Improving Reliability & Safety Performance of Solenoid Valves by Stroke Testing

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Abstract

Solenoid valves integrated into the design of emergency shutdown (ESD) valves used in industrial process systems, can tend to bind, i.e., to become stuck in one position, when not moved for long periods of time. This binding, also known as failure due to excessive stiction, has significant negative impacts on the valve’s reliability and safety performance. It is a serious and costly problem normally addressed by expensive and time-consuming manual proof tests which typically require a process shutdown to perform testing. This paper describes an effective, alternative in-service testing protocol, known as valve stroke testing, which verifies whether or not the solenoid valve is stuck in position. It recommends a best practice procedure for implementing the valve stroke test. It provides a quantitative example of how valve stroke testing significantly improves safety performance when performed frequently (at intervals of one week or less) or even infrequently (at intervals of three to six months).

1. Introduction

In an industrial setting such as a chemical plant, oil refinery or a deep sea oil rig, there are safety instrumented systems in place which will promptly bring about a safe shutdown of a process if certain hazardous conditions are detected. Such safe shutdowns frequently involve isolating a process fluid flow, often accomplished by the use of an ESD valve.
Two of the ways an ESD valve can fail are it can function spuriously (also known as a spurious trip) or it can fail to function. If the ESD valve functions spuriously, it unnecessarily shuts down a properly working process in a safe manner; this type of failure is classified as a safe failure or fail safe. If the ESD valve fails to function, it loses the ability to shut down the process should a shutdown be required; this type of failure is categorized as a dangerous failure or “fail danger.” If the process does not require shutdown while the ESD valve is in a state of dangerous failure, then no harm is done provided the dangerous failure is discovered and repaired before a hazardous condition necessitating a shutdown occurs. If, however, the ESD valve is in a state of dangerous failure when a hazardous condition necessitating a shutdown occurs and the ESD valve does not perform its function when required, the worst case consequences of this “failure on demand” can be catastrophic including loss of life, significant destruction of or damage to equipment and property, and severe environmental damage.

Some ESD valve failures can be detected by various diagnostic procedures while the ESD valve is in service. If these detected failures are promptly repaired, safety performance is improved. Some ESD valve failures cannot be detected while the ESD valve is in service and consequently, safety standards, e.g. [1, 2] require periodic “proof testing” to verify that the ESD valve will operate properly if called upon to initiate a process shutdown. Such testing usually requires an interruption of process operations and in some instances may require physical removal of various ESD elements from the process for testing. Hence, proof testing is relatively time-consuming and expensive compared to in-service diagnostic testing.

ESD valves often include a solenoid valve of some type in the ESD valve design with the solenoid valve remaining in an energized state while the process operates normally and with the solenoid valve being de-energized, causing its seat to move to a different position, to initiate a safe process shutdown. Solenoid valves can fail to function on demand due to a number of different conditions called dangerous failure modes. In particular, based on a validated database of failure rates and failure modes for mechanical components [3, 4], one finds that a significant failure mode contributing to the dangerous failure rate of the solenoid valve is that of sticking or adhesion. This dangerous failure mode can lead to a failure to shut down when needed, i.e., a failure on demand.

Because the solenoid valve is one element of an ESD valve, it is often “at rest,” i.e., stationary, during normal plant operation. The failure mode where it has become “stuck” in one position cannot be observed, i.e., the dangerous failure is undetectable in normal operation. Traditionally, this failure mode is discovered during proof testing and, for this particular ESD element, proof testing usually necessitates a process shutdown. As proof testing is a time-consuming and expensive proposition, the proof test interval is scheduled as infrequently as possible consistent with the reliability and safety objectives of the end-user.

Safety standards rate safety performance by safety integrity level (SIL) which is an order of magnitude rating based on the computed value of average probability of failure on demand (PFDavg) over the time interval \([0, \text{T}_P]\) as defined in (Eq. 1). \(\text{T}_P\) is the time
interval between proof tests and PFD(t) is the time varying probability of failure on demand.

\[ PFD_{avg}(t) = \frac{1}{T_P} \int_0^{T_P} PFD(t) \, dt \]  
(Eq.1)

For a fixed value of \( T_P \) (Eq. 1) results in a particular value for \( PFD_{avg} \). Table 1 shows SIL levels assigned to different ranges of \( PFD_{avg} \).

<table>
<thead>
<tr>
<th>SIL Level</th>
<th>( PFD_{avg} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>( [10^{-2}, 10^{-1}] )</td>
</tr>
<tr>
<td>2</td>
<td>( [10^{-3}, 10^{-2}] )</td>
</tr>
<tr>
<td>3</td>
<td>( [10^{-4}, 10^{-3}] )</td>
</tr>
<tr>
<td>4</td>
<td>( [10^{-5}, 10^{-4}] )</td>
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But suppose we do not have a definite value of \( T_P \) in mind and want to set \( T_P \) as high as possible while still attaining a particular SIL rating. Then we are interested in \( PFD_{avg} \) as a function of time as given in (Eq 2).

\[ PFD_{avg}(t) = \frac{1}{t} \int_0^t PFD(s) \, ds \]  
(Eq. 2)

Assuming that the rate of dangerous failures can be represented by the constant \( \lambda_D \) and that the device for which \( PFD_{avg}(t) \) is being computed operates correctly when it is installed, then one major portion of \( PFD_{avg}(t) \) can be reasonably approximated by

\[ PFD_{avg}(t) \approx \frac{1}{2} \lambda_D \times t \quad 0 \leq t \leq T_P \]  
(Eq.2a)

Thus, \( PFD_{avg}(t) \) increases approximately linearly as \( t \) increases up to \( T_P \). The SIL rating that the device achieves can be altered by adjusting \( T_P \). In general, mechanical devices do not undergo in-service diagnostic testing and it is not until the time of proof testing that dangerous failures are discovered and corrected. Just after the time of proof testing, assuming that the proof test was complete and perfect so that all dangerous failures were discovered and corrected, \( PFD_{avg}(t) \) will return to zero and begin to increase linearly until the next proof test. Thus, over all \( t \), (Eq. 2a) is properly written as

\[ PFD_{avg}(t) \approx \frac{1}{2} \lambda_D \times t \quad 0 \leq t \leq T_P \]  
(Eq.2b)

Thus, the behavior of \( PFD_{avg}(t) \) over repeated proof test cycles results in a saw-tooth plot as shown in Figure 1 where \( T_P \) has been arbitrarily set at 2 years. Note that the purple line in Figure 1 is the maximally allowed \( PFD_{avg} \) to attain a SIL 3 rating. So with \( T_P \) set at 2 years, the example device would receive a SIL 2 rating. \( T_P \) would have to be decreased to approximately 1.25 years (the value of time when the \( PFD_{avg}(t) \) plot and the horizontal purple line first intersect) in order to receive a SIL 3 rating.
Figure 1. Plot illustrating the behavior of PFDavg(t) over time three inspection cycles when TP equals 2 years.

Solenoid valve failures due to sticking or adhesion contribute significantly to reducing safety performance because they increase $\lambda_D$ and result in reductions in TP, i.e., they result in more frequent process downtime to facilitate proof testing, in order to meet safety objectives. Thus, finding less costly ways to address this adhesion failure mode has value.

The remainder of this paper

- Describes the basic operation of a solenoid valve to the extent required to understand the remainder of the paper
- Explains the concept of “stiction”
- Describes the effects of stiction on solenoid valve operation
- Presents evidence that stiction increases to some maximum level over relatively short periods of time
- Proposes a means to effectively reduce or eliminate the increased stiction through appropriately timed valve stroke tests
- Describes how to assess the impact of valve stroke testing on PFDavg(t)
- Details “best practices” guidelines for implementing solenoid valve stroke testing
- Provides a quantitative example illustrating improvement of reliability and safety performance when stroke testing is implemented
2. Solenoid Valve Basics

A solenoid coil generates an electromagnetic field which can be used to change the position of a metallic plunger. In a solenoid valve, this action can then be used either directly or indirectly to control process fluid flow. Figure 2 illustrates direct control of process fluid flow. In Figure 2a, when an electric current passes through the solenoid coil the resulting magnetic field attracts the plunger and holds it within the coil allowing the process fluid to flow from left to right. In Figure 2b, when the electric current is removed from the coil, the electromagnetic field vanishes and the plunger is no longer held within the coil but falls blocking the path of the process fluid flow.

An example of using a solenoid coil for indirect process fluid control is a solenoid actuated pneumatic spool valve (see Figure 3). The solenoid valve typically controls compressed air which, in turn, positions another valve (not shown) which directly controls the process fluid. Thus the solenoid valve indirectly controls the process fluid.

Figure 3a shows the normal position of the valve for a particular application. In this coil design (which is different from that of Figure 2), when the solenoid coil is energized the magnetic field repels the plunger which is of a more complex design known as a spool. The spool, repelled by the magnetic field from the solenoid, is moved from left to right, changing the pathways allowing the flow of compressed air fluid. Consequently, when the solenoid coil is energized, the spool compresses the spring at the right end of the spool valve. In this spool position, ports x and y of the valve provide a pathway allowing compressed air to flow through the spool valve.

Figure 3b shows the emergency position of the valve in the event that an emergency shutdown of the process fluid is required. Now the solenoid coil is de-energized; the
removal of the magnetic field means that the spool is no longer being repelled by the magnetic field. Without this magnetic force to push the spool to the right, the spring decompresses pushing the spool to the left, back inside the solenoid coil. In this spool position, port x is blocked which prevents compressed air from flowing through the spool valve to pressurize a valve actuator while ports y and z are open to provide a vent for pressure in the actuator.

Figure 3a. Spool valve showing an open pathway from ports x to y for compressed air flow due to the solenoid being energized and compressing the spring.
Figure 3b. Spool valve showing a closed pathway from ports x to y, blocking the flow of compressed air and venting air pressure by opening ports y to z. The solenoid is de-energized and the spring is not compressed.

Note the presence of O-ring seals (shown in blue) in both the simple solenoid valve (Figure 1) and the spool valve (Figure 2). They are in place to ensure that the fluid does not escape the valve chambers while also ensuring that no foreign elements can enter the fluid’s environment. The O-rings surround both the plunger (Figure 1) and the spool (Figure 2) on the surfaces where the plunger or spool are in very close proximity (but not actually touching) the valve chamber walls.

While this introduction captures the main ideas needed to understand the remainder of this paper, the reader should be aware that actual valve designs are more complicated than presented here. Some use fluid pressures rather than springs to move the spool. Many other design differences exist. But all contain O-rings which are involved in a particular failure mode known to significantly affect solenoid valve reliability and safety performance. This failure mode is caused by excessive “stiction”.

3. Stiction

3.1 What is Stiction?

Many studies and organizations have defined stiction, i.e., static friction, in different ways. A few examples of the various definitions are as follows:

- According to Olsson [5], stiction is defined as “short for static friction as opposed to dynamic friction. It describes the friction force at rest. Static friction...
counteracts external forces below a certain level and thus keeps an object from moving.”

- According to Entech [6], “stiction is a tendency to stick-slip due to high static friction. The phenomenon causes a limited resolution of the resulting control valve motion. ISA terminology has not settled on a suitable term yet. Stick-slip is the tendency of a control valve to stick while at rest and to suddenly slip after force has been applied.”

- According to Horch [7], “The control valve is stuck in a certain position due to high static friction. The (integrating) controller then increases the set point to the valve until the static friction can be overcome. Then the valve breaks off and moves to a new position (slip phase) where it sticks again. The new position is usually on the other side of the desired set point such that the process starts in the opposite direction again.” This is an extreme case of stiction. On the contrary, once the valve overcomes stiction, it might travel smoothly for some time and then stick again when the velocity of the valve is close to zero.

- According to Ruel [8], the Instrument Society of America (ISA)(ANSI/ISA-S51.1-1979) described “stiction as the resistance to the start of motion, usually measured as the difference between the driving values required to overcome static friction upscale and downscale.” The definition was first proposed in 1963 in American National Standard C85.1-1963.

- According to Ruel [8], “stiction is a combination of the words stick and friction, created to emphasize the difference between static and dynamic friction. Stiction exists when the static (starting) friction exceeds the dynamic (moving) friction inside the valve. Stiction describes the valve’s stem (or shaft) sticking when small changes are attempted.”

In the definitions above, all agree that stiction is the act of being “stuck” by static friction which prevents one surface from moving against another. Further, if the external force becomes greater than the static friction, the stiction between two surfaces will be overcome and the object will begin to move again [9].

Stiction between two surfaces can be the result of many factors including: corrosion, cold welding, i.e., metal on metal adhesion, breakdown of the lubrication boundary layer, change in the viscosity of the lubrication, build-up of deposits, contamination or foreign material on the contact surfaces, chemical reactions between the metal or lubrication, deterioration and breakdown of the valve’s sealing components, etc.

This paper defines stiction as the resistance to the start of motion usually measured as the difference between the external force being applied in order to overcome the static friction and the force to maintain movement between the two contacting or working surfaces.
3.2 Stiction in the Context of a Solenoid Valve

In normal operation, the O-rings in the solenoid valve create a smooth transition while the plunger or spool is in motion. Because the O-rings are in direct contact with the valve chamber walls, in order for the plunger/spool to begin to move, it must first overcome the stiction between the O-rings and the chamber walls. Once in motion, the plunger/spool must overcome the sliding or dynamic friction between the O-rings and walls but, since the dynamic friction is usually significantly less than the nominal level of stiction, it is generally not of concern. By design the magnetic and spring forces in the solenoid valve are sufficient to overcome the nominal level of static friction and, depending on the design specifics of the solenoid valve, generally have excess force sufficient to overcome about 2 to 2.5 times nominal stiction. Once the stiction is overcome, the plunger/spool will continue to move. However, a common and troublesome problem can occur when the valve is at rest, i.e., stationary, for a length of time because the stiction between the O-ring and the valve chamber walls increases over time from its nominal level until it reaches some maximum value. It is possible that the increases in stiction may reach a level where the forces generated by the solenoid coil and/or spring (in the case of a spool valve) are no longer sufficient to overcome the increased stiction. Consequently, when the valve is called upon to close, it is unable to do so. However, if the excessive stiction is overcome, stiction reverts to its original nominal level though it does begin to increase again once the valve stops moving.

3.3 Evidence that Stiction Increases with the Length of Time the Contact Surfaces are Stationary

3.3.1 Expert Knowledge

Mechanical engineers and technicians who routinely work with solenoid valves are familiar with the experience of trying to “stroke”, i.e., move through its range of motion, a valve that has been stationary for an extended time. They report that it is not uncommon for extra force to be required to move the valve after it has been stationary for a month or more. However, they are unable to say when within the month the increased stiction reaches a critical level that causes the valve to stick because it cannot generate sufficient force to overcome the increased stiction.

3.3.2 O-Ring Manufacturer’s Findings

In the Parker O-ring Handbook [10] it is noted that the “coefficient of starting friction”, i.e., stiction, increases when the O-ring has been stationary for between 1 week and 1 month after which time the stiction plateaus. One specific graph (Figure 5-7 in [10]) of “break out friction”, i.e., stiction, vs. “delay between cycles” shows the stiction force plateauing at approximately 300 hours. “The theory has been proposed and generally accepted that the increase in friction on standing is caused by the rubber O-ring flowing into the micro-fine grooves or surface irregularities of the mating part”[10].
3.3.3 Experimental Study to Determine Equilibrium Rest Time

Zhao and Bhushan [11] conducted an experimental study on the effects of lubrication thickness, lubrication viscosity, and the length of rest time, i.e., the length of time the contact surfaces remain stationary, on the increases in stiction in magnetic thin-filmed disks. Based on their results they introduced the concept of equilibrium rest time, i.e., the time by which the maximum stiction is reached due to lack of motion. After conducting experiments with three different lubricants and holding the disks in a stationary position over extended periods of time, they found that a maximum stiction is reached by approximately 275 hours or about 11.6 days. The equilibrium rest time for the different lubricants are reached at slightly different points in time, but all are reached before about 275 hours [11]. Even though these experiments do not involve O-rings, it is interesting that a maximum level of stiction is reached and results regarding the time required to reach the stiction plateau are consistent with the information available in [10].

3.3.4 Reliability Declaration Per ISO 13849

In a declaration [12] regarding the reliability indicators and information for use of a specific solenoid actuated pneumatic valve with respect to the safety standard EN ISO 13849-1 [13], it is specifically stated that the “valve must be operated at least once per week or once per shift to insure the intended function.” The data supporting this declaration was obtained by cycle testing during which the solenoid valve was never at rest for any significant time. This statement recognizes that the results of cycle testing are valid only if periodic valve movement is maintained. In the absence of such periodic movement, the failure rates derived from the results of cycle testing [14] cannot be considered valid when applied to components in applications where these components spend significant times at rest.

3.3.5 Section Summary

From this multi-source evidence we can conclude that, as a rule of thumb, O-ring stiction increases with valve inactivity and reaches a maximum value at approximately 275 hours. Further, stiction levels can be returned to nominal or near nominal levels if the increased stiction can be overcome by valve motion. This suggests that increased stiction can be dealt with in a more cost effective way than proof testing and that solenoid valve reliability and safety performance can be significantly improved.

4. Solenoid Valve Stroke Testing

In a stroke test, the solenoid coil is de-energized for a short period of time to see if the spring can fully decompress moving the spool in one direction through its full range of motion. Then when the coil is re-energized, the spool must again move, in the opposite direction, through its full range of motion. The reader may be familiar with the term “partial stroke testing” which refers to moving a valve through only a small portion of its range of motion to establish that it can be moved. In the case of solenoid valves, a partial stroke test is not possible. All stroke testing of solenoid valves will involve a full stroke.
If the solenoid valve is directly controlling process fluid, the stroke testing could lead to an unacceptable disruption of process fluid, so in the case of direct process fluid control, in-service solenoid valve stroke testing is impractical and without special redundant architectures, must be done when the process is shut down. However, if a solenoid valve is indirectly controlling process fluid, a full stroke of the solenoid valve (provided that the full stroke takes place over a short enough period of time) will generally not cause a significant disruption of the process fluid flow but will briefly alter the position of the actuator/valve assembly that the solenoid is controlling. This may be negligible or may result in a small perturbation to the process fluid flow that in most cases will be acceptable. At the completion of the valve stroke test, which is performed with the valve in service, either the solenoid valve has been verified to be operable or a dangerous failure due to stiction has been detected.

The success or failure of the solenoid valve stroke test can be determined indirectly by observing the actuator pressure and/or actuator valve stem movement because a full stroke test of the solenoid valve also performs a partial stroke test of the ESD. A small decrease in actuator pressure with corresponding actuator valve stem movement indicates a successful solenoid valve test as well as a successful ESD test. No decrease in pressure indicates a failure somewhere in the ESD but not necessarily of the solenoid valve itself. Some automatic stroke test devices measure the actuator pressure and actuator stem movement then automatically indicate pass/fail via a discrete output. Stroke testing the solenoid valve provides reliability and safety improvements not only to that device but also to the entire ESD as well.

4.1 Assessing the Reliability & Safety Improvements Due to Stroke Testing

This concept of solenoid valve stroke testing offers an opportunity to eliminate or at least address the failures of solenoid valves due to stiction as well as to address detectable non-stiction failures and, consequently, to improve solenoid valve reliability and safety performance. To aid in clearly understanding the beneficial reliability and safety effects of stroke testing, we note that the dangerous failures will be due either to the stiction failure mode or some non-stiction failure modes. The failures due to stiction are all detectable via valve stroke testing. The non-stiction failures are further divided into those failure modes which are detectable and those which are undetectable by valve stroke testing. We define the failure rates associated with these three cases as $\lambda_{\text{Dstiction}}$, $\lambda_{\text{Dnon-stictionDetectable}}$, and $\lambda_{\text{Dnon-stictionUndetectable}}$, respectively.

4.1.1 Case 1: No Valve Stroke Testing

In the case where no valve stroke testing is performed, the failure rates of all dangerous failure modes are included in $\lambda_D$, i.e.,

$$
\lambda_D = \lambda_{\text{Dstiction}} + \lambda_{\text{Dnon-stictionDetectable}} + \lambda_{\text{Dnon-stictionUndetectable}}
$$

(Eq. 3)

and (Eq. 3) is substituted into (Eq. 2a) to compute $\text{PFDavg}(t)$ at $t = T_P$. Provided all dangerous failures are discovered and repaired as a result of the manual proof test, the
resulting plot of $PFD_{avg}(t)$ will be a saw-tooth plot where $PFD_{avg}(t)$ returns to 0 after each proof test.

4.1.2 Case 2: Infrequent Valve Stroke Testing

By “infrequent valve stroke testing” we mean testing that occurs less frequently than once per week. Typically, infrequent testing occurs once every three to six months. As with Case 1, the failure rates of all dangerous failure modes are included in $\lambda_D$ so that (Eq. 3) again applies. However, there are some noteworthy differences between Case 2 and Case 1.

In Case 2, we assume that any dangerous failures detected as a result of the valve stroke test are promptly and completely repaired. Indeed, if prompt repair (within 168 hours) is not made, the value in performing the stroke test is reduced. Thus, Case 2 has nearly the same effect as a manual proof test, albeit a slightly incomplete one. It will detect all but the failures associated with the failure rate $\lambda_{D,non-stictionUndetectable}$. Thus, $PFD_{avg}(t)$ is governed by (Eq. 2a) expect that $t$ now equals $TVST$, the interval of the valve stroke test, and after each interval of length $TVST$ $PFD_{avg}(t)$ does not return to zero but is reduced to a small residual value (due to $\lambda_{D,non-stictionUndetectable}$) which will not be eliminated until the time of a complete manual proof test. Thus, the plot of $PFD_{avg}(t)$ for this case will resemble a saw-tooth plot as is shown in the quantitative example in Section 6 but one whose peaks increase slightly each cycle until the time of manual proof test. [Note: for the example parameter values used in Section 6, this increase in peak values is too small to be seen in the plots.]. So, infrequent valve stroke testing with prompt and complete repair of detected failures will decrease $PFD_{avg}$. As a result, it may be possible to increase $TP$ without negatively impacting the safety performance of the solenoid valve.

4.1.3 Case 3: Frequent Valve Stroke Testing

By “frequent valve stroke testing” we mean in-service testing that occurs at least once per week and includes complete and correct repairs of all detected failures within 168 hours. Since the stroke testing is performed before the increase in stiction reaches its maximum, there is a significant chance that the stroke test will succeed in moving the valve and disrupt the buildup of stiction returning it to its nominal level. Thus, while the valve stroke test is designed to detect stiction-related failures there is a significant chance that frequent valve stroke testing will prevent the failures due to this failure mode from occurring effectively setting $\lambda_{D,stiction}$ to 0. Therefore, for Case 3 only the failure rates associated with non-stiction failure modes are included in $\lambda_D$, i.e.,

$$\lambda_D = \lambda_{D,non-stictionDetectable} + \lambda_{D,non-stictionUndetectable}$$ \hspace{1cm} (Eq. 4)

and (Eq. 4) is substituted into (Eq. 2a) to compute $PFD_{avg}(t)$ at $t = TVST$ which in this case is 168 hours or less. Thus frequent valve stroke testing clearly decreases $PFD_{avg}$. As a result, it may be possible to increase $TP$ without negatively impacting the safety performance of the solenoid valve.
4.2 Setting the Frequency of the Valve Stroke Test

While valve stroke testing will have beneficial results on PFDavg even if performed infrequently, **ideally we would like not simply to detect failures due to stiction but also to actually prevent them**. So, is stroke testing once per week sufficiently frequent to insure that stiction build up will be disrupted before it exceeds the valve’s available excess force? Unlike random failures truly represented by a constant failure rate (meaning that failures occur with equal probability at any time during the interval between diagnostic tests), failures due to stiction are unlikely to occur very early in the time interval between tests when stiction levels have not increased very much and more likely to occur once stiction levels have increased beyond the level that the excess force of the valve can overcome. Thus, while we know that, as a rule of thumb, the maximum level of stiction is reached at about 275 hours, we also need to consider how fast the stiction builds towards its maximum value in order to determine the most appropriate interval for valve stroke testing.

In [11], plots of log₁₀ stiction force vs. log₁₀ rest time (time of inactivity) are given for the three lubricants studied. These log-log plots show an approximately linear increase in stiction from a nominal stiction level until a plateau is reached at about 275 hours. This indicates that the stiction increases as a power function meaning the increase is proportional to $t^n$. Thus the increase in stiction force over time would be modeled as

$$\text{Increase in stiction force} = \alpha t^n \quad 0 \leq t \leq t_{\text{max}} \approx 275 \text{ hrs} \quad \text{(Eq.5)}$$

where $\alpha$ is a constant of proportionality. Now, for the purposes of this example let us assume that the maximum stiction is three times nominal stiction. This implies that the maximum increase in stiction force at 275 hours would be twice nominal stiction which when added to the initial nominal stiction would give a total stiction force of about three times nominal stiction. For the lubricants studied, $0.07 < n < 0.17$. Thus stiction can increase very rapidly to its plateau value. For example, if $n = 0.17$, then at one week (168 hours) the stiction would increase by almost 92% of its maximum possible increase making the actual stiction force equal to nominal + $(0.92 \times 2 \times \text{nominal})$ for a total stiction of 2.85 nominal value.

If these example values applied to the solenoid valve, would it have enough excess force to overcome this amount of stiction? Possibly, but maybe not. However, our problem is that the experiments described in [11] were not on solenoid valves and we do not know what values of $n$ might apply to any given solenoid valve or even if the solenoid valve O-ring stiction rises as a power function.

4.3 Considering an Alternative to Valve Stroke Testing

In some end-user circles there persists the common belief that valve stroke testing risks a plant shutdown due to a false trip and that a better safety solution is to provide a much higher safety margin (greater excess force) to overcome increases in stiction. However, those who are well versed in solenoid design realize that a higher safety margin to
overcome stiction actually results in a greater false trip rate. This occurs because a higher safety margin to overcome increases in stiction requires a bigger spring. A bigger spring requires a bigger coil which, in turn, requires more energy to power the coil. These increased energy requirements result in a higher likelihood that the coil burns out which results in a higher false trip rate. Therefore, if we seek to optimize the false trip rate while improving reliability and safety, then valve stroke testing provides a good solution.

5. Recommended “Best Practices” for Implementing Solenoid Valve Stroke Testing Based on Current Knowledge (March 2013)

Based on currently available information consistent over multiple sources, i.e., that stiction reaches a maximum value in about 275 hours, we recommend as best practice, the following approach to solenoid valve stroke testing:

- Begin solenoid valve stroke testing on a weekly basis recording whether each test verified valve movement or indicated the valve was stuck (in which case, initiate prompt repairs)
- After a few months of testing, if the number of times the valve is found stuck seems excessive (by engineering judgment) then halve the test interval (to 3-4 days)
- Repeat the above procedures with this new test interval until an optimum test interval is identified such that stroke testing generally verifies valve movement.

In some instances, the initial one-week test interval may not be adequate. Because low power (less than 2 Watts) solenoid valves generally are designed with less excess force available, they may not develop adequate force to overcome increases in stiction that may build up even before the one-week test interval. In these cases, a shorter initial stroke test interval may be warranted.

To avoid false trips, the partial stroke testing device which initiates the full stroke of the solenoid valve must be set up properly:

- the pressure drop in the actuator should not be allowed to go to zero during the stroke test. Many designs limit the pressure drop to a minimum value while still fully exercising the solenoid valve.
- the minimum actuator pressure should be established to overcome deadband yet provide minimum movement of the valve controlling the process fluid. Many valves allow a small movement without imposing a flow restriction. A small movement is all that is necessary.
- "quick exhaust valves" should not be used as these devices are non-linear and often lock in the pressure exhaust causing a false trip. Instead, linear pneumatic boosters should be used.
6. Assessing the Reliability & Safety Improvements Due to Stroke Testing

In order to present a realistic quantitative example of the reliability and safety performance improvements that can result from valve stroke testing, a failure mode effects and diagnostic analysis [15] was performed on a solenoid valve from manufacturer X, model Y. The predicted values for the various constant failure rates are given in Table 2.

Finally, consider the behavior of PFDavg(t) due to the solenoid valve for each of the three cases. For our example parameter values, PFDavg(t) was computed for Case 1 with proof testing performed every 2 years (TP = 2 years), for Case 2 with valve stroke testing performed once every six months (TVST = 6 months) and for Case 3 with valve stroke testing performed once per week (TVST = 168 hours). The results are plotted in Figure 4. Figure 5 illustrates the plot of PFDavg(t) for Case 3 magnified to show its detail. Note that in Figure 4 the purple horizontal line represents the maximally allowed value of PFDavg for which the valve could receive a SIL 3 rating. Without valve stroke testing, the valve can only be rated at SIL 2. With valve stroke testing every six months or once a week the PFDavg(t) remains below the SIL 3 rating level without proof testing. Note that this does not mean that proof testing can be completely eliminated as other dangerous undetected failures can exist that need to be discovered and corrected through proof testing. It does mean that it may be possible to increase the proof test interval significantly while maintaining a SIL 3 rating.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Failures/10^9 hrs operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>λ_Dstiction</td>
<td>103.7</td>
</tr>
<tr>
<td>λ_Dnon-stictionDetectable</td>
<td>84.3</td>
</tr>
<tr>
<td>λ_Dnon-stictionUndetectable</td>
<td>1.9</td>
</tr>
</tbody>
</table>
Figure 4. Plots of PFD_{avg}(t) for Case 1 with T_P = 3 years, Case 2 with T_{VST} = 6 months and Case 3 with T_{VST} = 1 week.

Figure 5. PDF_{avg} for the example solenoid valve as a function of time, in hours showing a weekly stroke test (every 168 hours).

7. Conclusions and Recommendations

Even infrequent solenoid valve stroke testing can have significant beneficial impacts with respect to improvements in reliability and safety performance. However, if a solenoid valve stroke test at a frequency of once per week (or more) is feasible within a given application, it should be implemented per the best practices strategy given above.
Clearly, the timing of valve stroke tests could be optimized if we had better models of how stiction increases with valve inactivity. Manufacturers may wish to undertake controlled tests and data collection on different valve designs within their product lines to better understand this stiction phenomenon. This would permit them to make recommendations regarding valve stroke testing that would improve reliability and safety performance and possibly increase the time intervals between required proof testing.

8. Acknowledgement

The authors would like to acknowledge the helpful discussions with and comments from Steven Close and Hal Thomas both of whom are with exida.

9. References


10. Abbreviations and Terms

ESD – Emergency Shutdown

PFD – Probability of Failure on Demand

PFD\text{avg} – Average of the Probability of Failure on Demand on the time interval \([0, t]\)

PFD\text{avg}(t) – Average of the Probability of Failure on Demand at time \(t\)

SIL – Safety Integrity Level

\(T_P\) – Time interval between proof tests

\(T_{VST}\) – Time interval between valve stroke tests

\(\lambda_D\) – Constant failure rate for dangerous failures

\(\lambda_{D\text{stiction}}\) – Constant failure rate for dangerous failures due only to stiction

\(\lambda_{D\text{non-stictionDetectable}}\) – Constant failure rate for dangerous detectable failures due to causes other than stiction

\(\lambda_{D\text{non-stictionUndetectable}}\) – Constant failure rate for dangerous undetectable failures due to causes other than stiction