PARTIAL-STROKE TESTING OF BLOCK VALVES

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Features	Discussion of partial stroke testing of block valves
Purpose	Enhanced diagnostics can be used to achieve higher safety integrity level using partial stroke testing.
Related codes, standards, and recommended practices	Instrumentation, Systems, and Automation Society (ISA), ANSI/ISA 84.00.01-2004, “Application of Safety Instrumented Systems (SIS) for the Process Industry,” Research Triangle Park, NC International Electrotechnical Commission (IEC), IEC 61508, “Functional Safety of Electrical/Electronic/Programmable Electronic Safety Related Systems,” Geneva, Switzerland International Electrotechnical Commission (IEC), IEC 61511, “Functional Safety: Safety Instrumented Systems for the Process Sector,” Geneva, Switzerland

ANSI/ISA 84.00.01-2004 (ISA 84) and IEC 61511 are new functional safety standards, covering the design, implementation, operation, maintenance, and testing of safety instrumented systems (SIS). Successful implementation of the safety lifecycle model associated with these standards hinges on an essential design constraint---the safety integrity level (SIL). The SIL is a numerical benchmark, related to the probability of failure on demand (PFD). SIL is affected by the design quality, e.g., device integrity, voting, and common cause faults and by the operation and maintenance strategy, e.g., diagnostics and testing interval.

For many operating companies, one of the most difficult parts of complying with the standards is the testing interval often required for final elements, such as emergency isolation valves or emergency block valves.

Traditionally, these valves have been tested at unit turnaround, using an off-line, full-stroke test to demonstrate performance. Thirty years ago, turnarounds were relatively frequent, occurring on average every two to three years. Due to successful mechanical reliability and preventive maintenance programs, many operating companies have been able to extend unit turnarounds. In some industries, it is now common to have turnaround intervals of 5 to 6 years. Extended turnaround intervals yield great economic returns through increased production. However, extended turnaround intervals also mean that block valves are expected to go longer between function tests, yet still achieve the same performance. This is simply not possible.

When SIL 2 or SIL 3 performance is required, five-year function tests are inadequate. Consequently, it is necessary to supplement the off-line full stroke test. This involves implementation of valve diagnostics, such as partial stroke testing, or alternate testing strategies, such as on-line full stroke testing.

Many users consider partial stroke testing (PST) as a cost effective alternative to on-line full stroke testing (FST). The use of PST often eliminates the need for full flow bypasses, reducing engineering, capital, and installation costs, as well as potentially removing a bypass that could be inadvertently left open. Partial-stroke testing improves the block valve performance, as measured by the Average Probability of Failure on Demand (PFD_{AVG}). The amount of the reduction is dependent on the valve and its application environment.

This chapter will discuss how to determine the actual impact of the partial-stroke test on PFD_{AVG}. It will also present a discussion of the three partial-stroke testing methodologies that are currently being evaluated and used by industry.

PARTIAL-STROKE TEST METHODOLOGY

There are three basic types of partial-stroke test equipment: mechanical limiting, position control, and solenoid valves. Each type involves different levels of sophistication and risk.

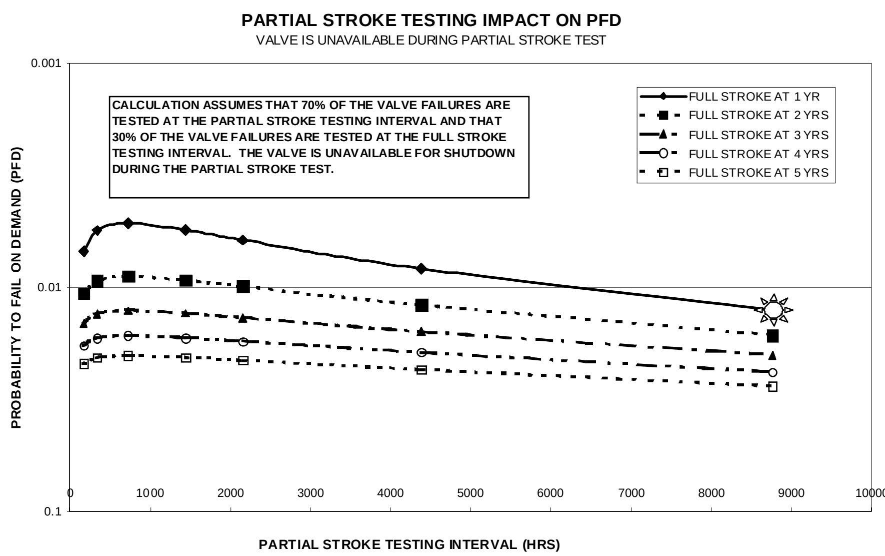
Mechanical Limiting

Mechanical limiting methods involve the installation of a mechanical device to limit the degree of valve travel. When mechanical limiting methods are used, the valve is not available for process shutdown.

The mechanical devices used for partial stroke testing include collars, valve jacks, and jammers.

- ✓ Valve collars are slotted pipes that are placed around the valve stem of a rising stem valve. The collar prevents the valve from traveling any farther than the top of the collar. Any fabrication shop can build a valve collar, suitable for test use.

- ✓ A valve jack is a screw that is turned until it reaches a set position. The valve jack limits the actuator movement to the screw set position. The valve jack is ordered from the valve manufacturer when the valve is purchased. Valve jacks work with both rising stem valves and rotary valves.



- ✓ Mechanical jammers are integrated into the rotary valve design. They are essentially slotted rods that limit valve rotation when placed in position using an external key switch. Since the jammer is integrated into the rotary valve, the jammer must be purchased from a valve manufacturer. A contact can be provided for the key switch to allow annunciation in the control room whenever the key is used.

Mechanical limiting methods are inexpensive in terms of capital and installation costs. These methods are manually initiated in the field and are manpower intensive.

A limit switch or visual inspection is used to confirm block valve movement. Successful test implementation and return of the block valve to normal operational status are completely procedure driven. For valve collars and jacks, bypass notification to the control room is entirely procedural. For the jammer, automatic notification using the key switch contact can be provided.

Two of the biggest drawbacks to these methods are the loss of protection that occurs during the test and the lack of assurance that the valve is in or has been returned to normal status. There is no way to know for certain that the jack or jammer has been completely retracted without actuating the valve. Furthermore, unauthorized use of the valve jack or jammer cannot be determined by casual inspection. This means that the valve could potentially be out of service with operations personnel unaware of the situation.

These methods do not add to the normal operating spurious trip rate. However, there is the potential for a spurious trip during the partial-stroke test. For valve collars, the main culprit of spurious trips is improper installation, causing the collar to pop off the stem when the valve begins to move. Jacks and jammers must be placed in service by the technician; so procedural mistakes can result in the valve closing completely rather than just partially. Therefore, these methods are really only as good as the written procedures and technician training.

Position Control

Position control uses a positioner to move the valve to a pre-determined point. This method can be used on rising stem and rotary valves. Since most emergency block valves are not installed with a positioner, this method does require installation of additional hardware. Consequently, cost is a major drawback for the position control method.

A limit switch or position transmitter can be used to determine and document the successful completion of the tests. If a smart positioner is used for the position control, a HART maintenance station can collect the test information and generate test documentation. Of course, the use of a smart positioner and maintenance station further increases the capital cost.

Some manufacturers have promoted the use of the positioner in lieu of a solenoid valve for valve actuation. However, most positioners do not have a large enough vent port (C_v) for rapid valve closure. Consequently, a solenoid valve should still be used for valve actuation. This solenoid valve must be installed between the positioner and the actuator.

The positioner does contribute to the spurious trip rate during normal operation, since the positioner can fail and vent the air from the valve. When a solenoid valve is installed between the positioner and the actuator, the safety functionality is never lost during the partial-stroke test. De-energizing the solenoid valve will shut the valve, regardless of the positioner action.

Solenoid Value

A partial-stroke test can be accomplished by pulsing a solenoid valve. The solenoid valve can be the same as the one used for valve actuation, resulting in a lower capital and installation costs for this method than other methods. If the actuation solenoid valve is used, this method will also test the solenoid valve's capability to execute safe shutdown.

Simplex Solenoid Valves

The Minerals Management Service, which oversees safety for oil and gas operations for US offshore waters provides one method for partial stroke testing. This method relies on the operator to pulse a single solenoid valve by turning a field-mounted switch, which de-energizes the solenoid coil for as long as the field operator holds the switch. The field operator monitors the valve position and releases the button when the operator confirms valve movement. When the valve moves, it can be inferred that the solenoid valve successfully vented. Of course, the main risk is that the operator may hold the switch too long, allowing the valve to close sufficiently to disrupt the process, resulting in unit shutdown.

It is also possible to automate the single solenoid valve test using a pulse timer is adjusted to achieve the desired valve travel. Valve travel confirmation is accomplished using a limit switch or position transmitter, allowing automatic documentation of test status. Since a failure of the solenoid valve or block valve may result in excessive block valve travel, the pulse timer should be voted with the limit switch or position transmitter. If the valve reaches its desired travel point before the pulse timer is finished, the solenoid valve is reset. The test can be programmed in the SIS logic solver with the test implemented automatically on a programmed cycle time or initiated by the operator per a maintenance schedule.

Another method is to measure the block valve position as related to air pressure in the actuator during the time of the solenoid pulse. This results in a “fingerprint” of the breakaway pressure for block valve closure, which can be compared with the original valve “fingerprint.” In order for this method to be effective, maintenance must have a specific procedure for examining the fingerprint to identify that the block valve is degraded and to respond with corrective action.

When a simplex solenoid valve is being used to PST the block valve, the solenoid is de-energized and then re-energized. If the solenoid valve does not reset, the test becomes a trip. Using redundant solenoid valves can essentially eliminate this problem.

Redundant Solenoid Valves

When arranged in a 2oo2 configuration, redundant solenoid valves provide improved reliability during normal operation and reduce the probability of a spurious trip during the PST. For processes that are sensitive to spurious trips, the reliability improvement is typically sufficient to justify the additional capital and installation costs.

There are commercially, available solenoid valve packages that provide on-line diagnostics of solenoid coil failure, facilitate on-line solenoid valve testing, and perform on-line, partial stroke testing of the block valve. One particular package (patent pending) operates in a 1oo1HS (one-out-of-one hot standby) configuration. During normal operation, the air signal passes through the package from the signal source to the valve actuator. When a trip occurs, the solenoid package vents the air from the valve actuator and allows the valve to move to its fail-safe position.

With the 1oo1HS, one solenoid valve is used as the primary actuation solenoid and is confirmed on-line using a pressure switch. A secondary solenoid valve is off-line and confirmed in the vented state (off-line state) by a pressure switch. The safety logic solver is programmed so that if the primary solenoid valve goes to the vent state without being commanded (as detected by the pressure switch), the secondary solenoid valve is energized, preventing the spurious trip.

Solenoid valve testing is performed by cycling the solenoid and by verifying that each solenoid valve successfully vents and resets using the pressure switches. The 1oo1HS can be used for PST by incorporating a PLC timer to pulse the power to the solenoids for just long enough to achieve the partial stroke. To verify the movement of the valve, a position transmitter or limit switch is used. The position indication is also used to prevent over stroking of the block valve, i.e., if the valve moves too far during the timed stroke, the solenoids are re-energized. For preventative maintenance activities, over stroke or under stroke alarms can be configured to let maintenance know if the valve is moving too quickly or too slowly during the test.

Impact of PST on SIL and $MTTF^{spurious}$ for a SIS

Safety Integrity Level (SIL) is defined by the average probability of failure on demand (PFD_{AVG}) for demand mode SIS. In ISA 84 and IEC 61511, there are four SIL classes. Each SIL class provides an additional order of magnitude risk reduction as shown in Table 1. The SIS standards require an examination of the PFD_{AVG} to ensure that the risk reduction assigned to the SIS is met. It is important to note that SIL is not a property of a specific device. It is a SIS property, encompassing the field sensors through the logic solver to the final elements (e.g. solenoid valve, block valve, or pump motor control circuit).

SIL is an important concept for safe operation, but plant management demands that the process plant operate at a high utilization rate. If an SIS is installed which has a low Mean Time to Failure Spurious ($MTTF^{spurious}$), the project will be considered a failure, regardless of the SIL that the SIS achieves. Consequently, any SIS assessment should include an analysis of the $MTTF^{spurious}$.

Let's examine a typical SIS, including transmitters, a redundant logic solver, solenoid valves, and block valves. In order to perform the PFD_{avg} and $MTTF^{spurious}$ calculations, failure rate data is required. This data can be selected from various industry published databases. The values used in this analysis are shown in Table 2.

For illustration purposes, the analysis will be presented in two parts: 1) the impact of PST on block valve performance and 2) the impact of PST on the SIS performance. For the latter case, a dual solenoid valve package (1oo1HS) will be used for block valve actuation and PST. Other PST methods can be assessed using similar techniques. The results for other PST methods may provide very different results for PFD_{AVG} and $MTTF^{spurious}$. Consequently, the results presented in this chapter should not be generalized for all PST equipment. The reader is further cautioned to ensure that any data used during SIL verification is appropriate for their application. In other words, the results presented here may not be directly applicable to the reader's application.

Block Valve Analysis

Block valve components can be examined to determine which failures potentially result in the valve not operating when a process demand occurs. The causes of failures and associated modes of failure are shown in Table 3. The PFD_{AVG} can be calculated using the dangerous failure rate (λ^D) and the testing interval (TI). The mathematical relationship, assuming that the mean time to repair is small compared to the testing interval and that λ^D*TI is much small than 0.1, is as follows:

$$PFD = \lambda^D * TI/2$$

Thus, the relationship between PFD and TI is linear. Longer test intervals yield a larger PFD_{AVG}. The OREDA database has data for various valve types and sizes. For the purposes of illustration, a $MTTF^D$ of 40 years will be used. The failure rate λ^D can be calculated from the $MTTF^D$, using the simplified equation:

$$\lambda^D = \frac{1}{MTTF^D}$$

For a $MTTF^D$ of 40 years, this yields a dangerous failure rate of 2.5E-02 failures per year. The valve failure rate varies with type, size, and operating environment (e.g., process chemicals, deposition, polymerization, etc.). The reader should determine the appropriate failure rate for the specific application.

The PFD, based on 2.5E-02 failures per year, is shown in Table 4 for various testing intervals. As expected, the valve performance at a 5-year testing interval is not the same as the valve performance at a 2-year testing interval. Due to the degraded performance at longer testing intervals, many companies have found that they must test the block valves on-line. Once facilities for on-line testing are installed, full-stroke testing can easily be performed. However, since a full-stroke test involves full contact of the valve seating members, frequent stroking can cause excessive wear to the block valve seat. This is a serious concern for soft-seated valves. Increased testing may achieve a higher integrity, but cause damage to the valve seat, leading to earlier valve failure.

Another major concern is that the plant is unprotected while the block valve is in bypass for testing. The fraction of the time that the valve is in bypass must be considered in the PFD calculation. If the valve is bypassed every six months for testing and the test takes 1-hour, the PFD is increased by 2.28E-04. For longer bypass periods or more frequent testing, the impact on the PFD is even more significant. To maintain safety, operating procedures must include a list of the actions to be taken when the valve is in bypass, such as continuous monitoring of critical process variables and when manual shutdown should be initiated.

An option to a full-stroke test is a partial-stroke test. The test involves moving the valve from the fully open position. This tests a portion of the valve failure modes. The remainder of the failures is tested using a full-stroke test. The main purpose of the partial-stroke test is to reduce the required full-stroke testing interval.

How does partial-stroke testing affect the PFD? The valve failures are modeled in two parts: 1) those failures that can be tested using the partial stroke (PS) and 2) those failures that can only be tested using a full stroke (FS). For the calculation, the dangerous failure rate, λ^D, must be divided into what can be tested at the partial-stroke ($\lambda^D{}_{PS}$) and what can only be tested with a full-stroke ($\lambda^D{}_{FS}$). To determine the percentage of failures that could be detected using PST, the failure mode distributions for various valve types and sizes contained in the Offshore Reliability Data Handbook (OREDA) were examined. This evaluation can be done for any valve type, based on the application environment and the shutoff requirements.

Table 5 provides a listing of typical dangerous failures and failure modes for block valves. The test strategy indicates whether the failure mode can be detected by partial-stroke testing or only by full-stroke testing. Based on the OREDA data, the typical percentage of the failures that can be detected by a PST is 70% for many valve types and services. Additional analysis can be performed to justify a higher percentage of detected failures. However, it is very difficult to substantiate a percentage greater than 85% for process industry applications. Those failures that are not detected during the PST are tested using an FST.

An imperfect testing model is used for calculating the PFD_{AVG} of the block valve when PST is utilized. The percentage of detected (PD) failures is used with the dangerous failure rate of the block valve, λ^D, testing interval, TI, and the mean time to repair, MTTR, as follows:

$$PFD_{AVG} = PD * \lambda^D * TI_{PST}/2 + (1-PD) * \lambda^D * TI_{FST}/2 + \lambda^D * MTTR \quad (5)$$

Table 6 provides a simple comparison of the PFD_{AVG} for block valves tested using FST only and using FST supplemented with PST. The PFD_{AVG} is shown as a function of the full-stroke testing interval. For this illustration, the partial stroke test is performed monthly. Similar calculations can be performed at other PST intervals. The results in Table 6 do not include the solenoid valve contribution to the PFD_{AVG}. The PFD_{AVG} for the single block valve is significantly reduced when PST is utilized. For double block valves, the PST lowers the PFD_{AVG} by nearly an order of magnitude.

The reader is cautioned that this breakdown is based on average valve performance and may not represent the breakdown for the reader's application. This evaluation should be done for each valve type, based on the application environment and the shutoff requirements. If the service is erosive, corrosive, or plugging, the failure rate and failure mode breakdown will be different from that shown in this chapter. If the valve is specified as tight-shutoff, the contribution of minor seat deformation or scarring may be more significant than shown in this chapter.

Using a dangerous failure rate of 2.5E-02 failures per year, Figure 1 shows the PFD when the test procedure requires bypassing the valve during the test. As expected, the PST does improve the PFD_{AVG} performance of the valve. The star illustrates the point where the partial-stroke test and full-stroke test are both conducted at a 1-year interval. This corresponds to the result shown for a 1-year full-stroke test in Table 1.

The downward trend of the curves for very frequent partial-stroke testing is due to the valve being bypassed during the test. This removal results in the valve not being available for the fraction of time that the valve is being tested. The calculation assumes that the total test time is 30 minutes. If the actual test time is longer, the effect will be more pronounced.

Figure 2 shows the PFD when the test procedure allows the valve to remain in service during the test. Very frequent partial-stroke tests improve the PFD substantially, because there is no loss of functionality during the test. Again, the star illustrates the point where the partial-stroke test and full-stroke test are both performed at a 1-year interval.

For both test procedures, partial-stroke testing does improve the valve performance. For example, 5-year full-stroke testing achieved a PFD of 6.25E-02 (Table 1). A 5 year full-stroke test supplemented with a 1-month (720 hours) partial stroke test achieved a PFD of 1.96E-02, which is an approximately 30% reduction in PFD. In the cases of 1-year and 2-year full-stroke testing, a single block valve can potentially achieve SIL 2 performance when supplemented with frequent partial-stroke tests. For longer full-stroke testing intervals, the valve performance can increase from low SIL 1 to high SIL 1, depending on the partial-stroke testing interval. From the graphs, it is easy to see that no amount of partial-stroke testing is going to allow a single valve to achieve high SIL 2 performance, let alone SIL 3 performance, at full-stroke testing intervals of 1 year or more.

Evaluation of Overall SIS Performance

Let's examine a typical SIS, including transmitters, a redundant logic solver, solenoid valves, and block valves. For the PFD_{avg} and $MTTF^{spurious}$ calculations, the failure rate data presented in Table 2 was used. In addition, the following assumptions were made:

- For redundant transmitters, it was assumed that analog signal comparison is performed and a fault alarm is initiated when the transmitters deviate unacceptably. "D" at the end of the voting

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architecture indicates the use of diagnostic coverage. The diagnostic coverage is assumed to be 80% for dual redundancy and 90% for triplicated redundancy.

- The PST can detect 70% of the valve dangerous failures.
- Common cause factor is assumed to be 2%.
- Mean time to repair is assumed to be 24 hours.

The results of the analysis were plotted using bar charts to illustrate the relative contribution of each device on the PFD_{AVG}.

Single Block Valve Case

For the simplex solenoid valve cases shown in Figure 3, the SIS only achieved SIL 1 at annual function testing. When PST is used to supplement the full stroke test, the SIS achieves very high SIL 1 to mid-range SIL 2. The individual bars can be examined to determine the major contributors to the PFD_{AVG}. For the 1oo1 and 2oo2D cases, the transmitter is the major contributing cause to the PFD_{AVG}. The impact of the transmitter can be decreased by changing the voting to 1oo2D or 2oo3D, which results in the single block valve being the major contributor.

For the spurious trip rate calculation, the logic solver was not included in the calculation, because the spurious failure rate can vary so much dependent on the specific architecture. Some logic solvers have high spurious trip rates and their contribution to the overall $MTTF^{spurious}$ can overwhelm the other SIS components. For this illustration, the logic solver was not included in this calculation to allow the examination of the field devices. For actual installations, the logic solver must be included in the PFD_{AVG} calculation.

The benefit of using the 1oo1HS is evidenced in Figure 4. In each case, the spurious trip rate was reduced significantly when the 1oo1HS is used instead of a simplex solenoid valve. The simplex solenoid valve cases had a spurious trip rate of 10 years for the 1oo2D transmitter case and 15 years for the other transmitter cases. When the 1oo1HS is used, the $MTTF^{spurious}$ exceeds 45 years for the 1oo2D transmitter case and exceeds 420 years for the 2oo2D and 2oo3D transmitter cases. If the plant life is 20 years, the single solenoid valve cases yield an average of 1.5 trips during the life of the plant. Even if a spurious trip costs only $100,000, the simplex solenoid valve will result in the loss of $150,000 over the life of the plant.

For the 1oo1HS cases, the $MTTF^{spurious}$ is greater than the plant life expectancy, yielding substantial savings.

Dual Block Valve Case

Dual block valves are used in many installations to provide greater assurance that the process is isolated. When dual block valves are used, it is common for test intervals to be extended to unit turnaround. Consequently, for the analysis, a five-year full stroke test was assumed for the logic solver, solenoid valves, and block valves, while annual testing was used for the transmitters.

For the simplex solenoid valve cases shown in Figure 5, the SIS achieved high SIL 1 to the borderline between SIL 1 and SIL 2 at 1-year full-stroke testing. When PST is used to supplement the full stroke test, the SIS achieves mid range SIL 2 with 1oo1 and 2oo2D transmitter voting. For 1oo2D and 2oo3D voting, the PST makes it possible to achieve SIL 3. Again, the individual bars can be examined to determine the major contributors to the PFD_{AVG}. As seen in the simplex block valve SIS, the transmitter is the major contributing cause to the PFD_{AVG} for the 1oo1 and 2oo2D transmitter cases. The contribution of the transmitter is seriously reduced when the voting is change to either 1oo2D or 2oo3D. In these latter cases, the major contributors to the PFD_{AVG} are the dual block valves.

Again, the benefit of using the 1oo1HS is evidenced in Figure 6. The $MTTF^{spurious}$ for the simplex solenoid valve cases is an average of 7 years. When the 1oo1HS is used for valve actuation, the $MTTF^{spurious}$ is more than 40 years for the 1oo2D transmitter case and more than 210 years for 2oo2D and 2oo3D transmitter cases. If the plant life is assumed to be 20 years, the simplex solenoid valve cases yield an average of 2.8 trips during the life of the plant. Again, if a spurious trip costs $100,000, the plant will lose more than $280,000 over the life of the plant due to spurious trips.

CONCLUSION

Partial-stroke testing does provide measurable improvement of the PFD over full-stroke testing alone. The amount of improvement is dependent on the specification, configuration, and application environment. The three partial-stroke testing methodologies offer choices between manual and automated testing.

It is important to remember that partial-stroke testing is used to achieve diagnostics on the valve in lieu of on-line, full-stroke testing. Some of these methods presented in this chapter have a higher potential for spurious block valve closure (e.g., on-line spurious actuation or unintentional actuation during test) than others. For processes that are sensitive to spurious trips, the selection of specific method should take into account not only the diagnostic capability, but also the reliability.

Whichever method is selected, procedures must be written to ensure that the block valve is not tripped during testing, the test is properly carried out, incorrect valve performance is documented, and maintenance is performed to return valve to fully functional status. The main primary is that partial stroke testing can reduce the full-stroke testing interval required to achieve the required SIL performance.

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Table 1. Relationship between SIL, PFD_{AVG}, & Risk Reduction

SIL	PFD_{AVG}	Risk Reduction
4	0.0001 to 0.00001	10,000 to 100,000
3	0.001 to 0.0001	1,000 to 10,000
2	0.01 to 0.001	100 to 1,000
1	0.1 to 0.01	10 to 100

Table 2. Failure Rate Used In The Analysis

Device	$MTTF^{D}$ (Years)	$MTTF^{spurious}$ (Years)	Data Sources (1)
Transmitters	100	100	OREDA data for various transmitters
Redundant Logic Solver	5,000	Not included in analysis	Vendor data for 1oo2D, 2oo3D, or 2oo4D logic solvers
Solenoid Valve	60	15	TR84.00.02 data
Pressure Switch	75	60	CCPS data
Block Valve	40	455	OREDA data

(1) Due to the nature of the analysis presented in this chapter, values were selected to represent generic devices rather than specific devices. For the evaluation of an actual SIF, failure rate values representing the specific devices should be used.

TABLE 3. Causes of Block Valve Failures and Associated Modes of Failure

Causes of Failures	Modes
Actuator sizing insufficient for valve actuation	Valve fails to close (or open)
Valve packing is seized	Valve fails to close (or open)
Valve packing is tight	Valve is slow to move to closed or open position
Air line to actuator crimped	Valve is slow to move to closed or open position
Air line to actuator blocked	Valve fails to move to closed or open position
Valve stem sticks	Valve fails to close (or open)
Valve seat is scarred	Valve fails to seal off
Valve seat contains debris	Valve fails to seal off
Valve seat plugged due to deposition or polymerization	Valve fails to seal off

Table 4. PFD_{avg} for a Typical Block Valve as a Function of Testing Interval

(Note: does not include contribution of the solenoid valve)

Testing Interval	PFD_{avg}
1 year	1.25E-02
2 years	2.50E-02
3 years	3.75E-02
4 years	5.00E-02
5 years	6.25E-02

Table 5. Dangerous Failures, Modes and Test Strategy

Failures	Failure Modes	Test Strategy
Actuator sizing is insufficient to actuate valve in emergency conditions	Valve fails to close (or open)	Not tested
Valve packing is seized	Valve fails to close (or open)	Partial or full-stroke
Valve packing is tight	Valve is slow to move to closed or open position	Partial or full-stroke, if speed of closure or resistance to closure is monitored.
Air line to actuator crimped	Valve is slow to move to closed or open position	Partial or full-stroke, if speed of closure or resistance to closure is monitored. Physical inspection
Air line to actuator blocked	Valve fails to move to closed or open position	Partial or full-stroke
Valve stem sticks	Valve fails to close (or open)	Partial or full-stroke
Valve seat is scarred	Valve fails to seal off	Full-stroke test with leak test
Valve seat contains debris	Valve fails to seal off	Full-stroke test
Valve seat plugged due to deposition or polymerization	Valve fails to seal off	Full-stroke test

Table 6. Comparison Of PFD_{avg} For Block Valve(s) Undergoing FST Only Or FST With Monthly PST

(Note: does not include common cause failures or the contribution of the solenoid valve)

FST Interval (Years)	Single Block Valve		Dual Block Valves	
	FST only PFD_{AVG}	FST and monthly PST PFD_{AVG}	FST only PFD_{AVG}	FST and monthly PST PFD_{AVG}
1	1.25E-02	4.55E-03	1.58E-04	2.07E-05
2	2.50E-02	8.30E-03	6.28E-04	6.89E-05
3	3.75E-02	1.21E-02	1.41E-03	1.45E-04
4	5.00E-02	1.58E-02	2.51E-03	2.50E-04
5	6.25E-02	1.96E-02	3.92E-03	3.82E-04

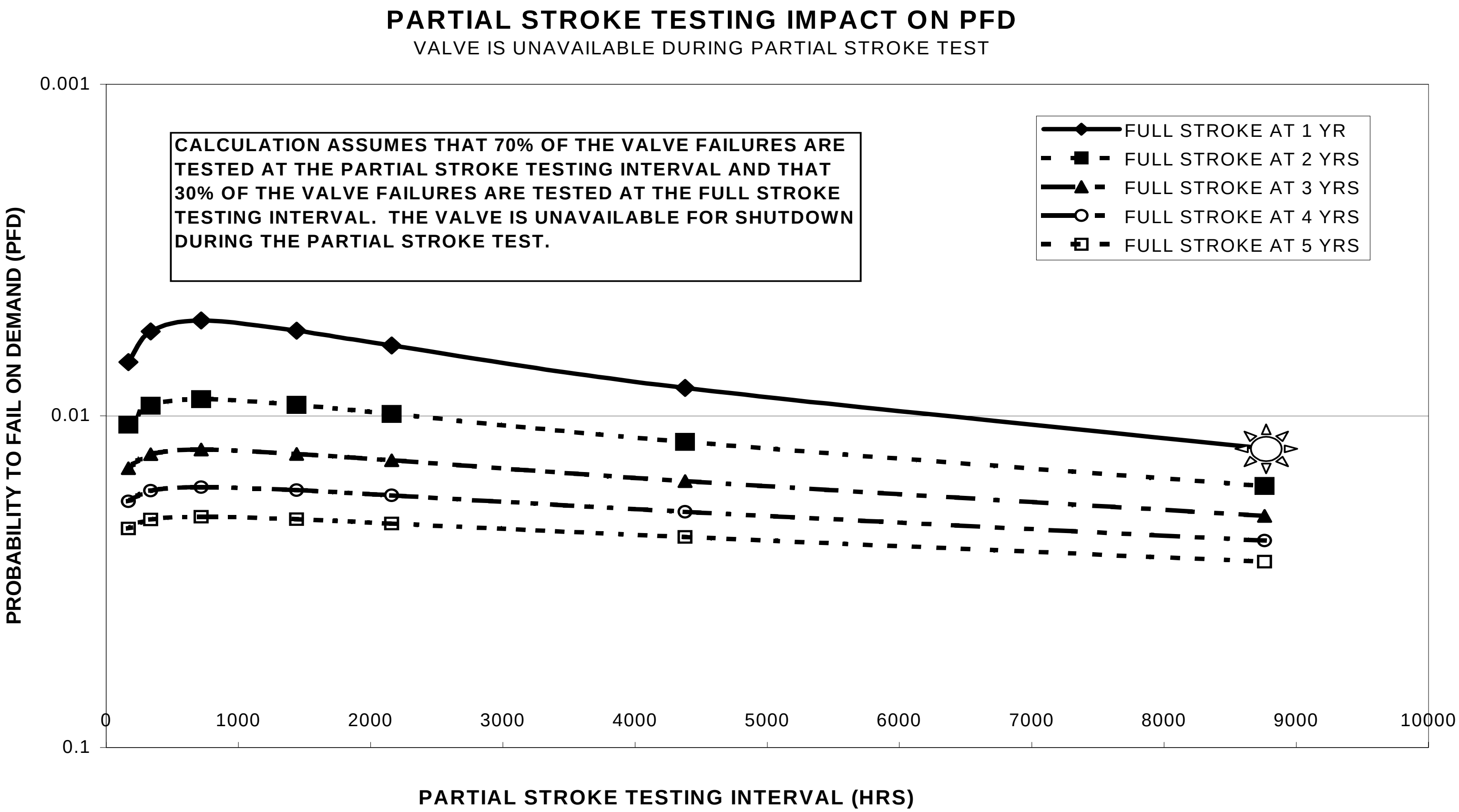

Figure 1. Relationship Between PST Interval and PFD – Valve is Unavailable During the Test

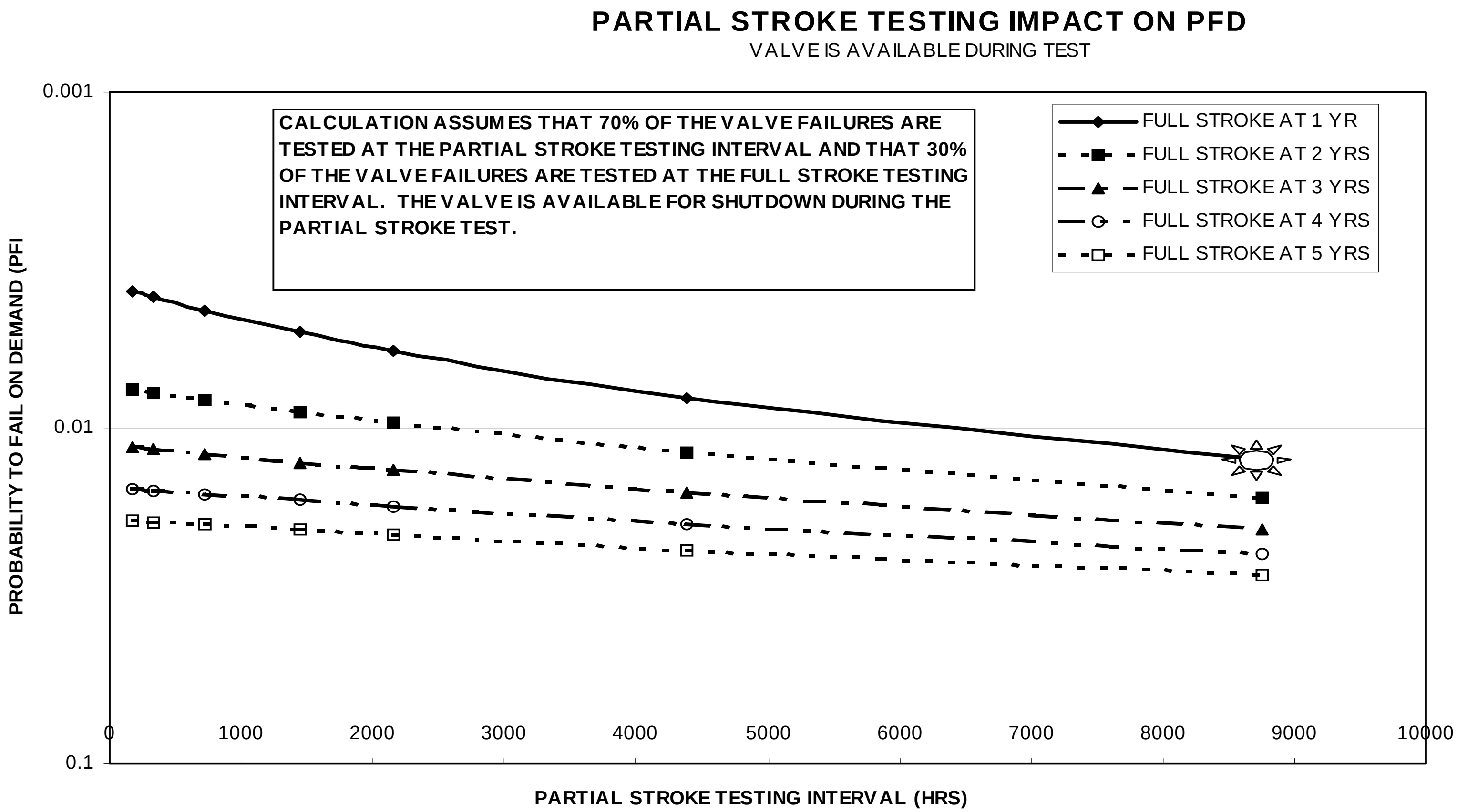

Figure 2. Relationship Between PST Interval and PFD – Valve is Available During the Test

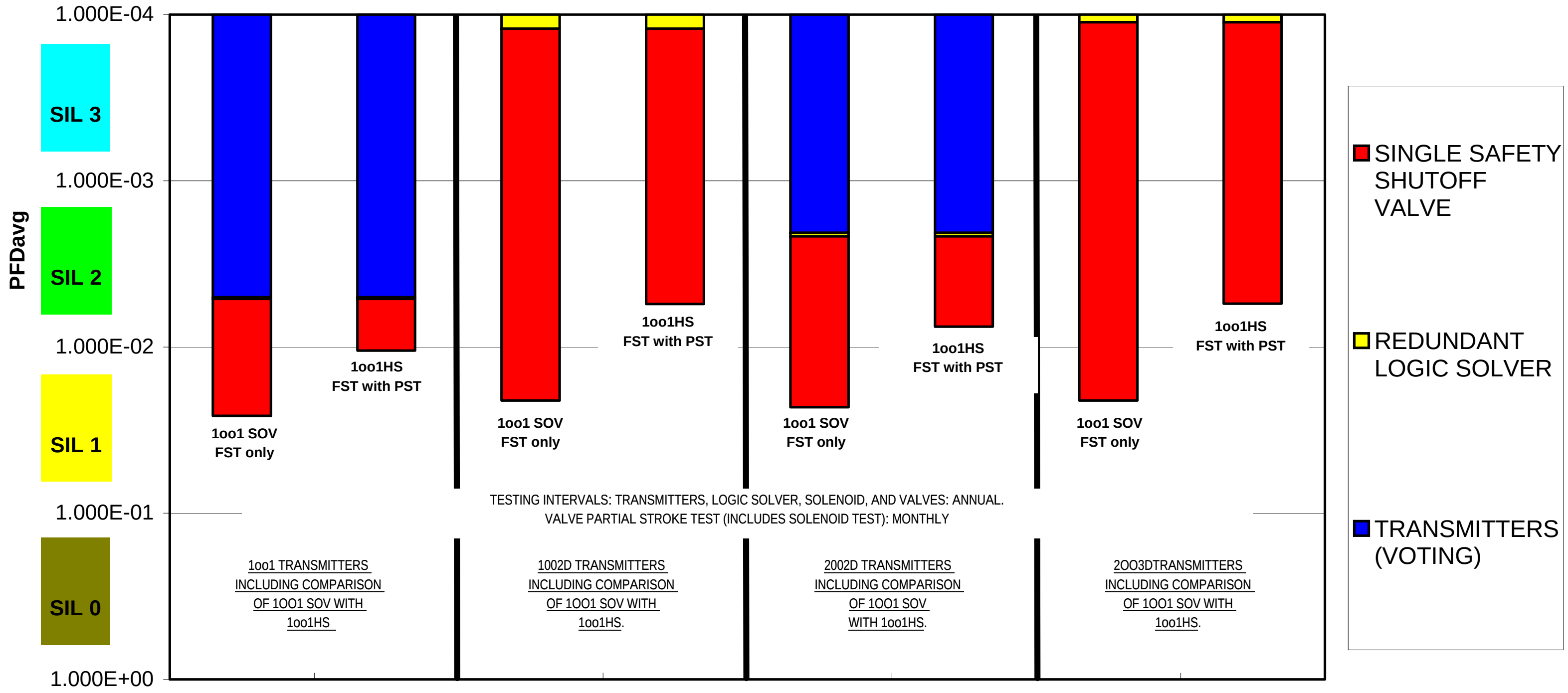

Figure 3. Plot of PFD_{AVG} showing the benefit of using PST of a single block valve

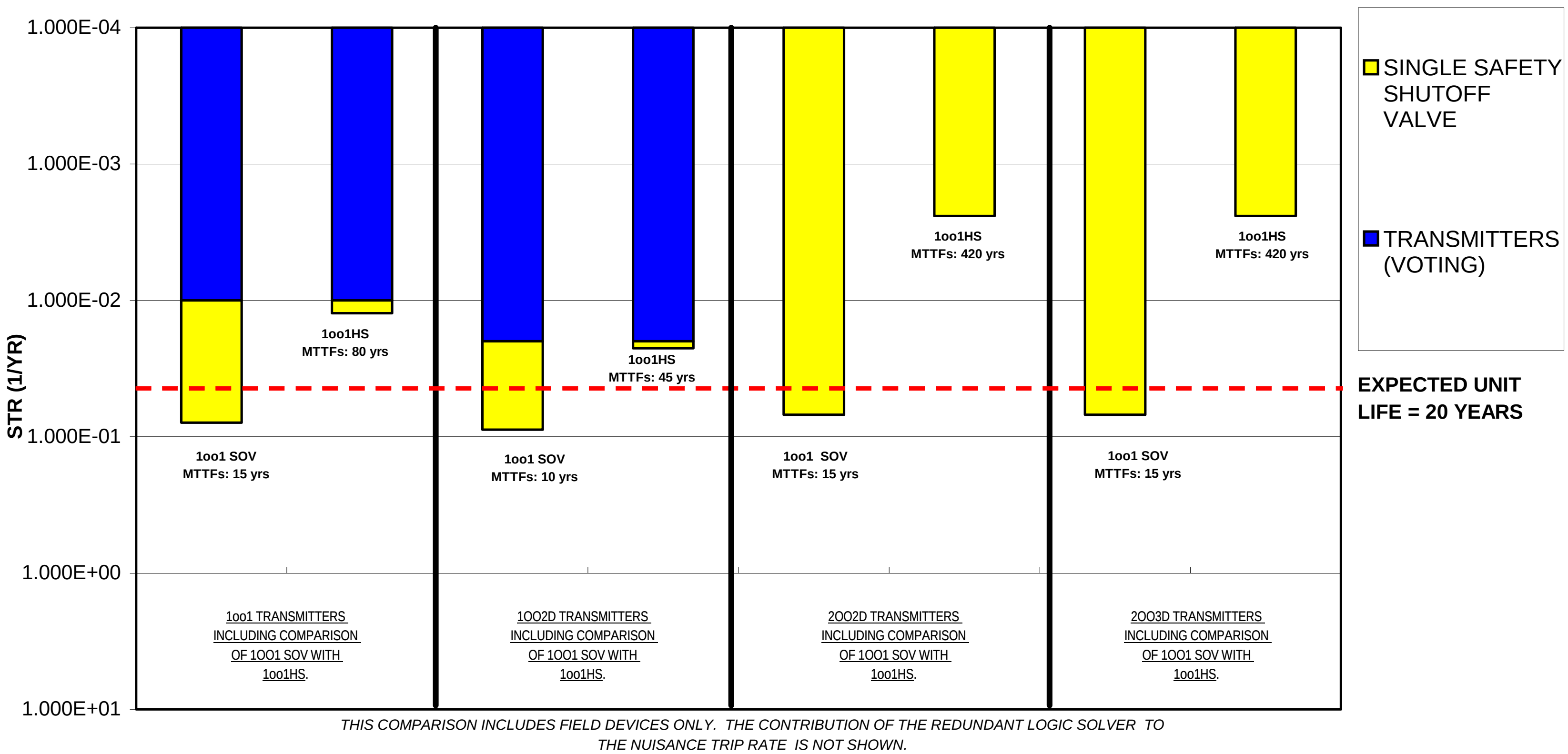

Figure 4. Plot of $MTTF^{spurious}$ showing the benefit of using PST of a single block valve

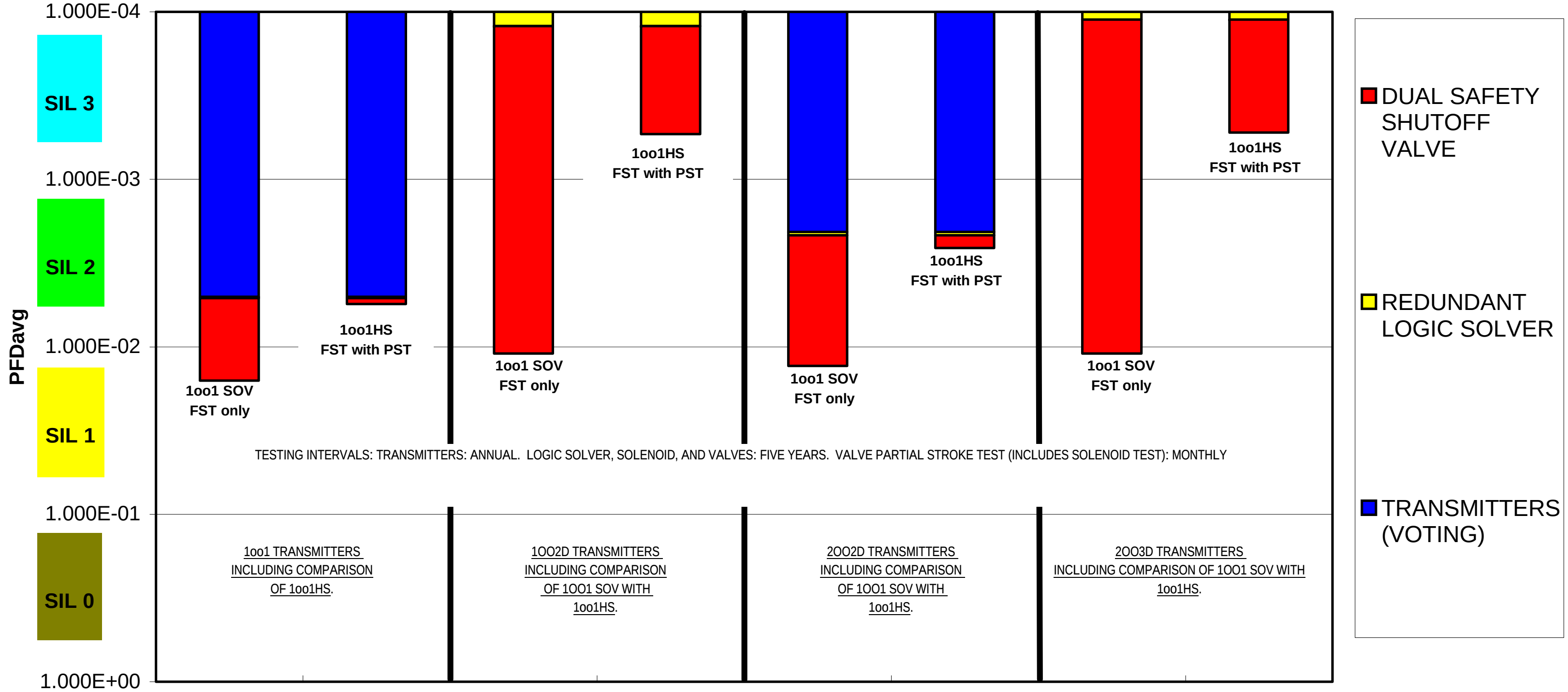

Figure 5. Plot of PFD_{AVG} showing the benefit of using PST of a dual block valve

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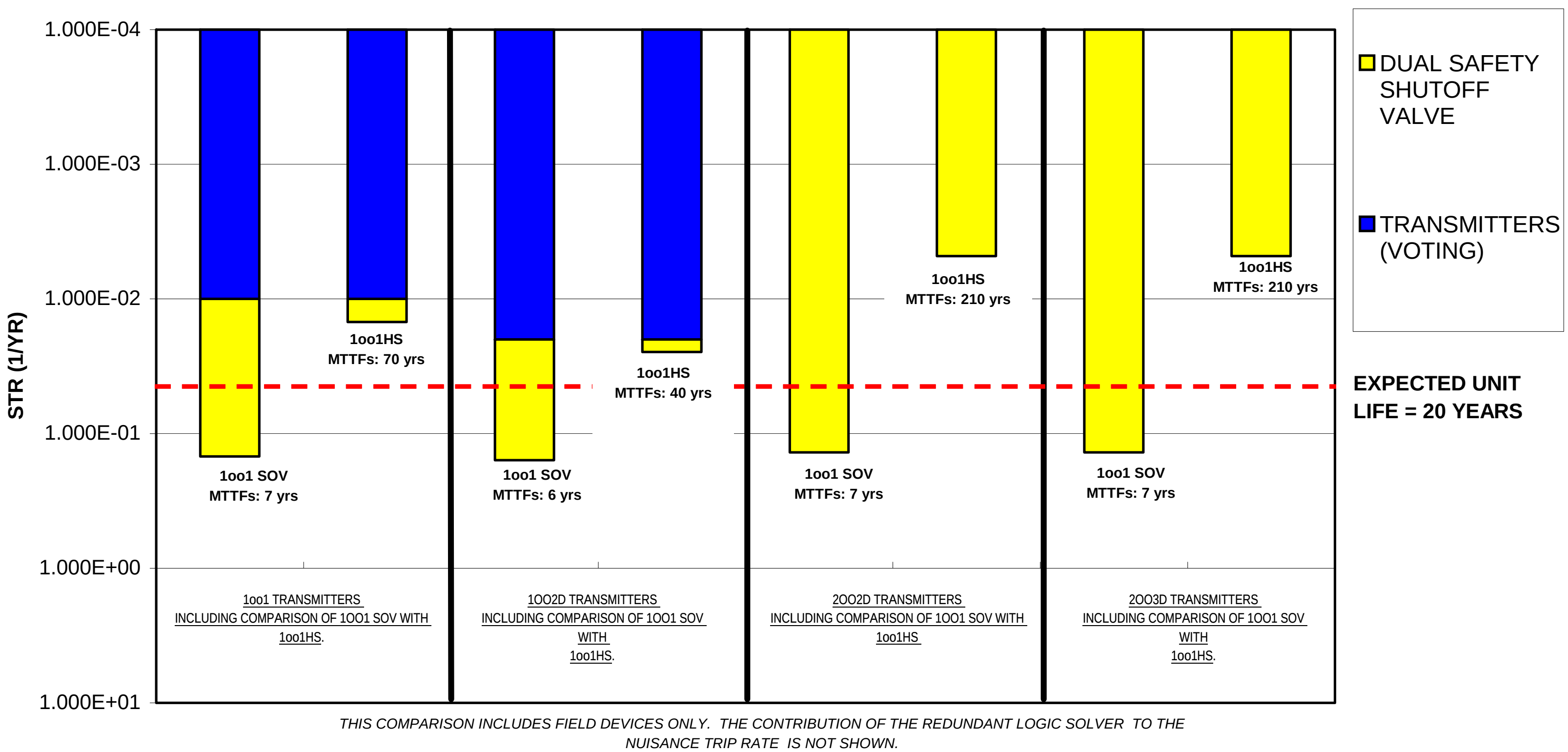

Figure 6. Plot of MTTF^{spurious} showing the benefit of using PST of a dual block valve