OF MAINTENANCE ACTIONS ON THE PFDavg OF SPRING OPERATED PRESSURE RELIEF VALVES

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## ABSTRACT

The safety integrity level (SIL) of equipment used in safety instrumented functions is determined by the average probability of failure on demand (PFDavg) computed at the time of periodic inspection and maintenance, i.e., the time of proof testing. The computation of PFDavg is generally based solely on predictions or estimates of the assumed constant failure rate of the equipment. However, PFDavg is also affected by maintenance actions (or lack thereof) taken by the end user. This paper shows how maintenance actions can affect the PFDavg of spring operated pressure relief valves (SOPRV) and how these maintenance actions may be accounted for in the computation of the PFDavg metric. The method provides a means for quantifying the effects of changes in maintenance practices and shows how these changes impact plant safety.

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## 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. While there are many possible design variations, Figure 1 and the following description provide sufficient background to understand the research presented in this paper.

In a properly operating SOPRV a spring exerts a downward force/pressure on the disc pressing the disc against the seat. The seat is the top surface of the wall of the nozzle. The green circles in Figure 1 are not intended to describe the shape of the seat but merely to indicate its position. The orifice area is the circular opening at the top of the nozzle where the nozzle meets the disc. 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. 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.

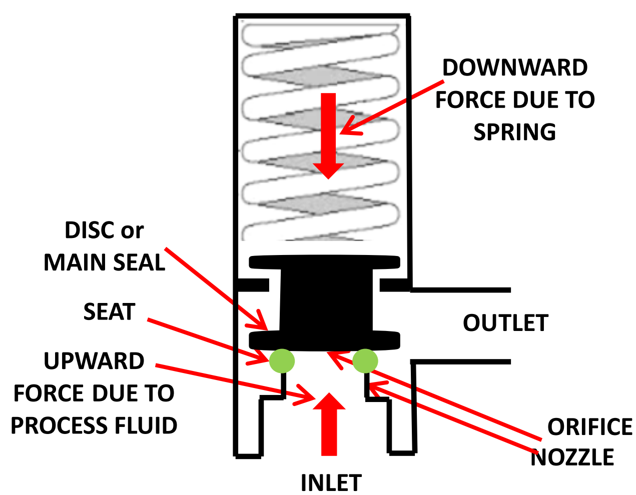


**Fig. 1 Conceptual representation of a typical SOPRV**

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 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.

The SOPRV can fail in a number of ways. If the SOPRV either opens or fails to form a fluid tight seal when the process pressure is within normal ranges, the valve is said to leak and this is usually 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 "fail to open" (FTO), or to be "stuck shut," and this is a dangerous failure. PFDavg measures the average probability of being in this dangerous failure mode at the time excessive process pressure needs to be relieved. In a process, the occurrence of excessive pressure is called a demand on the SOPRV; hence the metric average probability of failure on demand.

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. If accurate proof test records are kept by the end user, the results of the proof tests can form the basis for estimating the failure rate of the equipment in the service of the end user from which PFDavg can be computed. Further, if the FTO failures are analyzed, types of failures which the end user can eliminate or reduce in the future by maintenance actions can be identified. Implementation of these maintenance actions will reduce the failure rate and impact PFDavg.

The remainder of this paper,

- provides background information about the computation of PFDavg relevant to the study
- describes the source of data, rationale for data choice, and summarizes the relevant data
- presents an analysis of the proof test failure data for a particular group of SOPRV
- provides examples of categorizing the FTO and using the results to calculate the necessary parameters for computing PFDavg
- shows the impacts of three different levels of maintenance actions on PFDavg under two different assumptions about infant mortality failures and compares these to the ideal case
- closes with a discussion of the results and conclusions.

## Nomenclature

| | |
|---|---|
| API | American Petroleum Institute |
| ASME | American Society of Mechanical Engineers |
| FFD | field failure data |
| FTO | fail to open |
| FPT | fail proof test |
| in | inch(es) |
| PFDavg | average probability of failure on demand |
| PIF | probability of initial failure |
| PIIMF | probability of initial or infant mortality 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 |
| $T_P$ | length of time interval between periodic proof testing |
| $\lambda_D$ | dangerous constant failure rate |
| $\lambda_{DFFD}$ | dangerous constant failure rate based on FFD |
| $\lambda_{MDI}$ | minimum dangerous constant failure rate assuming ideal conditions |
| $\lambda_{DR}$ | dangerous constant failure rate assuming more realistic conditions |
| #IIMF | number of initial and infant mortality FTO |
| #ULA | number of useful life and aging FTO |

## BACKGROUND

In order to understand how PFDavg can be affected by maintenance actions, it is necessary first to understand exactly what PFDavg is and how it is computed. PFDavg is defined by

$$PFDavg = (1/T_P) \int_0^{T_P} PFD(t)\, dt \qquad (1)$$

where $T_P$ is the time interval from initial installation (or re-installation after maintenance) until proof test and PFD(t) is the time varying probability that the SOPRV will be in a state of FTO during that time interval, i.e., that the SOPRV is in a state of dangerous failure. The most complete representation of PFD(t) incorporates the effects of all possible dangerous failures including initial failures, infant mortality failures, useful life failures and failures due to aging. Note that useful life refers to the in-service time of a SOPRV on a proof test interval during which it does not show any signs of aging or wear out.

IEC standards [1, 2] require that PFD(t) account only for so called "random" failures during the useful life of the equipment. If PFD(t) is limited to this requirement, then the equipment dangerous failure rate is predicted or estimated by a constant failure rate, usually designated $\lambda_D$. This description of PFD(t) in terms of only a single parameter, $\lambda_D$, is consistent with the assumptions that:

- the equipment was properly chosen for its intended application
- all infant mortality failures were eliminated by complete and perfect burn-in (for electrical equipment) or run-in (for mechanical) equipment
- the equipment was correctly installed and calibrated, and correctly functioned when installed

- all in-service maintenance was correctly and completely performed on schedule
- the equipment was maintained so that no aging occurred prior to proof testing which was correctly and completely performed on schedule.

In essence, this description models the safety effects of failures that are beyond the influence of any actions (including maintenance actions) taken by the end-user because it is assumed that the end user is already perfectly and completely executing every possible end user action to ensure correct functioning of the equipment. In this paper, the constant failure rate under these assumptions is designated $\lambda_{MDI}$ meaning the minimum dangerous failure rate assuming ideal conditions. In this case, it is easily shown that PFDavg is well approximated by

$$PFDavg \approx 0.5 * \lambda_{MDI} * T_P. \qquad (2)$$

However, realistically, the assumptions required for Eq. 2 to be valid are not likely to be met and therefore the constant failure rate obtained under those assumptions should be thought of as a goal for the end user to strive toward rather than a reasonable failure rate actually being attained in practice. Unfortunately, for those end users who cannot validate through their own accurate failure records that they are actually achieving this $\lambda_{MDI}$ value, the use of PFDavg computed per Eq. 2, i.e., per the minimal IEC requirements, likely provides a *very* false sense of safety when compared to that which is actually being achieved.

IEC does not require nor does it prohibit inclusion of other types of failures in the failure rate supporting PFDavg. In [3, 4, 5] it was established that SOPRV which are not tested prior to installation, have a significant probability of being in a state of dangerous failure when installed, i.e., the probability of initial failure (PIF) is non-zero. Clearly, other types of failure may also occur. For example, if proof testing is not performed on schedule, the SOPRV may enter a life phase where aging becomes a factor in failures. Infant mortality failures due, perhaps, to latent manufacturing defects are also possible. It is the opinion of the authors that it is important to include all failures types discovered in field failure data or reasonably anticipated/expected to occur (even if not observed in field failure data) in the computation of PFDavg.

But if an analyst is to include initial failures (which require one parameter), infant mortality failures (which require a minimum of two parameters), useful life failures (which require one parameter) and failures due to aging (which require a minimum of two parameters), the task seems overwhelming. Fortunately, it has been shown in [6] that PFDavg can be conservatively approximated by

$$PFDavg \approx PIIMF + 0.5 * (1 - PIIMF) * \lambda_{DR} * T_P \qquad (3)$$

where PIIMF is the probability of initial failure (the percent of the total population installed in the FTO state) plus the probability of infant mortality failure (the percent of the total population that initially function but which fail in the FTO state before the end of the defined infant mortality period), and $\lambda_{DR}$ is the constant failure rate calculated based on the actual or expected number of useful life failures plus the actual or expected number of failures due to aging. Thus, the conservative approximation requires only two parameters. The *R* in the subscript of $\lambda_{DR}$ in Eq. 3 indicates that the failure rate is based on more realistic conditions.

## DATA SOURCE

Data for this study came from Savannah River Site (SRS). As previously described in [7], 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 [8]. 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. Test pressure is increased on the test stand 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 those 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 [9] and American Petroleum Institute (API) RP 581 [10]. This ratio of 1.3 has also been used in other data analysis [11]. 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 [12]. 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 [7]. 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 Choosing a Subpopulation of Stainless Steel Trim SOPRV for this Study

IEC safety standards [1, 2] assign a SIL to an individual item of safety equipment not to a population of similar equipment. However, it is rare that any end user has sufficient proof test data for a given manufacturer and model at a given site under similar set pressures (which are known to affect the occurrence of FTO [5, 6]) to be able to estimate the required parameters for a specific item of equipment.

In previous studies [5, 6] of both new and used SOPRV with stainless steel (SS) trim several characteristics were identified that were statistically significant in the discovery of FTO failures. Therefore, this study is based on a specific subpopulation of very similar (though not identical) SOPRV which are known to possess all of a set of four characteristics which are relevant to the discovery of FTO on proof test. Specifically, the data for this study has been limited to proof tests of used ASME Boiler and Pressure Vessel Code Section VIII [13] SOPRV which have all of the following characteristics:

- stainless steel (SS) trim, i.e., an SOPRV in which the nozzle/seat and disc are made of SS
- set pressure less than 150 pound per square inch gauge (psig)
- orifice diameter less than or equal to 1.0 inch (in.)
- contain at least one carbon steel component.

### Summary of Available Data

The dataset for this study consists of 195 proof tests which were performed at SRS over an approximate 10 year period from 2003 until September of 2012. Figure 2 shows the distribution of SOPRV by set pressure (psig) vs diameter (in.) with those SOPRV found to be FTO indicated by red circles. There are a total of 13 FTO; two red circles overlap at the point (0.29, 80) and 4 red circles overlap at the point (0.50, 70).

While a subpopulation of 195 tests may seem small to some analysts, it is actually a very large number of tests to have available from a single site. Similarly, the number of FTO is also significant. For every test in the study population, the following information can be identified: manufacturer and model number, current test date, set pressure, proof test pressure (first lift pressure), R, SOPRV orifice diameter, as well as identifying information linking the test back to a more complete database at SRS. For almost all tests, it is also possible to identify the previous proof test date (which is needed to compute the time the SOPRV was in service), the average pressure of the three lifts following first lift if those tests were performed, the scheduled proof test interval and the fluid service.

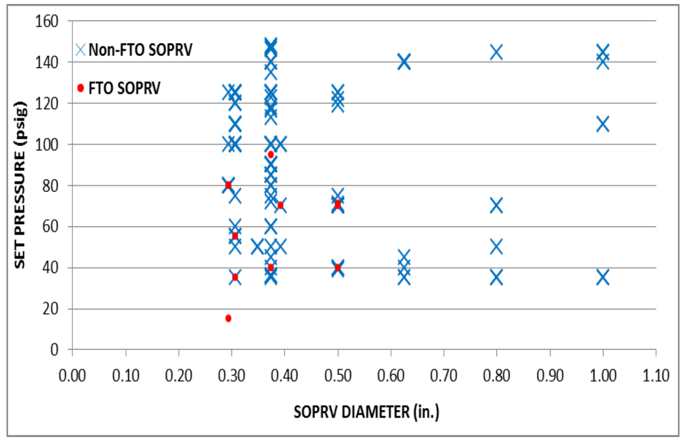


**Fig. 2 Plot of distribution of SOPRV by orifice diameter and set pressure with FTO SOPRV noted**

## ANALYSIS OF FTO'S DISCOVERED

The RCA of the 13 FTO were studied to determine the cause of each failure and to assess the extent to which the failure could have been influenced by the actions of the user. Figure 3 shows a plot of the proof test ratio, R, vs the year of proof test with tests that discovered FTO SOPRV designated as either random, i.e., currently beyond the reasonable influence of the user, or the responsibility of the user. The manner in which these determinations were made is explained as follows.

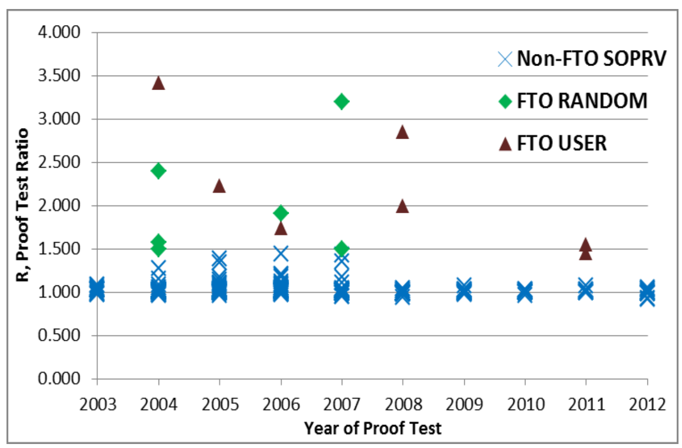


**Fig 3. Plot of distribution of SOPRV by proof test ratio, R, and year of proof test with FTO SOPRV noted as to cause: random vs user responsibility**

Two FTO from different manufacturers discovered in 2004 (both with R ~ 1.5) each had three subsequent lifts after first lift which averaged within 2 psig of their respective set pressures. Both were tested within their assigned proof test interval. There was no evidence of corrosion. The cause of these FTO was deemed to be adhesion of the SS trim components. These are random failures currently beyond user influence. It is interesting to note that in [4] it was shown that FTO due to SS adhesions form in the same proportions in new and used SS trim SOPRV. Further, in [5] it was shown that new SS trim SOPRV with the characteristics of this study population exhibit a 0.8% probability of FTO due to SS adhesions. (The Wilson Score [14] 95% confidence interval on this point estimate was [0.0031, 0.0200].) This implies that it is reasonable to expect 195 SOPRV * 0.008 FTO/SOPRV = 1.56 FTO due to SS adhesions in this study population and in fact there were two.

Two FTO on the same physical SOPRV discovered in 2004 (R = 2.4) and 2007 (R = 3.2) each had three subsequent lifts after first lift which averaged within 1 psig of the SOPRV set pressure. Both tests were within the assigned proof test interval for the SOPRV. There was no evidence of corrosion. This same SOPRV had been tested new in 2001 (R = 0.94). The two most recent tests appeared to behave like an adhesion failure. In fact, based on the 2007 test, the SOPRV qualified to be re-tagged without disassembly and returned to service. However, SRS personnel conservatively recommended disassembly, inspection, and rebuild based on the overall SOPRV test history and the increasing test ratios. Disassembly showed no evidence of internal problems. In the process of rebuild it was discovered that the wrong spring was used in the original assembly. This manufacturer/assembler defect was not detectable by proof testing the new valve in its “as-arrived” condition. These FTO are deemed to be random failures beyond the reasonable influence of the average end user. In this case, the diligent safety culture of SRS evidenced by the decision to disassemble and rebuild a SOPRV which qualified for re-tagging led to the discovery and elimination of this particular failure in the future at their site. However, it is possible for other random failures due to essentially undetectable manufacturing defects to be introduced through other SOPRV.

Two FTO from the same manufacturer (but different models) discovered in 2006 (R = 1.9) and 2007 (R= 1.5) each had three subsequent lifts after first lift which averaged at or within 2 psig of their respective set pressures. Both tests were near the assigned proof test intervals for the SOPRV, one being about six weeks and the other about 8 weeks past a 3 year proof test interval. In both cases there was evidence of deterioration, specifically, caused by galvanic corrosion [15]. This phenomenon occurs when two dissimilar metals are in contact in the presence of a corrosive fluid. These FTO are deemed to be random failures. Corrosive fluid may contact the internals of the SOPRV at random times and in random quantities affecting exactly how much corrosion develops over time. Further, corrosion may not be the sole cause of the FTO. Corrosion results in an extra “sticking force” (in addition to the spring force) that the SOPRV must overcome in order to open. But in [5] it was shown that 46% of new SS trim SOPRV will develop some degree of adhesion and in [4] it was shown that statistically, adhesion failures develop in the same proportions in new and used SOPRV. Therefore, it seems likely that adhesions of some degree develop in about half of used SOPRV. Thus, the FTO may be caused by a combination of “extra sticking” due to both adhesion and corrosion. The user may be able to influence this failure mode but probably only by replacing the SOPRV with a different design.

Two different SOPRV of the same make and model were discovered to be FTO in 2005 (R = 2.3) and 2008 (R = 2.0). No lifts after first lift were obtained in either case. Both tests were within the assigned proof test interval for the SOPRV. The causes of failure were significant corrosion of carbon steel components. After the 2005 test, the SOPRV was disassembled and two parts were found to be made of carbon steel in an otherwise completely SS SOPRV. SRS queried the manufacturer as to whether the two parts were intended to be carbon steel and the reply was that one was intended to be SS (in this case, an assembly defect) and the other was indeed intended to be carbon steel. SRS requested a custom option to have all SS components but the manufacture did not comply. After the 2008 FTO the site was instructed to remove all of these SOPRV from service and replace with them with a different design. Despite the assembly defect, these FTO were deemed responsibility of the user because SRS intended to use an all SS SOPRV for the particular application but in fact purchased a SOPRV with a carbon steel component. Had the SOPRV been correctly assembled, it would likely still have failed due to corrosion of the single carbon steel part the manufacturer intentionally used in the design.

One FTO discovered in 2008 (R = 2.9) was tested within its assigned proof test interval but failed due to excessive corrosion. The SOPRV had been installed in outdoor service without necessary weather protection. This FTO was deemed the responsibility of the user. A similar SOPRV in this population under similar conditions (no weather protection) proof tested with R = 1.4 in 2006.

Four FTO were discovered in 2004 (R = 3.4), 2006 (R = 1.7) and 2011 (R = 1.5, R = 1.5) with the common characteristic that the SOPRV were left in service too long. In each case, the SOPRV were proof tested 11 – 15 months after their assigned proof test intervals. In three of the four cases the failures involved corrosion but in one case the failure seemed to be due solely to SS adhesion. It is impossible to know for certain whether user adherence to the assigned proof test intervals would have completely eliminated these failures. However, these FTO were deemed the responsibility of the user and, in fact, SRS reduced the assigned proof test intervals for the two SOPRV tested in 2011.

Table 1 summarizes the analysis of the FTO’s recorded in the field failure data.

## DETERMINING PARAMETER VALUES FOR PIIMF AND $\lambda_{DR}$ UNDER DIFFERENT MAINTENANCE SCENARIOS

### How to Calculate the Parameter Values

In order to determine the values of the parameters PIIMF and $\lambda_{DR}$ in Eq. 3 from the field failure data, it is necessary

**Table 1 Summary of Analysis of FTO's**

| FTO# | Year | R | Cause of FTO | Type |
|---|---|---|---|---|
| 1 | 2004 | 1.5 | SS adhesions | Random |
| 2 | 2004 | 1.5 | SS adhesions | Random |
| 3 | 2004 | 2.4 | Manufacturer Defect | Random |
| 4 | 2007 | 3.2 | Manufacturer Defect | Random |
| 5 | 2006 | 1.9 | Galvanic corrosion cell | Random |
| 6 | 2007 | 1.5 | Galvanic corrosion cell | Random |
| 7 | 2005 | 2.3 | Corrosion inappropriate design choice | User |
| 8 | 2008 | 2.0 | Corrosion inappropriate design choice | User |
| 9 | 2008 | 2.9 | Corrosion unprotected exposure to weather | User |
| 10 | 2004 | 3.4 | Corrosion in service too long | User |
| 11 | 2006 | 1.7 | Corrosion in service too long | User |
| 12 | 2011 | 1.5 | Corrosion in service too long | User |
| 13 | 2011 | 1.5 | SS Adhesion in service too long | User |

to know when the failure occurred as this will determine if a FTO belongs to the categories of initial failure or infant mortality failure (and should be included in the computation of PIIMF), or if the FTO belongs to the categories of useful life failure or failure due to aging (and should be included in the computation of $\lambda_{DR}$).

Let #IIMF be the number of FTO identified as having been present at the time of installation or as having occurred during some predefined interval early in the SOPRV service. Then PIIMF is computed as

$$PIIMF = \#IIMF / \text{total number of proof tests} \quad (4)$$

Let #ULA be the number of FTO identified as having occurred either during the SOPRV useful life or due to aging. Then $\lambda_{DR}$ is computed as

$$\lambda_{DR} = \#ULA / \text{total in-service time of the SOPRV proof tested} \quad (5)$$

Recall that it is important to limit the population under consideration to SOPRV that have very similar characteristics.

### Categorizing the FTO from this Data Study

Unfortunately, proof testing does not determine the *time of failure*; it determines only the *time of discovery of failure*. However, reasonable engineering judgment can be used to categorize the FTO's appropriately in order to calculate PIIMF and $\lambda_{DR}$.

Specifically, since corrosion usually develops over time at known rates, failures due to corrosion *generally* are either useful life failures (as in the case of galvanic corrosion cell) or aging failures (as in the case of SOPRV left in service too long). For the purposes of examples in this paper, all eight FTO involving corrosion (FTO# 5-12) are assumed to belong to the useful life or aging categories. This need not be the case for other sets of field failure data.

The timing of failures due to SS adhesions alone is a complete unknown. They could be useful life failures and for the purposes of this paper, failure FTO#13 is assumed to be a useful life failure. Yet, other types of mechanical "sticking" failures [16, 17] are known to develop over very short time intervals that would cause them to be reasonably classified as infant mortality failures. However, it is not clear if these short time frames might apply to SS adhesions also. For the purpose of examples in this paper, it was decided to assign two of the SS adhesion failures (FTO# 1-2) in two different ways; specifically in maintenance scenarios designated with an *a* they are assigned to the useful life failure category while in scenarios designated with a *b* they are assigned to the infant mortality category. This allows for examples of computing PIIMF involving infant mortality as well as examples of computing $\lambda_{DR}$.

This leaves two failures (FTO# 3-4) due to the manufacturer/assembler using the wrong spring. Again, there is no clear evidence to suggest when failure occurred due to this defect. For the purposes of examples in this paper, this FTO is included in the useful life category.

Since SRS performs pre-installation testing of all SOPRV, it is assumed that there are no initial failures for which to account. In one example of computing PIIMF below, a scenario is considered which includes initial failures.

### Calculating the Parameters for Different Maintenance Scenarios

In order to consider how maintenance practices affect PDFavg, it is necessary to consider several different scenarios. Scenario 1 consists of the maintenance practices at SRS *prior to* 2003 which largely generated the proof test data described in this paper. SRS has an average proof test interval of approximately 3.8 years for the population of SOPRV in this study. Thus, it takes a considerable amount of time for changes in maintenance practices implemented after 2003 over a period of years (as FTO are discovered and analyzed) to be measureable in future proof test data. Consider that only three FTO for this population chargeable to user responsibility were discovered prior to 2008.

In Scenario 2, representing current and future safety performance at SRS, it is assumed that the changes in maintenance practice instituted between 2003 and 2012 continue in place and result in a 70% decrease in FTO deemed chargeable to user responsibility. Therefore, the #ULA chargeable to the user is reduced from 7 to 2 reducing #ULA overall by 5. In this scenario the number of random FTO remains unchanged.

In Scenario 3 it is assumed that another end user employs maintenance practices similar to SRS's pre-2003 practices and in addition this end user does **not** perform pre-installation testing. Based on prior research [5] indicating a 0.8% occurrence of initial failures due to SS adhesions and another 0.1% occurrence of manufacturing defects which could have been removed by pre-installation testing, it is possible to alter PIIMF to include the effects on PFDavg of not performing pre-installation testing. For a population of 195 proof tests, this adds about 2 FTO chargeable to user responsibility categorized as initial failures. Thus it adds 2 FTO to #IIMF.

As indicated above, for each of the first three scenarios, failures due to FTO# 1 and 2 are assigned a) first to the useful life failure category (and included in #ULA) and b) then to the infant mortality category (and included in PIIMF).

In Scenario 4, the model assumes that only random failures are included and treated as occurring during useful life thus implementing IEC minimum requirements and computing $\lambda_{DI}$.

Based on Eqs. 4 and 5, a population of 195 tests, total in-service time of 737.7 years, and the above assumptions, Table 2 summarizes the parameter values computed for each of the Scenarios 1a – 3b. For Scenario 4 the value of $\lambda_{MDI}$ is computed as

$\lambda_{MDI}$ = 6 FTO /737.7 years = $8*10^{-3}$ dangerous failures/years

$$= 9 * 10^{-7} \text{ failures/hour} \quad (6)$$

but with the understanding this value applies only to Eq. 2 where effectively PIIMF equals 0.

**Table 2 Summary of Parameter Values for Scenarios 1 - 3**

| Maintenance Scenario | | PIIMF (probability) | $\lambda_{DR}$ failures/hr | #IIMF | #ULA |
|---|---|---|---|---|---|
| SRS pre-2003 | 1a | 0 | $2.0 * 10^{-6}$ | 0 | 13 |
| | 1b | 0.01 | $1.7 * 10^{-6}$ | 2 | 11 |
| SRS post-2012 | 2a | 0 | $1.2 * 10^{-6}$ | 0 | 8 |
| | 2b | 0.01 | $9.3 * 10^{-7}$ | 2 | 6 |
| SRS pre-2003 without pre-installation testing | 3a | 0.01 | $2.0 * 10^{-6}$ | 2 | 13 |
| | 3b | 0.02 | $1.7 * 10^{-6}$ | 4 | 11 |

## MODELING THE IMPACTS OF MAINTENANCE ACTIONS OF PFDavg

The SIL level of an SOPRV is determined by the PFDavg at the time of proof testing. Table 3 gives the conversion between PFDavg and SIL levels.

**Table 3 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 | $[10^{-5}, 10^{-4})$ |

Using Eqs. 2 and 3 with the appropriate values for $\lambda_{DI}$, PIIMF and $\lambda_{DR}$ for the various scenarios, PFDavg was computed as a function of $T_P$ for each scenario. Figure 4 shows the plots for Scenarios 1a, 2a, 3a, and 4. Figure 5 shows the plots for Scenarios 1b, 2b, 3b, and 4. In these plots it is possible also to determine how PFDavg changes as the proof test interval, $T_P$, changes.

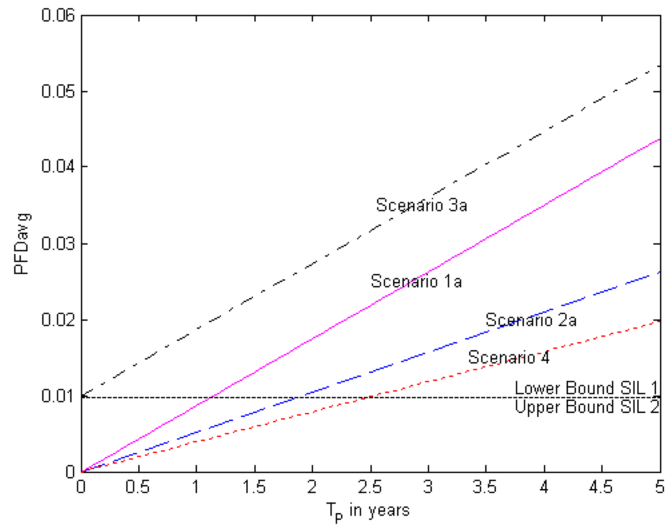


**Fig 4. Plots of PFDavg vs $T_P$ for Maintenance Scenarios 1a, 2a, 3a, and 4.**

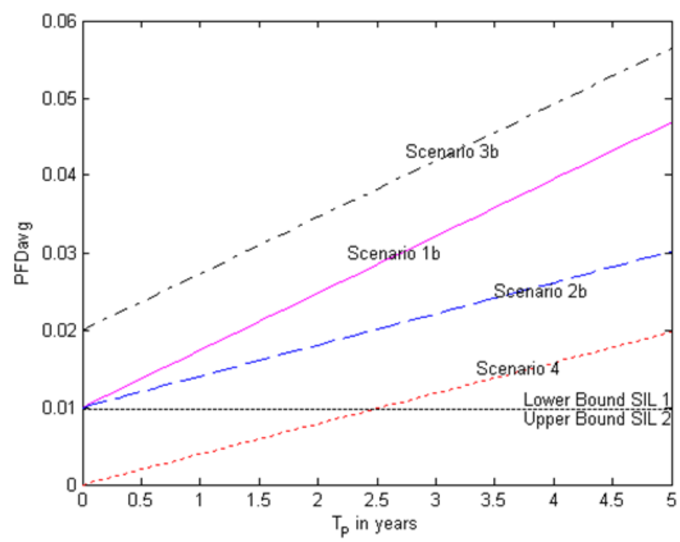


**Fig 5. Plots of PFDavg vs $T_P$ for Maintenance Scenarios 1b, 2b, 3b, and 4.**

## DISCUSSION

### General Observations

In practice, many analysts who compute $\lambda_D$ from field failure data (FFD) do so as

$$\lambda_{DFFD} = \text{\#FTO / total operating time.} \quad (7)$$

This implicitly assumes all FTO are useful life failures. There have long been anecdotal reports of $\lambda_{DFFD}$ being two or more times that of $\lambda_{MDI}$ as computed by others per IEC minimum requirements.

Comparing $\lambda_{MDI} = 0.9*10^{-6}$ from Eq. 6 to $\lambda_{DR} = 2*10^{-6}$ from Scenario 1a based on SRS FFD which assumes all FTO to be useful life failures, the factor of 2 is obvious. To the best knowledge of the co-authors, this study provides the first hard evidence of this anecdotally observed factor of 2.

Examining Figure 4 and comparing Scenarios 1a and 2a, it is clear that changes in maintenance practices *at a given site* affect PFDavg. Furthermore, by comparing Scenario 2a to Scenario 4 it is possible to measure improvements against the ideal benchmark. It is also noteworthy to compare Scenarios 1a and 3a where it is clear that the same population of SOPRV can have quite different PFDavg based on even small differences in maintenance practices *between different sites*.

The same observations can be made for Figure 5. However, Figure 5 also emphasizes the very significant impacts on PFDavg if any infant mortality failures are, in fact, occurring. This makes clear the need to better understand the timeframes required for "sticking" conditions such as adhesions to develop.

Lastly it is important to note that the values of PFDavg computed in the foregoing examples are specific to this very narrow subpopulation of SOPRV. Other SOPRV subpopulations, including those with SS trim incorporating carbon steel components and having either orifice diameters greater than 1.0 in. or set pressures greater than or equal to 150 psig, or both, have significantly fewer FTO than the subpopulation studied here.

### Implications for End Users

Some end users do not have sufficient FFD of their own for analysis and therefore rely on estimations or predictions of $\lambda_{MDI}$ made per IEC minimum requirements. These end users are cautioned that their reliance on $\lambda_{MDI}$ to compute PDFavg and SIL and, especially, to justify increasing proof test intervals is extremely ill-advised.

If an end user has FFD, it can, of course, be used to estimate $\lambda_{DR}$. Then $(\lambda_{DR} - \lambda_{DI})$ * total in-service time provides a rough estimate of the number of discovered FTO that might be influenced by changes in maintenance practices.

## CONCLUSIONS

This study clearly shows that the safety performance of equipment is a function not only of the equipment itself but of site specific end user practices as well. This means that for an end user to assess realistically the safety being achieved by a particular piece of safety equipment at a specific site, $\lambda_{MDI}$ as provided by the manufacturer or assessed by other means meeting IEC minimum requirements, must be modified to reflect the realities of that end user's practices. The methods presented in this paper provide a framework for accomplishing this task.


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