

PARTIAL STROKE TESTING SIMPLE OR NOT?

Vendors Promise Increases to MTBFs of 13,000 Years...

Is This Realistic? By Bill Mostia Jr., PE

Partial stroke testing (PST) has moved into the forefront of testing of safety instrumented system (SIS) valves. The partial stroke testing systems on the market range from purely mechanical devices to sophisticated, computerized systems that can automatically test the valve and provide sophisticated diagnostics and valve test signatures.

The premise of partial stroke testing is simple, but there are a number of aspects that make it a bit more complicated. While partial stroke testing can provide significant assistance in meeting safety integrity goals, there are mathematical limits to the improvements in risk reduction factor (RRF) that can be achieved by partial stroke testing, as well as practical limits that have to be considered in the design of a partial stroke testing system.

Most papers and articles on partial stroke testing only discuss the valve in the partial stroke test model. There are other components in the valve train that need to be considered depending on the type of partial stroke test system. These can include electromechanical solenoids, pneumatic solenoids and other pneumatic components, hydraulic solenoids and other hydraulic components, quick exhaust valves, intrinsic safety barriers, interposing relays, partial stroke devices, etc.

These components need to be taken into account in calculating the probability of failure on demand average of the valve train that can be achieved by partial stroke testing.

Many of these devices have significant failure rates, and failure rate data may vary or be difficult to obtain. Fortunately, the partial stroke testing diagnostic coverage rate for many of these components is high, but not necessarily 100%. Operation of some of these devices during partial stroke testing may increase the potential for spurious trips.

One of the capabilities of sophisticated systems is the ability to detect degraded performance in the form of changing system parameters (speed, pressure, start time, cycle time, etc.) or a change in a valve signature, which is a plot of testing parameters such as pressure, position, time, etc., or some combination thereof. The idea is that at some point degradation of these parameters or signa-

tures will trigger a "failed" valve signal due to a "prediction" of a future failure.

The detection of failures in the "future" compared with detection of failures in "now" is a concept of SIS testing that is commonly overlooked. This concept is that not only must a tested system work properly during test, it must also be returned to service "good as new." For electronic-based systems, this is relatively easy since the probability of an electronic device failing within the first 100 hours is considered the same as the probability of the device failure in the 10,000-hour time period.

While valves and other mechanical components are typically assumed to have a constant failure rate for SIS analysis, this may not be the general case without additional maintenance to return the valve or other mechanical components to the "good as new" state. This may also be aggravated if partial stroke testing is used at high test rates.

TABLE I.

TYPICAL FAILURE RATE DATA

| Item | Dangerous failure rate, 1/yr | PST diagnostic coverage |
|------------------------|------------------------------|-------------------------|
| Generic ball valve | 1.18E-02 | 65% |
| Generic 3-way solenoid | 2.10E-02 | 99% |

Since future prediction of potential failures detects degradation of the valve performance, it provides a method for satisfying the need to return the valve to "good as new" condition. This is true for the valve during partial stroke test for the parts that the PST tests, but it is also true for test of a valve at a full stroke test or at the full test interval to detect that a valve is not in the "good as new" condition.

The use of a partial stroke test system at the full test or during a test where a full stroke test is performed to evaluate valve parameters can detect degradation of valve performance. This would also apply to other mechanical components in the valve train tested during PST. Determination of the meaning of the test parameters measured by the partial stroke test system in relation to future failures remains somewhat of a difficulty.

What Do We Gain From PST?

Another benefit of partial stroke testing is that it provides limited exercise of the valve. One of the most commonly reported SIS valve failures is “stuck.” Exercising a valve is one method to minimize the potential of the valve sticking.

The valve typically is not the only mechanical element in a valve train. Commonly, there are also electro-mechanical solenoids, and there may be other mechanical elements such as pneumatic solenoids and quick exhaust valves. These elements can have failure rates that sometimes rival that of the valve. It is these devices that can really benefit from partial stroke testing because they are typically exercised more fully than the valve.

Partial stroke testing has been somewhat oversold. Supposedly, you can reduce the number of valves you need, full test once in a blue moon, use one valve in SIL 3, or test 90%-plus of your valve. One article states, “A test every quarter plus an annual full closure test will improve the valve’s Safety Integrity Level as defined by IEC 61508 approximately 30-fold.” Or as one company stated: “reduce their hazard rate from one failure every 1,500 years to a rate of one failure every 13,000 years.”

There are some very basic limitations of partial stroke testing. To illustrate this we will use the basic partial stroke test equation of a valve train. This is given by:

$$PFD_{avg} = DC_{PT} \times \lambda_D \times \frac{TI_{PT}}{2} + (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (1)$$

Where PFD_{avg} = probability of failure upon demand average of the valve train, DC_{PT} = composite diagnostic coverage factor of the partial stroke valve test (composite diagnostic coverage of all components in the valve train), λ_D = the combined dangerous failure rates of the components in the valve train, TI_{PT} = the partial stroke test interval, and TI_{FT} = the full valve test interval. The full proof test diagnostic coverage is considered to be 100% and the mean time to repair is considered not significant (discussed later in this article).

First, look at how much we can gain on the PFD_{avg} side. If we take the limit of equation 1 as the partial stroke test interval (TI_{PT}) goes to zero, (i.e. the time between partial stroke tests is zero; which is the fastest but unattainable partial stroke test rate), we get:

$$\lim_{TI_{PT} \rightarrow 0} (PFD_{avg}) = DC_{PT} \times \lambda_D \times \frac{0}{2} + (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (2)$$

or

$$\lim_{TI_{PT} \rightarrow 0} (PFD_{avg}) = (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} = (1 - DC_{PT}) \times \text{Full Test } PFD_{avg} \quad (3)$$

What this means is that the very best you can achieve in PFD_{avg} improvement is the PFD_{avg} of the part not tested by the partial stroke test—i.e., $(1 - DC_{PT})$ multiplied times the PFD_{avg} achieved by only testing at the full test interval rate. For example, if you assume a partial stroke test composite diagnostic coverage of $DC_{PT} = 80\%$, the best you can do is a PFD_{avg} improvement of a factor of 5 or 20% of the original PFD_{avg} . A $DC_{PT} = 90\%$ for the valve train will give you a gain of 10% of the full test PFD_{avg} or a factor of 10 while a $DC_{PT} = 70\%$ would give you a factor of about 3 improvement.

An interesting effect can occur when a low-failure-rate partial stroke device replaces high-failure-rate equipment in the valve train. While the equipment failure rate of the valve train improves, the partial stroke test diagnostic coverage can go down substantially because the valve is now the dominant component of the valve train in regard to diagnostic coverage.

Now look at it from extending the full test frequency while maintaining the same PFD_{avg} achieved without partial stroke testing. As we saw with Equation 3, at the limit, the PFD_{avg} given is:

$$PFD_{avg-Limit} = (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (4)$$

If we wish to maintain the same PFD_{avg} with the new test interval:

$$PFD_{avg-Limit} = (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (4)$$

At the limit:

$$PFD_{avg-Limit} = (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (4)$$

or

$$PFD_{avg-Limit} = (1 - DC_{PT}) \times \lambda_D \times \frac{TI_{FT}}{2} \quad (4)$$

For the case where the partial stroke diagnostic coverage is 80%, our ratio of new to old test rate that can be achieved at the limit is 5, or the same factor that we gained with the PFD_{avg} improvement as the goal with diagnostic coverage of 80%. So, if I have a test rate of once a year and a partial stroke test diagnostic coverage of 80%, the very furthest I can move my test frequency out using Equation

7 to is five years and maintain the same PFD_{avg} .

The same would apply to a diagnostic coverage of 90% where test time gain is a factor of 10. Remember, factors such as erosion, corrosion, material buildup, polymerization, abuse, degradation of the part of the valve not tested, and the unknown over time, may practically limit the extension of the test frequency time.

This is a numbers game and large composite diagnostic coverages make improvements easier. Claims of large gains or high diagnostic coverage should be looked at very carefully.

We have looked at the perspective of the improvement of PFD_{avg} and the test interval time extension from partial stroke testing. But that may not be telling us all there is about the limits of the partial stroke testing. At what rate should we test?

For example, testing every 10 minutes seems a bit excessive, while once every six months hardly seems worthwhile. If we do it once an hour, we will partial stroke the valve 8,760 times a year; or for a life of 10 years, 87,600 times. We need to consider wearout for the mechanical elements of the valve train.

What are some of the other limits of the partial stroke test rate? What about the possibility of spurious trips? The PST does increase the possibility of a spurious trip during test, since we are giving the valve a command to move and then rescinding that command so the valve only moves a short amount. That would appear to increase the possibility of a spurious trip over just letting the valve sit there. And spurious trips result in process upsets that can mean off-spec product, lost production, and, from Operations' perspective, more work.

Spurious trips also have safety implications. When responding to the spurious trip's process upset, operators may respond inappropriately, leading to a safety incident. Startup after a spurious trip is typically considered more dangerous than during normal operations.

There also can be a human psychological factor present. Online testing of any sort can be looked upon with a jaundiced eye by Operations, and testing more often than is absolutely necessary may be frowned on.

What about from the PFD_{avg} math? Are there some limits to be found there?

Let us look at what we gain by increasing the test rate and see if there can be a compromise between PFD_{avg} or risk reduction factor ($RRF = 1/PFD_{avg}$) improvement and the concerns of increased spurious trips.

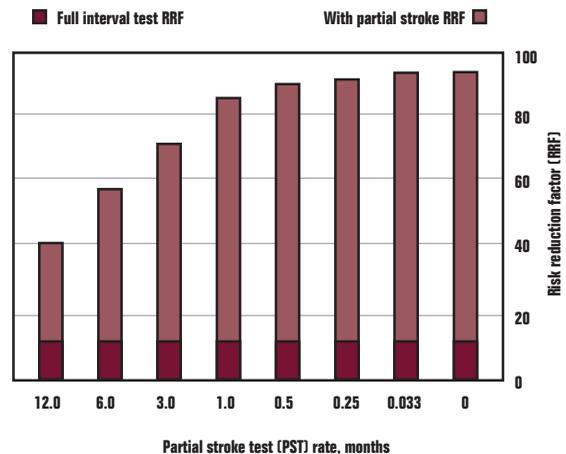
There are many combinations of failure rates, test coverages, test rates, etc., so for illustration purposes, three cases were chosen. These cases are full test intervals of five years, three years, and one year with a valve train composite diagnostic coverage of 87%. The valve train consisted

of a generic three-way solenoid and a generic ball valve. The equipment failure rate data are from Exida's 2003 *Safety Equipment Reliability Hand-book*, and are shown in Table I.

A 100% full interval proof test coverage was assumed and partial months have been rounded off to match common test intervals (for example, testing at 0.25 months is the equivalent to once a week). There are many partial stroke arrangements and this analysis may not be representative of all possible PST arrangements. As a result, each PST arrangement should be looked at individually.

FIGURE 1.

FULL TEST INTERVAL: 5 YEARS



FOR A FIVE-YEAR FULL TEST INTERVAL WITH 87% DIAGNOSTIC COVERAGE, THE RISK REDUCTION FACTOR IMPROVES LITTLE BY DOUBLING THE PARTIAL STROKE TEST RATE FROM EVERY MONTH (1.0) TO TWICE A MONTH (0.5).

Figure 1 illustrates the risk reduction factor (RRF) plotted against the partial stroke test frequency in months (0.033 is daily and "0" is the limit) for a five-year full test interval and an 87% composite diagnostic coverage (valve and solenoid). It can be seen that the RRF starts to flatten out at about one month.

The gain in RRF from 1 month (85) to 0.5 month (90) is only an RRF gain of 5, but we have to more than double the test frequency from 60 times to 130 times to get it. The gain from 0.5 months to 0.25 months is only 2 (90 to 92) but we would need to PST 260 times to get it. The limit is a RRF of 95.

Now look at a full test interval of three years and an 87% composite diagnostic coverage (valve and solenoid). In Figure 2, we see a flattening of RRF starting out at about between once a month and 0.5 months. At one

month, our RRF is 133, and if we roughly double our frequency to every two weeks, we will get a RRF of 145 or a gain of 12 by going from 36 to 78 tests. However, going to the next level, from every two weeks to every week, we get a gain of only 145 to 151, or a gain of 6 by testing 156 times. The limit is a RRF of 158.

Now, if we look at a 12-month full test frequency with 87% composite diagnostic coverage in Figure 3, we can see a flattening of RRF starting around testing at 0.25 months. But the flattening is not as pronounced, and there is still quite a bit of RRF to be gained but at the price of additional testing.

For example, going from 0.5 months (26 tests—RRF = 375) to once a week (52 tests—RRF = 418) gains 43 in RRF. Going from once a week (52 tests—RRF = 418) to once a day (365 tests—RRF = 464) for a gain in RRF of 46 requires a seven-fold increase in testing rate (from 52 tests to 365 tests). The limit is the RRF of 473.

We can draw some conclusions regarding the partial stroke test rate:

1. There are points of diminishing returns where the amount of testing has to increase substantially to gain a relative small amount of RRF.
2. These effects are due to the relative size of the partial stroke test contribution to the full test contribution. Two things affect the size of the full test contribution in this regard: the full test interval, TI_{FT} , and the partial stroke diagnostic test coverage, or actually $1-DC_{PT}$. This is simply a matter of a number getting smaller and smaller (the partial stroke test contribution) and having less and less effect on a larger number (the full test contribution which is becoming the dominant number in the equation).
3. It would seem that once a month for longer full-test intervals is a good balance between RRF gain and the amount of testing, and is a good starting point. Testing once a month seems also to be a good test frequency from an operational perspective.
4. Blindly setting a fast partial stroke test speed without considering the possible limits on testing frequency

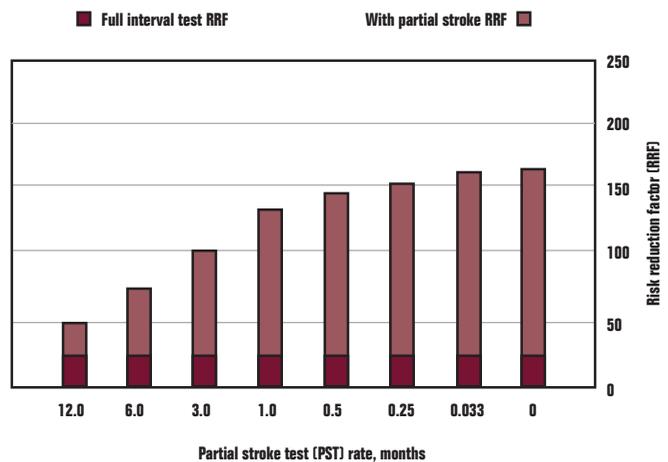
can lead to excessive testing and increased valve train wear with little gain in RRF.

Effect on the Safe Failure Fraction

Many partial stroke test arrangements provide automatic operation and are a form of automatic diagnostics. IEC 61508-2 defines the safe failure fraction (SFF) as “the ratio of the average rate of safe failures plus dangerous

FIGURE 2.

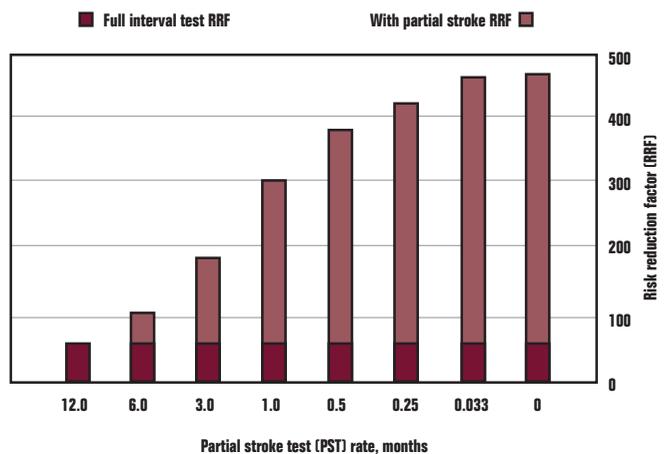
FULL TEST INTERVAL: 3 YEARS



WITH A THREE-YEAR FULL TEST INTERVAL AND 87% DIAGNOSTIC COVERAGE, MOST OF THE RISK REDUCTION FACTOR FOR PARTIAL STROKE TESTING IS ACHIEVED AT A PARTIAL STROKE TEST FREQUENCY OF TWICE PER MONTH.

FIGURE 3.

FULL TEST INTERVAL: 1 YEAR



WITH ANNUAL FULL-STROKE TESTING AND 87% DIAGNOSTIC COVERAGE, THE RISK REDUCTION FACTOR DUE TO PARTIAL STROKE TESTING CAN BE INCREASED SIGNIFICANTLY BY TESTING WEEKLY OR EVEN MORE OFTEN.

detected failures of the subsystem to the total average failure rate of the subsystem.”

Since automatic partial stroke testing will detect some dangerous failures that a system with only a full proof test will not, a certain amount of the total dangerous failures are converted to dangerous detected failures, assuming timely action is taken upon failure detection by the PST system. If these are considered in the safe failure fraction calculation, the safe failure fraction will improve with partial stroke testing. The SFF is used in IEC 61508 in determining architectural constraints, which provides limits on hardware fault tolerance (redundancy) in the application of SIS devices.

There is some controversy over whether the intent of the safe failure fraction is met by automatic diagnostics that operate with long diagnostic test intervals (months, for example) as opposed to the speed of the automatic diagnostics one would see in a logic solver or a safety transmitter. While 61508 also states “diagnostic tests may operate either continuously or periodically, depending on the diagnostic test interval,” 61508 does not supply much guidance on automatic diagnostics when considered with the safe failure fraction.

Whatever type of partial stroke testing system you choose, you will need maintenance and operational procedures and training. All these systems will add additional maintenance hours, some more than others, and some will add computer equipment.

In the final analysis, a safety instrumented function is a system of components. The $PF_{D_{avg}}$ of the SIS is determined by all the components. When a component is the dominant component in the $PF_{D_{avg}}$ equation for the system—and the valve train is commonly so—the reduction in that component’s $PF_{D_{avg}}$ can have significant effect on the system $PF_{D_{avg}}$.

However, if, for example, the valve train is not the dominant component or the PST causes the valve train not to be the dominant component as a result of the PST, further reduction in the valve train $PF_{D_{avg}}$ will not significantly affect the system $PF_{D_{avg}}$. 

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