USING STATISTICAL PROCESS CONTROL METHODOLOGY TO IMPROVE THE SAFE OPERATING ENVELOPE

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Abstract

Failure limits used to assess impairments from Operating Manual Tests (OMT) are often established using licensing limits from safety analysis. While these determine that licensing conditions are not violated, they do not provide pro-active indications of problems developing with system components.

This paper discusses statistical process control (SPC) methods to define action limits useful in diagnosing system component problems prior to reaching impairment limits. Using data from a specific OMT, an example of one such application is provided. Application of SPC limits can provide an improvement to station operating economics through early detection of abnormal equipment behaviour.

1. Introduction

Operating Manual Tests (OMTs) are used at the Point Lepreau Generating Station (PLGS) to ensure that specific system equipment meets defined limits of acceptable performance and availability. Limits are defined within the OMTs for Special Safety Systems that often refer to an Impairments Manual to determine the level of system impairment if the limits are exceeded. These impairments limits, which are based on safety analysis constraints, are documented in the station Safe Operating Envelope (SOE) (Reference 1). In many cases, these are the only limits within the OMT and constitute a pass/fail condition for the test. In the case of a fail condition, the operator is required to determine the impairment level.

While these limits effectively maintain the license limits for the station, they are re-active to a possible impairment condition and may not assist the System Specialist to pro-actively determine when equipment is degrading beyond acceptable norms. An approach to tracking degrading performance and defining maintenance limits used in many other industries is to use statistical process control (SPC) methods to define maintenance action limits.

This paper seeks to show that useful pro-active limits can be applied to various plant procedures by using simple SPC methods to determine action limits for system health monitoring.

2. Statistical Process Control Method

The following analysis is provided as an example showing some of the benefits of a SPC approach to define equipment performance limits that are based on observed performance. These limits could be used within the System Health Monitoring program to define a process to be applied by the System Specialist. The example provided is for the testing of opening times for Dousing Suction Valve 3432-PV11(which is 1 of 4 Dousing Tank Isolation Valves). This timing requirement is defined in the Emergency Core Cooling SOE basis document as a safety critical parameter for that valve. The approach is equally applicable to most equipment covered by system testing.

The SOE timing requirements for PV11 are presented in Table 1 from SOE documentation. Note that the Unsafe Fault (Slow) condition is defined based on safety analysis whereas the Nominal and Tolerable performance ranges are based on values defined in the OMTs.

Table 1 3432-PV11 Value Opening Time Requirements

FAULT STATES	TESTED OPENING TIME	COMMENTS
Unsafe Fault (Fast)	N/A	Fast opening is not a safety concern.
Tolerable Fault (Fast)	< 5 s	OMT-63432.58
Nominal	5 to 10 s	OMT-63432.58 OMT-63432.57 OMT-63432.52 Note that with back-up N_2 supplies, the expected opening time is from 5 to 10 seconds (OMT-63432.20).
Tolerable Fault (Slow)	> 10 s	OMT-63432.58
Unsafe Fault (Slow)	64 s	Based on Safety Analysis value.

2.1 3432-PV11 OMT Data

The System Specialist for ECC has provided a record of PV11 valve opening time data from all OMT results for this analysis. There are multiple OMT's that measure these values as follows:

OMT	Number of Test Cycles Within the Procedure	Test Frequency
OMT-63432.14 Rev 8	1	Yearly
OMT-63432.26 Rev 9	1	~ Quarterly
OMT-63432.48 Rev 4	1	~ Quarterly
OMT-63432.52 Rev 4	4	Quarterly
OMT-63432.57 Rev	4	Monthly
OMT-63432.58 Rev	2	Monthly

OMT	Number of Test Cycles Within the Procedure	Test Frequency
OMT-63432.59 Rev 4	2	Monthly

For the purposes of this paper, data from OMT-63432.57 will be used as an example to demonstrate the benefits of a statistical approach when more than one test cycle is applied within a test.

OMT-63432.57 is performed on a monthly basis and specifies four test cycles in the procedure, in which opening time is determined at each of the four cycles. The PLGS test data that has been provided extends from January 2002 until January 2008 and consists of over 300 individual values of valve opening times for PV11. The OMT methodology used determines the valve timing using an operator to activate the valve handswitch, start a stop watch, and observe the valve position EMI. When the EMI indicates the valve is fully open the stop watch time is recorded.

2.2 3432-PV11 Data Analysis

All of the statistical data analysis presented here was performed using the standard statistical software MINITAB Release 14 (Reference 2) used in SPC programs worldwide.

2.2.1 Normality Test

To start the data analysis, we determine if the test data follows a normal distribution, which would indicate that the test data is subject to normal random errors and not subject to any special cause errors.

Figure 1 shows a graphical summary plot for the entire test data recorded as described above. The figure indicates that the test data does not follow a normal distribution as it shows two overall data groupings, one large group around 6 seconds and the second group around 15 seconds. Other data provided on the right of the figure indicates that the data is highly positively skewed (Skewness = 7.9883), and also highly peaked (Kurtosis = 87.08). For a normal distribution both of these values should approach zero. An example of a normal distribution is shown in Figure 2. This data is from channel E of the High Rate Log Neutron trip signal and was extracted from the PLGS data acquisition system, (SEDE), and so is not an outcome of human performance variance. It shows Skewness and Kurtosis values near zero and is typical of normally distributed data.

The two distinct groupings in Figure 1 indicate there is some special cause for the data distribution such that it does not follow a normal random error distribution. Discussions with the system specialist revealed that maintenance was performed on PV11 in mid-2002 to speed up the valve opening response time.

Since data prior to mid-2002 is no longer representative of current valve performance, it was eliminated from the data set. The resulting plot for the new distribution is shown in Figure 3 and now represents 284 data points (71 tests, 4 cycles per test). Again, this distribution is more positively skewed and peaked than a normal distribution but is improved from Figure 1.

Regardless, the 95% confidence intervals for the mean of the data are between 5.49 and 5.61 seconds while the 95% confidence intervals for the median are between 5.4 and 5.5 seconds.

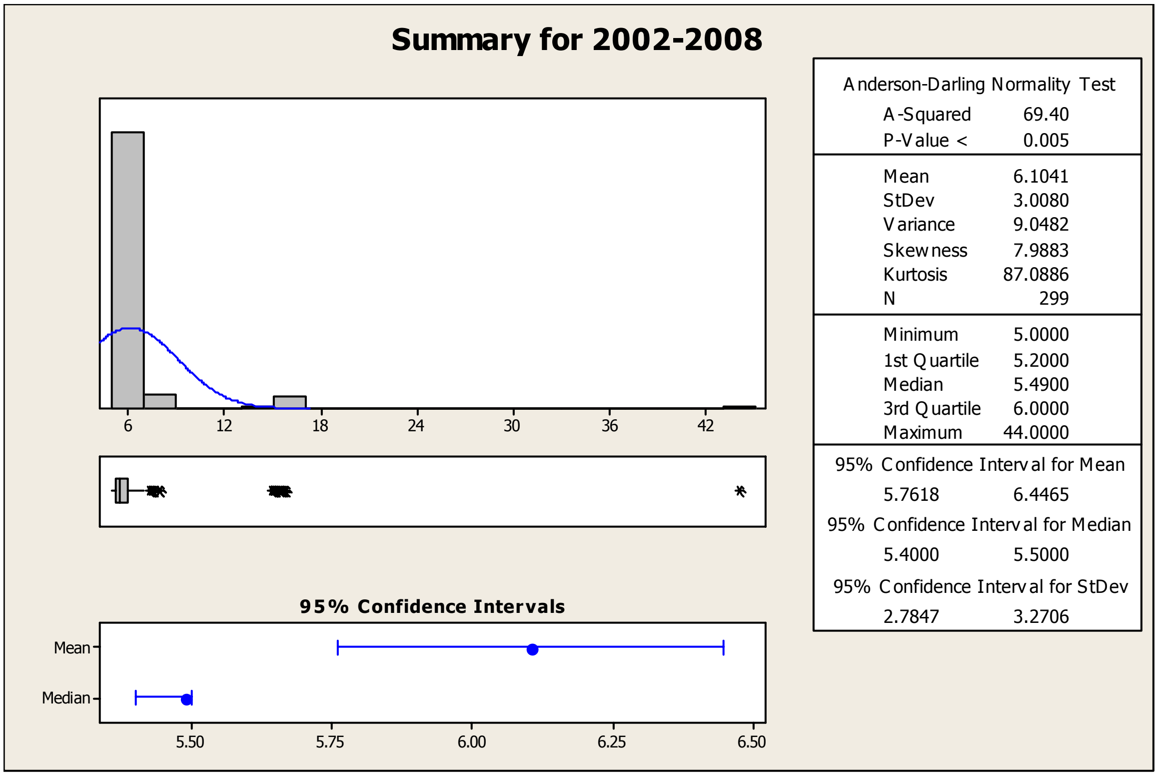

Figure 1 Distribution Plot for all Available Data

The mean value is larger than the median as a consequence of the outlying data points in the 6.5 to 8 second range. These values are suspect as they fall outside of the 95% confidence intervals for the overall distribution. With σ representing the standard deviation of a set of test data, then the $\pm 2\sigma$ limits (2 x standard deviation) represent the control limits at a 95% confidence interval. The $\pm 3\sigma$ limits represent the 99.73% confidence interval.

Further useful observations can be made from Figure 3 regarding the nature of the test data. It is shown that there are three main groupings for the data, those at 5, 5.5 and 6 seconds.

Examination of the raw data collected from the tests shows that some data has been recorded as whole numbers, others at one decimal place, and the remainder at two decimal places. From this, it is concluded that one reason for the form of the data distribution is the lack of guidance within the test procedure as to what constitutes a valid timing reading from the stop watch. Details should be provided within the OMT defining the number of acceptable significant figures to be recorded.

Additionally, the lack of outlying values on the left side of the distribution is also a consequence of the method of testing. The data reveals that there are no values recorded that are less than five seconds. Since the operator records the valve opening time by stopping the watch when an EMI flips to the open position, there is never a tendency to under-predict the valve opening time. That is, the operator always reacts to the movement of the EMI and so does not predict that movement is about to occur. Hence, the data distribution is positively skewed toward a minimum value of five seconds. This reinforces that in timing the valve, the lag time associated with the initial signal to close and the EMI indicating full closure is never less than 5 seconds.

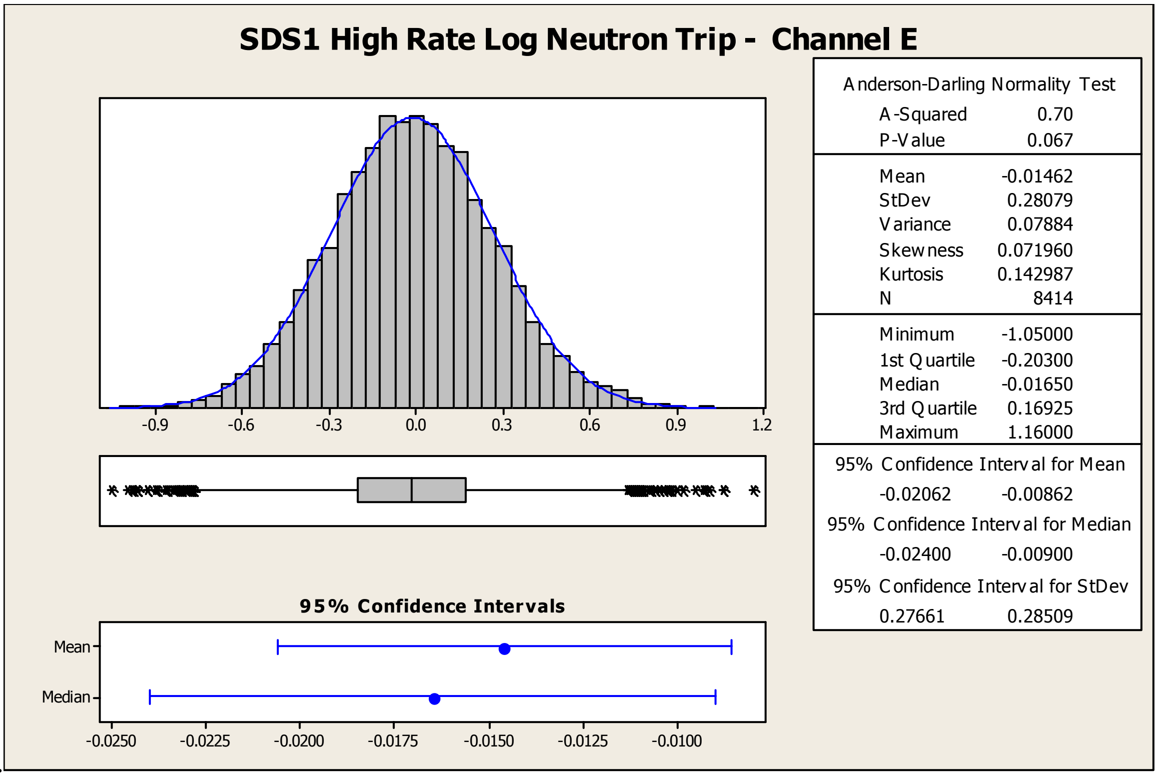

Figure 2 Example of Normal Distribtution from Plant Data

It is concluded that the test data is influenced by the following factors:

1. The reaction time of the operator observing the position change of an EMI.
2. The lack of procedural guidance for the significant figures to be recorded for valve timing.
3. Uncertainty in the instrument loop controlling the valve.
4. Variance of the actual valve closing time due to random errors.

List item two can be improved by modifying the test procedure and item three can be partially addressed by improvements to instrumentation. The test is conducted to determine the actual valve opening time performance but the results are also influenced by the reaction time of the operator.

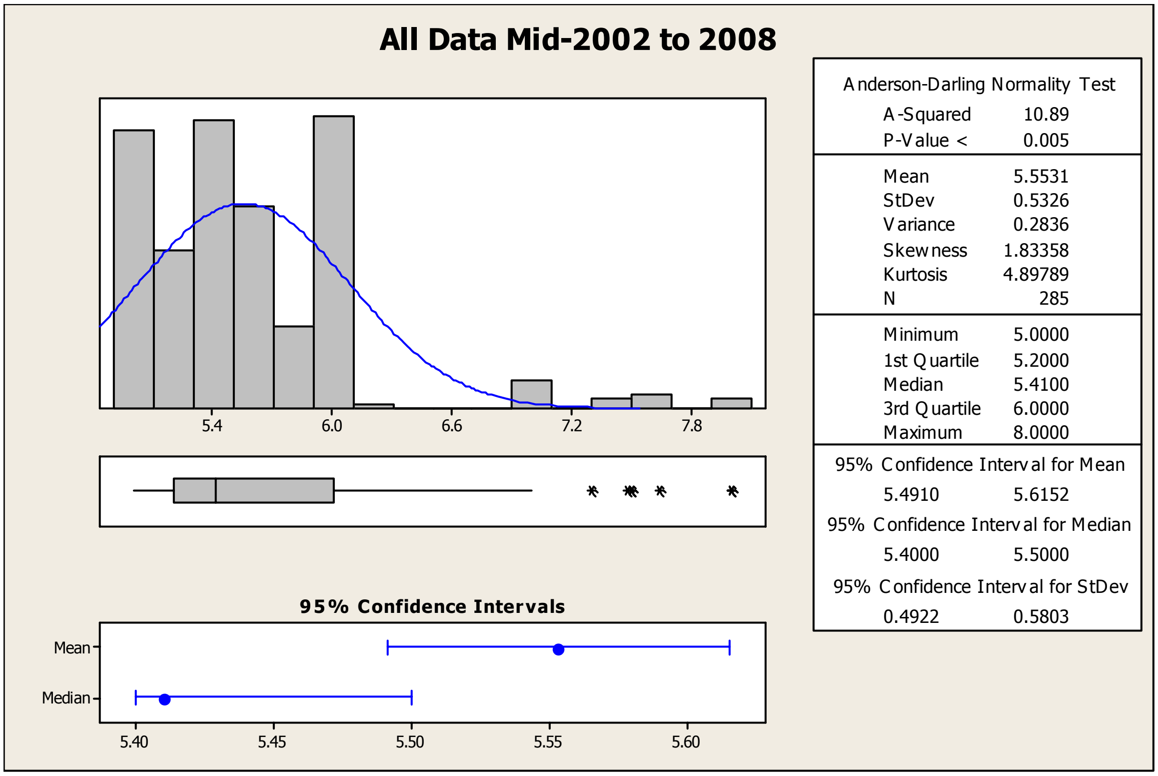

Figure 3 Distribution Plot for Mid-2002 to 2008 Data

2.2.2 Data Grouping Analysis

The next aspect of the test procedure to determine is whether the four individual test cycles conducted within each test are statistically equivalent. If so, data from each test can be grouped and the resultant mean values compared from one test to another to determine the valve timing characteristics. One method to determine this is an Analysis of Variance (ANOVA) test.

For the ANOVA test, the data from each of the four test cycles was grouped together, resulting in four data sets, each set containing seventy-one valve opening times, one for each recorded test. These data sets were compared using the ANOVA test to determine if one or more of the means represent different data populations. The hypotheses tested are:

H_o: $\mu_1 = \mu_2 = \mu_3 = \mu_4$ (The Null Hypothesis, i.e. each data set is equivalent).

H_a: at least one data set mean is different.

The resultant MINITAB ANOVA report is shown below.

One-way ANOVA: All Groups versus Groups

```
Source    DF       SS      MS     F      P
Groups     3    0.947   0.316  1.11  0.345
Error    280   79.604   0.284
Total    283   80.551

S = 0.5332   R-Sq = 1.18%   R-Sq(adj) = 0.12%

                           Individual 95% CIs For Mean Based on
Pooled StDev
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Level   N    Mean   StDev  ----+---------+---------+---------+-----
1      71  5.5869  0.6196           (------------*-----------)
2      71  5.5185  0.5226     (------------*-----------)
3      71  5.6280  0.5430               (------------*-----------)
4      71  5.4797  0.4306  (-----------*-----------)
                           ----+---------+---------+---------+-----
                             5.40      5.50      5.60      5.70
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From the above, the P value reported is an important indicator. In this method, if the P value is less than 0.05 it is concluded that at least one mean of the four groups is different. In this case, P = 0.345, indicating that the Null Hypothesis is accepted, that is, each of the test cycles is statistically equivalent. This is also shown by the horizontal bars in the figure above. These represent the 95% confidence interval for the mean of each group. If any of the horizontal bars do not overlap, then the means are not statistically equivalent. Since the bars all overlap, the Null Hypothesis holds. It is concluded that each of the test cycles within a single execution of a test, is statistically equivalent, therefore, each cycle is tested under equivalent conditions. The data from each of the four test cycles within a single test can be grouped together as representative of that test instance for comparison amongst each test run on different dates.

It is concluded that ANOVA tests provide an easy to use method to determine if data collected within a test from multiple test cycles are statistically equivalent.

2.2.3 Determination of Control Limits

Control limits are a statistical process control method to determine if there are special cause error conditions within the test data and to identify the validity of the test data. Using the MINITAB Control Chart features, the control limits can be calculated and plotted against the test data.

Figure 4 shows a chart in which the mean value from each test, determined from the four test cycles in a test, are plotted to determine the Upper Control Limit (UCL) and Lower Control Limit (LCL) for the test means. The UCL and LCL are the $\pm 3\sigma$ control limits and so represent a 99.73% confidence interval. Internationally accepted standards use the $\pm 3\sigma$ limits to determine if the data error is due to normal random errors or, if the $\pm 3\sigma$ limits are exceeded, the error is due to a special cause. Figure 4 shows that the UCL on PV11 opening time for test means is 6.15 seconds, and the LCL is 4.6 seconds. In addition, the data points marked with a square symbol and the number 1, indicate a failure of the control chart internal Test #1. Test #1 identifies those means that are greater than 3σ from the centre-line, indicating a special cause error. In Figure 4, five test cases are identified as being greater than the UCL. The control chart indicates that these tests are highly likely to contain erroneous data based on the normal behaviour of PV11 opening time. The UCL and LCL values can be used as test acceptance limits for the mean values recorded in a test. If a test does not pass these limits, it should be conducted again to verify the values. If the values are consistently in error, this would indicate that the performance of PV11 has changed and should be investigated. Currently, there are no checks within the OMT to determine the acceptability of the means of the four test cycles. This would be an easy modification to the test procedure that would establish SPC limits requiring a repeat of the test for verification of the results.

Figure 5 provides another type of control chart available in MINITAB. This is an Individuals chart in which data grouping is ignored. The plot shows the UCL and LCL representative of all individual valve opening times and how each of the 284 data points falls within the control limits. The UCL is found to be 6.51 seconds and the LCL is 4.95 seconds for individual valve opening times. There are 11 data points that exceed the UCL with no points less than the LCL. The overall PV11 opening time mean is 5.55 seconds. The plot shows that in 11 instances, the timing value is greater than the 3σ limit indicating that the individual valve timing data at these points is unreliable due to a special cause error. Plots such as this can be used to determine if test cycles should be repeated, or if the valve performance has degraded such that maintenance actions should be performed.

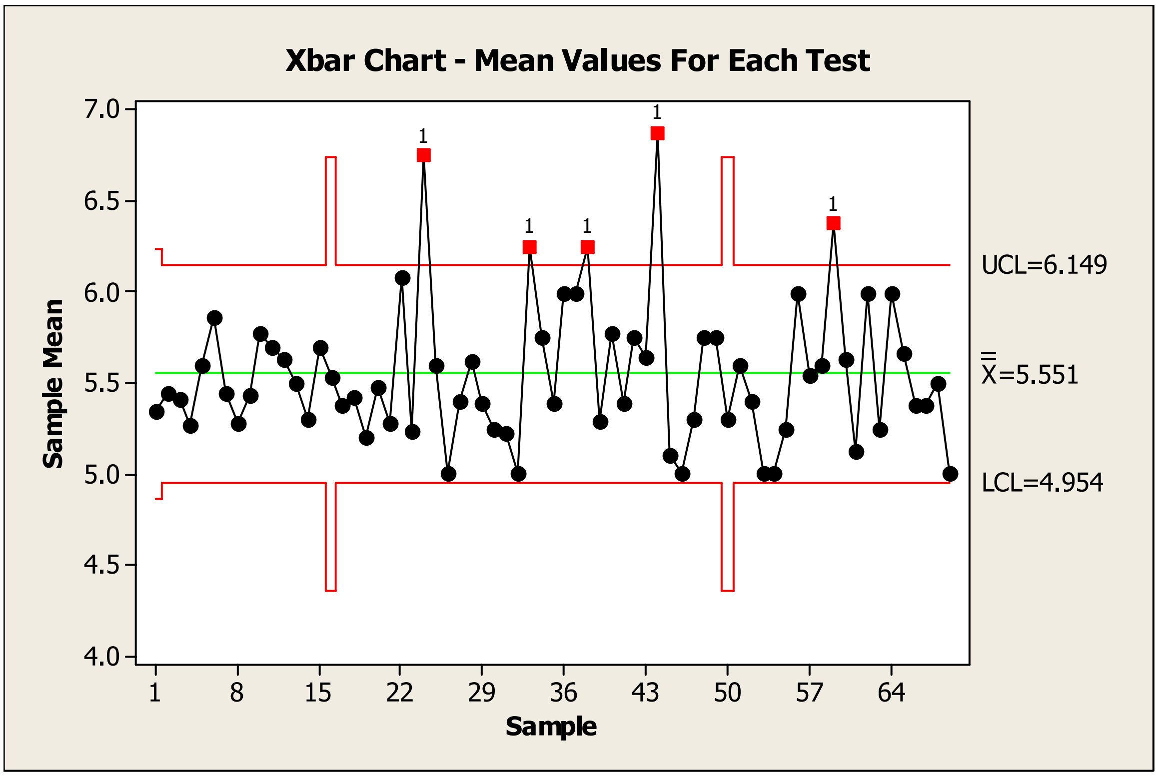

Figure 4 XBar Chart of Test Means

2.3 Discussion of Results

The values for Nominal, Tolerable and Unsafe fault opening times from the ECC SOE basis document have been presented in Table 1. These values are compared with the statistical process control data analysis and shown in Table 2. The following summarizes the results.

2.3.1 Nominal Values

The Nominal value opening times presented in Table 1 define a much broader range (5 to 10 seconds) than the SPC analysis of actual data would support. The analysis shows that the 3σ UCL for individual valve opening is 6.5 seconds. Consequently, any valve test showing a value greater than this is statistically outside of the 3σ control range for that valve and subject to a special cause error. Most likely these extreme values are caused by the inaccuracies involved when following the test procedures using stop-watch timing.

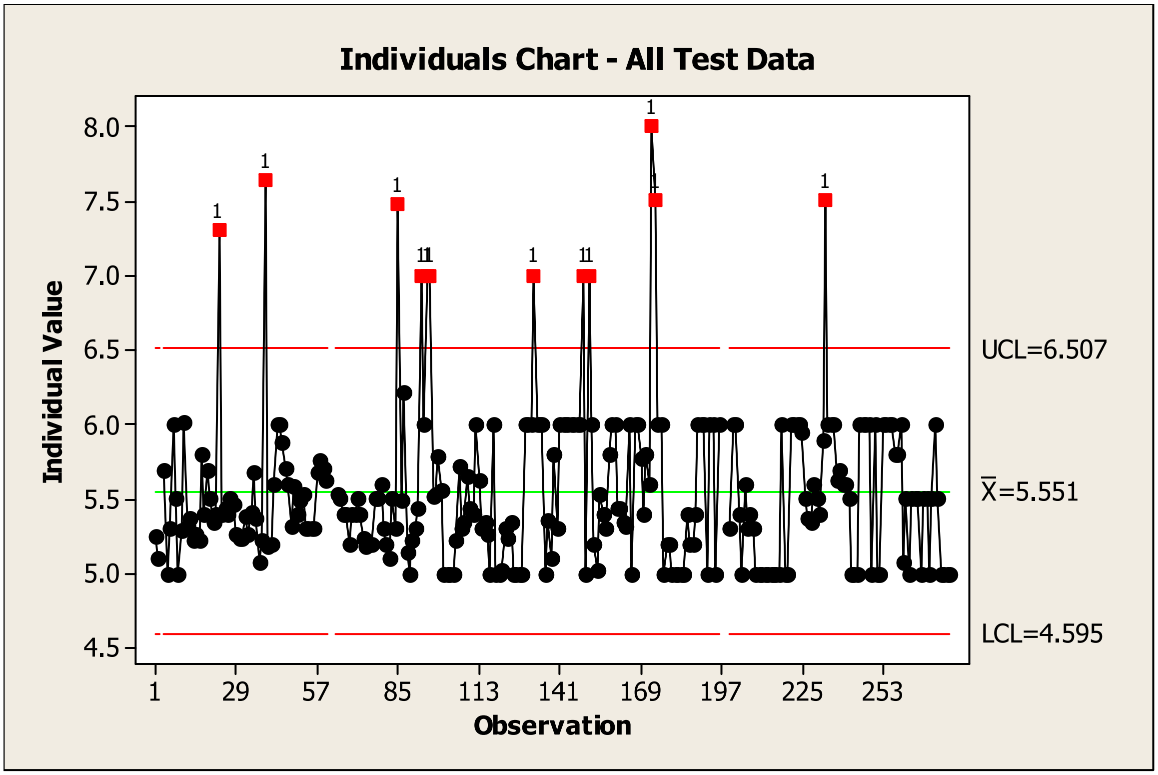

Figure 5 Individual Value Chart for All Test Data

2.3.2 Tolerable Faults

The range given in Table 1 for a Tolerable Fault (>10 seconds but less than 64 seconds) is so far outside the UCL as to be improbable unless the valve performance has been severely degraded and therefore not "Tolerable". The Tolerable values in the table run the risk of System Specialists misinterpreting what is actually tolerable on the basis of actual system performance versus limits defined in the OMTs. From the statistics, the Tolerable range would be more suitably defined as 6.5 to 8.0 seconds, corresponding to the rounded off range between 3 and 6σ. Even with this, it should alert the System Specialist that maintenance should take place on the valve as these are highly improbable values. An Action Limit could be defined based on the 3σ limit to alert the System Specialist to degrading system performance prior to the requirement to define an impairment. Consequently, the Tolerable Fault Limit could be set at greater than 8.0 seconds to define a Level 3 impairment requiring immediate repair.

2.3.3 Unsafe Faults

The Unsafe Fault value of 64 seconds, based on the SOE limit from safety analysis licensing constraints, shows that the safety analysis value is far outside of any normal performance statistics. While anything less than 64 seconds does not violate the site license conditions, it provides no pro-active indication that the valve performance is unacceptable which would be useful to System Health Monitoring. Instead, this is an indication of an immediate impairment of the Special Safety System.

3. Conclusion

Impairments limits typically have been established from safety analysis limits and documented in a station's Safe Operating Envelope. While this approach ensures that the station will be operated within its licensing constraints, it does not provide pro-active action limits that may recognize equipment maintenance requirements prior to failure. Using Statistical Process Control methods, system specialist may establish action limits on the basis of recognized statistical analysis. These methods are also useful to verify the effectiveness of the testing procedures.

4. References

[1] M. McIntyre, D. Reeves and R. Prime, "Implementation of an Improved Safe Operating Envelope", IYNC 2008, Interlaken, Switzerland, September 2008.

[2] Minitab Statistical Software, www.minitab.com