Transmitter Operation A Ten Year Perspective

Richard Rans – RANSolutions, Calgary Alberta Canada
Warren Peterson – TransCanada, Calgary Alberta Canada

ABSTRACT

Analysis of data over a ten year period reveals important transmitter operating and maintenance insights. Verification data has been factored into its uncertainty components of zero, slope (span), linearity, and hysteresis and then analyzed to demonstrate the long term stability capabilities of intelligent transmitters and expose factor that need to be monitored and controlled to minimize measurement uncertainty.

INTRODUCTION

In the late 1980's and early 1990's the use of analog differential and static pressure transmitters interfaced to flow computers routines was the emerging practice.

In 1990, a paper presented at the 2nd International Symposium on Fluid Flow Measurement [1] described the state of this practice for Electronic Flow Measurement (EFM) systems:

> *"EFM Calibration - The processing capabilities of the EFM device can be used to simplify the calibration process and compensate for transmitter deviation from ideal characteristics. Most EFM's provide calibration routines which prompt the user to simulate inputs, enter their engineering value, and then generate an individual calibration table for each transmitter. Dependent on the number of calibration points, the EFM's provide different degrees of compensation for transmitter non-linearity.*
>
> *This numerical processing technique can be enhanced by utilizing a series of up-scale and down-scale calibration points to characterize the transmitter hysteresis. The EFM can then generate a calibration table which is the mid-point of these up-scale and down-scale values, providing compensation for linearity and hysteresis"*

End to end calibration allowed the transmitter to be verified, zeroed and calibrated using only flow computer routines and calibration tables, without transmitter adjustment. The process also captures both the A/D and engineering values and this data was be used to generate verification data for the life of the transmitter.

In 1999, the use of this calculated verification process and its initial analysis was reported at the 4th International Symposium on Fluid Flow Measurement[2]:

> *Analysis of monthly routine electronic re-calibration and detection of calibration problems based on Primary to Check comparison identified four significant findings:*
>
> - *electronic calibrations enabled tracking calibration drift over time (The original calibration table of engineering values to A/D values can be compared to future calibrations done over the entire life of the facility unless the transmitter or transmitter range is changed)*
> - *analysis of calibrations over a three year time-frame indicated no significant calibration drift as long as there was no mechanical adjustment of the transmitter, no calibration problems caused by liquid or hydrocarbon contamination of the transmitter cell and no transmitter failure*
> - *routine monthly re-calibration caused more calibration problems that they fixed (The majority of re-calibrations didn't cause a problem, but ones that created a calibration problem exceed those correcting a calibration problem by a factor of between 2:1 and 10:1)*

[1] Richard Rans – "Real Time Measurement, Coordination Of Information Processing From The Field Meter To The Bill" – 2nd International Symposium on Fluid Flow Measurement, Calgary Alberta Canada, June 1990
[2] Richard Rans – "Timely Accurate Measurement Information; Management Of Data Collection, Validation, Maintenance And Publication Of Measurement Information" – 4th International Symposium on Fluid Flow Measurement, Denver Colorado USA, June 1999

- *primary to check comparisons identified all significant calibration problems*

This paper analyses verification data over time by comparing each transmitter verification to the median zero and slope verification of that transmitter. The data is then separated into their zero, slope, linearity and hysteresis effects and their trends analyzed. Although these test results are primarily for a single type of transmitter, the benefits can be extended to other types of intelligent transmitters through similar verification monitoring and analysis.

ANALYSIS SUMMARY

Because of the significant amount of new information being presented and analyzed, a summary of conclusions is being presented at the start to allow the reader to focus on the reasoning behind the conclusions and to question the validity of the supporting data as the information is being presented.

1. Advances in transmitter technology have resulted in designs with little or no calibration drift.
2. Verification differences have less to do with calibration drift and more to do with verification procedures, test equipment accuracy, routine variations that affect the transmitter output and defective or contaminated transmitters.
3. Calibrating transmitters while under the effect of short term influences introduces systematic bias into individual transmitter calibrations while only introducing noise into system balances. For example: Zeroing for a temporary 0.2% of span random influence can introduce a 1% of reading bias at 20% of operating range. This bias adjustment can introduce an $18,200/year error for a facility measuring $10,000/day of product.
4. Policies are required which establish acceptable verification tolerances and change maintenance procedures.
5. A number of influence factors can be determined from verification data once their results are viewed in context. Calibration cannot fix factors that are not calibration related.

DIFFERENTIAL PRESSURE TRANSMITTER ANALYSIS

Maintenance of analog transmitters has historically made a number of qualitative assumptions:
1. Differential pressure and static pressure transmitters routinely drift and require calibration
2. Calibration equipment is accurate because it is routinely inspected and calibrated at periodic intervals
3. Verification differences are primarily related to transmitter calibration drift errors which in turn requires calibration of the transmitter to zero out these verification differences
4. Transmitter zero and span adjustments interact which makes analysis of zero and slope errors impossible if the transmitter is adjusted

These assumptions have resulted in processes that compare the current transmitter verification to the previous calibration and assume that any as-found differences are the result of transmitter drift which requires calibration. Our analysis challenges these assumptions.

The Flow Computer Calibration Data Set

Figure 1 shows a typical as-found/as-left calibration reported by the flow computers used in this analysis.

Flow Computer Calibration				
	As-Found	As-Left	Eng Value	Voltage
0%	-0.528	0.000	0.000	0.9883937
20%	34.319	34.697	34.810	1.7889737
40%	69.191	69.466	69.620	2.5897141
60%	104.080	104.311	104.429	3.3908522
80%	138.972	139.162	139.239	4.1923571
100%	173.875	174.049	174.049	4.9942627
90%	156.521	156.695	156.644	4.5956693
70%	121.725	121.933	121.834	3.7961619
50%	86.904	87.158	87.024	2.9964166
30%	52.085	52.383	52.215	2.1970851

Figure 1 – Calibration Results Reported by the Flow Computer

The **As-Found** column is calculated by the flow computer at the time of the calibration using the flow computer measured voltage and calculating the engineering value using the flow computer calibration table from the previous calibration.

The **As-Left** column is calculated by the flow computer at the time of calibration using the flow computer calculated New Calibration Table as shown below in Figure 2. The measured voltage and the New Calibration Table is then used to calculate the As-Left engineering value. Notice the differences between the As-Left and Eng Value columns.

The **Eng Value** column is the engineering value of the source reference standard entered by the technician.

The **Voltage** column is the voltage measured by the flow computer at the time the source reference is applied.

Flow Computer Inputs

Eng Value	Voltage
0.000	0.988
34.810	1.789
69.620	2.590
104.429	3.391
139.239	4.192
174.049	4.994
156.644	4.596
121.834	3.796
87.024	2.996
52.215	2.197

Calibration Table Calculations

Eng Value	Up Scale Values	Down Scale Value	Average
0.000	0.988	0.988	0.988
34.810	1.789	1.794	1.792
69.620	2.590	2.597	2.593
104.429	3.391	3.396	3.394
139.239	4.192	4.196	4.194
174.049	4.994	4.994	4.994
156.644	4.593	4.596	4.594
121.834	3.792	3.796	3.794
87.024	2.990	2.996	2.993
52.215	2.189	2.197	2.193

New Calibration Table

Eng Value	Voltage
0.000	0.988
34.810	1.792
52.215	2.193
69.620	2.593
87.024	2.993
104.429	3.394
121.834	3.794
139.239	4.194
156.644	4.594
174.049	4.994

Note: Red Cells are calculated values.

- The Up Scale Values are calculated by linear interpolation using the Down Scale Values
- The Down Scale Values are calculated by linear interpolation using the Up Scale Values
- The Average is calculated by averaging the Up Scale and Down Scale Values

Figure 2 – Flow Computer Calculation of New Calibration Table

Figure 3 shows the calibration As-Found/As-Left results assuming that the measured results of the calibration as correct and that the As-Found values are due to calibration drift.

Flow Computer As-Found Based on Previous Calibration

Cal Set 5 Run 2 Run Use P
Date 2003-04-02 10:59

	Flow Computer Calibration				As-Found	
	As-Found	As-Left	Eng Value	Voltage	% Read	% Span
0%	0.427	0.000	0.000	0.99359		0.25%
20%	35.110	34.777	34.810	1.79405	0.86%	0.17%
40%	69.830	69.574	69.620	2.59484	0.30%	0.12%
60%	104.602	104.386	104.429	3.39582	0.17%	0.10%
80%	139.381	139.205	139.239	4.19719	0.10%	0.08%
100%	174.195	174.049	174.049	4.99942	0.08%	0.08%
90%	156.821	156.662	156.644	4.59914	0.11%	0.10%
70%	122.070	121.874	121.834	3.79833	0.19%	0.14%
50%	87.300	87.067	87.024	2.99728	0.32%	0.16%
30%	52.537	52.261	52.215	2.19656	0.62%	0.18%

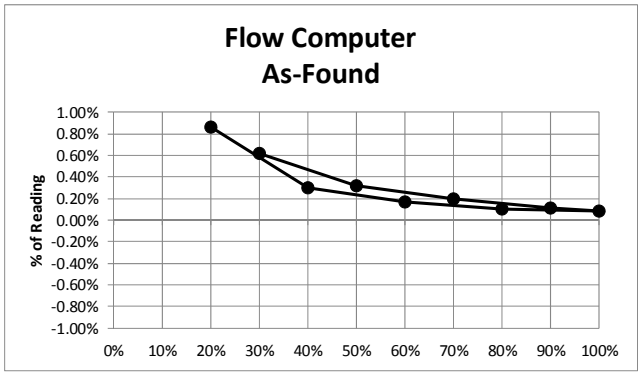

Figure 3 – Flow Computer As-Found/As-Left Calibration

Challenging Our Assumptions

But what if the As-Found differences are not caused by calibration drift? What if the differences are random variation in the transmitter output is caused by routine changes in operating conditions? What if the differences are caused by temporary changes to the transmitter performance when it is depressured? What if the reference standard or calibration procedure is causing the error?

To answer these questions we need to look at the reported data differently. Engineering and voltage columns can be used to calculate transmitter verification data for the period of time the transmitter is installed until the transmitter is adjusted because of three realizations:

1. The flow computer uses a calibration table to correct for calibration errors, not by adjusting the transmitter.
2. The transmitter voltage output is adjusted when the transmitter is ranged during installation, when the transmitter is re-ranged due to changes in operating conditions or if the transmitter drift is excessive.
3. Transmitter adjustments will show up as step changes in the verification data and can be identified during the analysis process.

Transmitter verification data can be calculated using only the **Eng Value** and **Voltage** data reported by the flow computer and the median zero and slope of the data for the period of time that the transmitter range does not change.

Flow Computer Calibration				
	As-Found	As-Left	Eng Value	Voltage
0%	-0.528	0.000	0.000	0.9883937
20%	34.319	34.697	34.810	1.7889737
40%	69.191	69.466	69.620	2.5897141
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70%	121.725	121.933	121.834	3.7961619
50%	86.904	87.158	87.024	2.9964166
30%	52.085	52.383	52.215	2.1970851

Figure 4 – Calibration Results Reported by the Flow Computer

Figure 5 shows the calculated verification data and Figure 6 describes the process of separating the As-found verification date into its Zero, Slope, Hysteresis, and Linearity components. All six verification data sets for this transmitter are shown in Appendix A.

Cal Set 5 **Run 2** **Run Use P** **Date 2003-04-02 10:59**

Verification Based on Median Voltage Zero and Slope

Zero 0.99359 **Median Zero** 0.99471
Slope 4.00583 **Median Slope** 4.00585

Verification (Compared to Median Voltage Zero and Slope)							
			Verification	Verification Components			
	Eng Val	Voltage	Total	Zero	Slope	Hysteresis	Linearity
0%	0.00	0.99359					
20%	34.81	1.79405	-0.23%	-0.14%	0.00%	-0.09%	0.01%
40%	69.62	2.59484	-0.14%	-0.07%	0.00%	-0.06%	0.00%
60%	104.43	3.39582	-0.10%	-0.05%	0.00%	-0.04%	-0.01%
80%	139.24	4.19719	-0.07%	-0.03%	0.00%	-0.02%	-0.01%
100%	174.05	4.99942	-0.03%	-0.03%	0.00%	0.00%	0.00%
90%	156.64	4.59914	-0.02%	-0.03%	0.00%	0.01%	0.00%
70%	121.83	3.79833	-0.02%	-0.04%	0.00%	0.03%	-0.01%
50%	87.02	2.99728	-0.02%	-0.06%	0.00%	0.05%	-0.01%
30%	52.21	2.19656	0.01%	-0.09%	0.00%	0.09%	0.01%

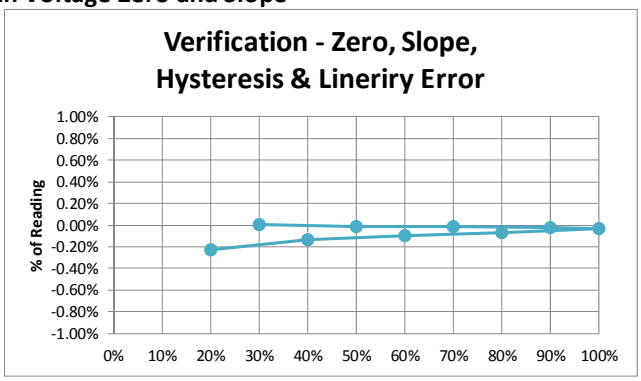


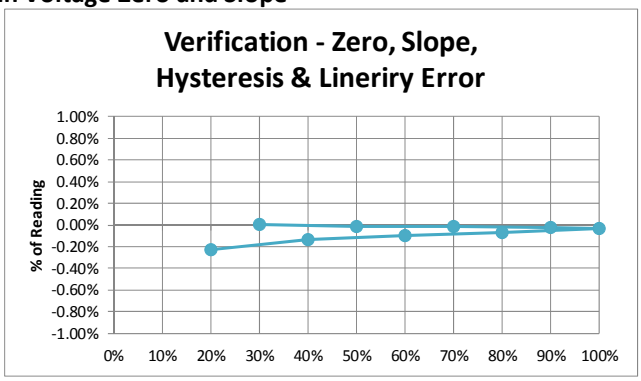
Figure 5 – Calculated Verification Data

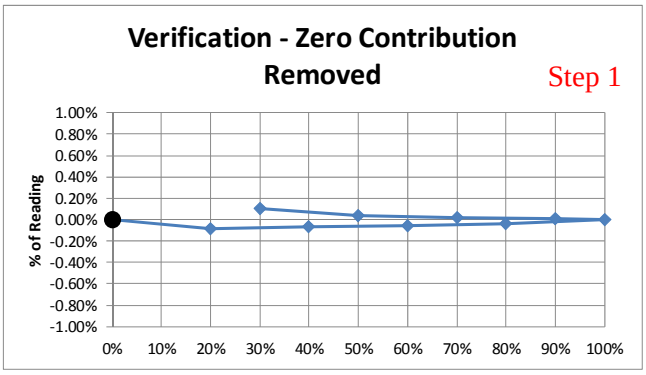
Cal Set 5 **Run 2** **Run Use P** **Date 2003-04-02 10:59**

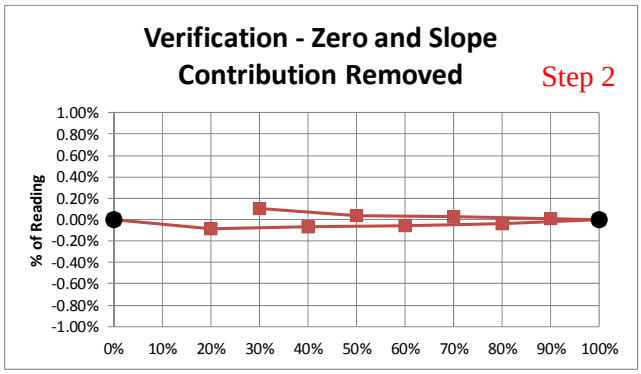
Verification Based on Median Voltage Zero and Slope

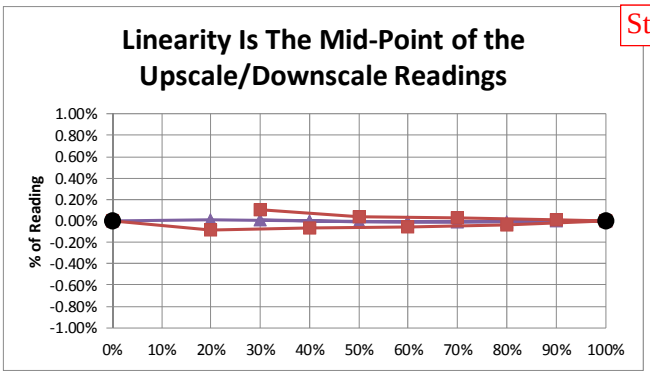
Zero 0.99359 **Median Zero** 0.99471
Slope 4.00583 **Median Slope** 4.00585

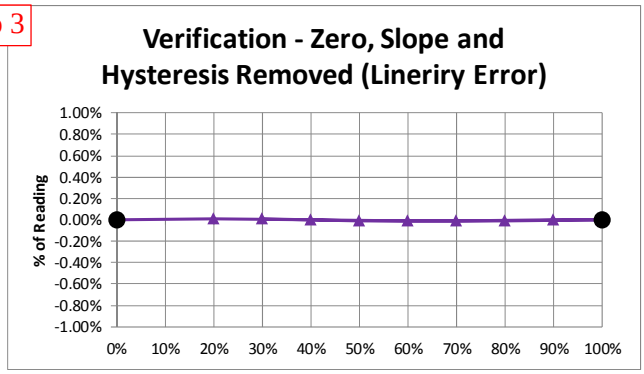
Verification (Compared to Median Voltage Zero and Slope)							
			Verification	Verification Components			
	Eng Val	Voltage	Total	Zero	Slope	Hysteresis	Linearity
0%	0.00	0.99359					
20%	34.81	1.79405	-0.23%	-0.14%	0.00%	-0.09%	0.01%
40%	69.62	2.59484	-0.14%	-0.07%	0.00%	-0.06%	0.00%
60%	104.43	3.39582	-0.10%	-0.05%	0.00%	-0.04%	-0.01%
80%	139.24	4.19719	-0.07%	-0.03%	0.00%	-0.02%	-0.01%
100%	174.05	4.99942	-0.03%	-0.03%	0.00%	0.00%	0.00%
90%	156.64	4.59914	-0.02%	-0.03%	0.00%	0.01%	0.00%
70%	121.83	3.79833	-0.02%	-0.04%	0.00%	0.03%	-0.01%
50%	87.02	2.99728	-0.02%	-0.06%	0.00%	0.05%	-0.01%
30%	52.21	2.19656	0.01%	-0.09%	0.00%	0.09%	0.01%











Step 1 calculates the verification zero uncertainty contribution from the indicated Zero voltage and Median Zero voltage. The zero uncertainty contribution is them removed for each of the remaining verification points with the results shown in the "Verification Components" table and the "Verification – Zero Contribution Removed" graph. (In this example the Zero error is
0.03 % of Span)

Step 2 calculates the verification slope uncertainty contribution from the indicated slope voltage and Median Slope voltage. The slope uncertainty contribution is them removed for each of the remaining verification points with the results shown in the "Verification Components" table and the "Verification – Zero and Slope Contribution Removed" graph. (In this example the Slope error is 0.00 % of Reading)

Step 3 calculates the verification hysteresis uncertainty contribution from the median of the upscale and downscale verification data after the zero and slope verification uncertainty has been removed as shown in the "Linearity is the Mid-Point of the Upscale/Downscale Reading" graph. The remaining linearity uncertainty results are shown in the "Verification Components" table and the "Verification – Zero, Slope and Hysteresis Contribution Removed (Linearity)" graph.

Figure 6 – The Verification Disaggregation Process

The Analysis Process

The above process was used to calculate verification data sets for each meter run and calibration range for approximately ten years of calibration data. The result was ~33,000 verifications divided into ~5900 data sets. Analysis of this much data can be overwhelming based on the sheer volume of data and the large number of insights it reveals. After working with this data set for a number of years the biggest challenge is seeing the forest for the trees.

On the other hand, presentation of summary analysis to support a conclusion without the detail is viewed with scepticism. The approach this paper will take to satisfy these two needs is to describe the data analysis process used, provide an example and then provide the analysis summary in the body of the paper and where possible to provide the details in appendixes.

The second technique used to simplify the analysis process is to choose a subset of the data that doesn't require a large number of assumptions. This was done by:

- limiting the analysis to primary transmitter data sets with over nine years of data and to exclude return runs
- using a simple outlier elimination process that only removes calibrations that have either a 1% of span zero error, a 1% of reading slope error or one or more linearity point that exceed 1% of reading
- using a visual review process to identify transmitters with a step change in the transmitter zero that would indicate the transmitter has a zero adjustment during its operating period

This reduces the number of data sets to 373 made up of 5758 verifications. (209 verifications were removed from the data set by the simple outlier elimination process described above.)

The trends have been calculated using the analysis method shown in Figure 5 – Calculated Verification Data (above). Appendix B shows all of the analysis data plotted in percent of operating range and as a function of time. Filtered verifications are indicated by a gap in the plotted data and the data set order has been sorted from smallest to larges zero standard deviation.

Long Term Calibration Drift

Statistical Process Control (SPC) principals were then applied to the data in an attempt to differentiate between calibration drift (SPC term is Special Cause) and routine variations (SPC term is Common Cause) to find the "signal" contained within the "noise". Statistical Process Control requires the following four conditions:

1. The process must be inherently stable over time. By limiting the analysis to transmitter data sets with more than nine years of verification data it is possible to graphically demonstrate that the transmitter calibration is inherently stable over time.
2. The process must be operated in a consistent manner. The operating conditions cannot be selected or changed arbitrarily. Because the same verification process is used and transmitter voltage is captured and reported by the flow computer with no adjustments being made to the transmitters (all adjustments are made in the flow computer calibration table), this condition is met.
3. The process average must be set and maintained at a proper level. This condition is met after the fact by using the verification data to calculate the median zero and slope of each calibration data set and then using these values as the process average. Calculation of the median value inherently excludes outliers compared to the calculation of the process average which will skew the average value if outliers are not removed.
4. The natural process spread must be less than the specified tolerance for the product. Although this requirement cannot be met as a pre-condition, the natural process spread can be determined from this analysis.

Although SPC process control charts and techniques are invaluable in determining if corrective action is appropriate, introducing them at this time adds a level of complexity that is not required. Analysis of calibration drift is best done by visual inspection of the data to determine:

- is there a trend indication of calibration drift?
- is there common cause noise that needs to be ignored?
- are there verification anomalies that should have been investigated and corrected versus just calibrating?

Figure 7 shows this process for six of the transmitter data sets:

- Set 410 appearing to have a zero drift of approximately 0.3% of Span over the ten year period with the remaining data sets having no discernible zero or slope drift.
- All nine data sets appear to have common cause noise in the approximately ±0.2% range.
- Set 4851 appears to have a verification anomaly in Q3 of 2001and Set 1895 appears to have a verification anomaly in Q1 2004 which is not present in the follow-up verification.

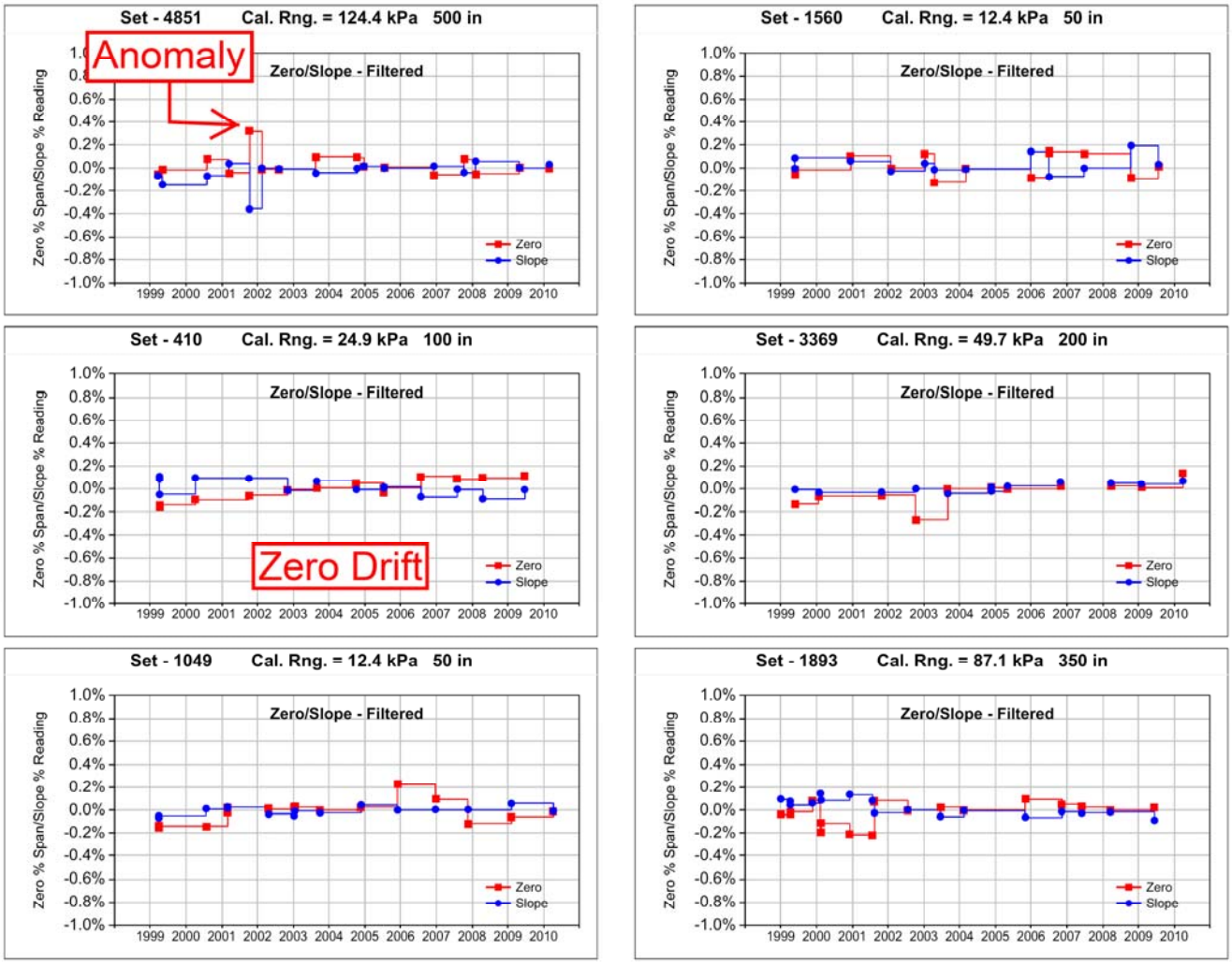


Figure 7 – Measureable Verification Attributes of Zero, Slope and Linearity

Remember the comment about not seeing the forest for the trees? Most measurement people want to increase the size of these graphs to focus on each point when in reality the long term calibration drift can be visualized when the data is displayed over time. So what does this data tell us?

1. It is harder to find significant calibration drift than it is to find significant random verification variations.
2. Transmitters with excessive random variability need to be replaced, not calibrated.
3. Verification anomalies can't be fixed by calibration, their cause need to be identified and corrected.

Visual review of the drift identified ~21 of the 373 data sets (~5.6%) had slope drift and ~35 of the 373 data sets (~9.4%) had zero drift. Table 1 summarizes the observations and Appendix C shows all 373 data sets.

Approximate 10 Year Drift (Based on Visual Analysis)																	
CalSet	Zero	Slope	CalSet	Zero	Slope	CalSet	Zero	Slope	CalSet	Zero	Slope	CalSet	Zero	Slope	CalSet	Zero	Slope
209		0.3%	715	0.5%		1882		0.2%	2376	1.3%		3259	0.7%		3701	-0.4%	
410	0.2%		1158	0.6%		1916		-0.2%	2395		-0.3%	3284	0.5%		3752	0.5%	
443	-0.7%	0.2%	1293		-0.2%	1986	0.7%		2450		0.5%	3378	1.0%		4319		-0.4%
445	0.2%		1379		-0.2%	1999		0.4%	2454		0.2%	3392	0.4%		4456	0.4%	
530	1.2%		1398	-0.2%		2170	0.7%		2653		-0.3%	3394	0.3%		4565	0.2%	
613	0.6%		1436	0.8%		2186	-0.5%		2655		0.9%	3404	0.2%		4856		0.2%
619	0.8%		1442	0.3%	0.2%	2228	-0.6%		2736		0.5%	3435	0.3%		5595	0.7%	
688	0.9%		1520	0.9%		2295		-0.3%	2821	0.8%		3574		0.4%	5750	0.4%	
712	-1.0%		1647		0.4%	2371	-0.6%	0.4%	2849	1.0%		3664		0.3%			

Table 1 – Summary of Data Sets With Zero or Slope Drift

The Effect of Zero/Slope/Linearity Verification Error over the Operating Range

One of the difficulties with looking at reported zero and slope verification data is determining their effect on the measurement uncertainty at any point with-in the transmitter operating range. The slope verification error is understandable because its reading value translates into an equivalent percent of reading error across the entire operating range. The zero verification error is more complex because it has a percent of span effect. This results in a growing percent of reading error as the operating point reduces from its maximum operating value. Figure 8 shows the % of Span and % of Reading errors associated with a Slope/Span Error and a Zero Error. Remember that the volume error of a differential pressure transmitter is ½ of the sensor % of Reading Error.

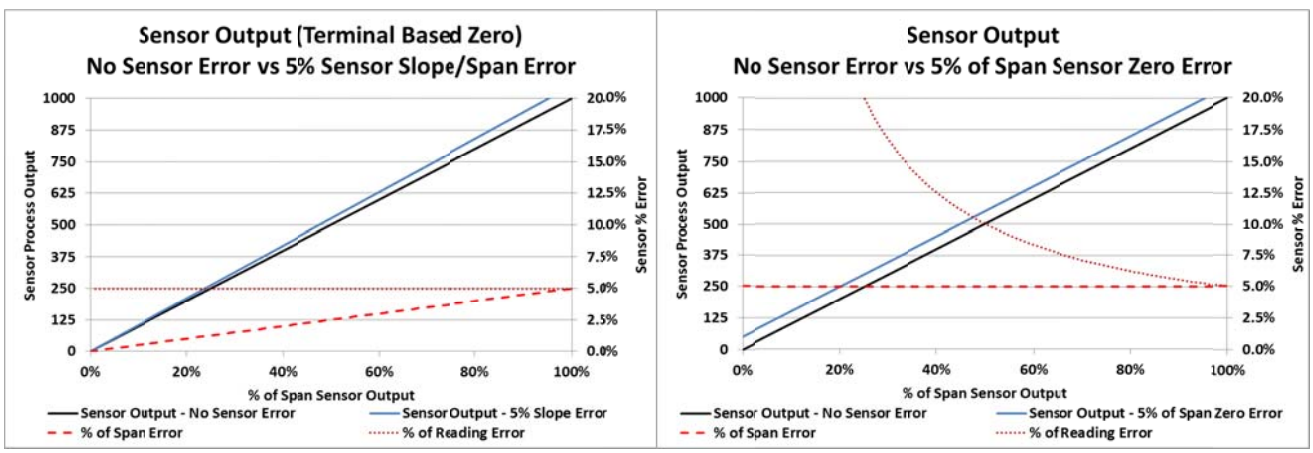


Figure 8 – Effect of Zero and Slope Errors over the Transmitter Operating Range

So how can we use this data set to understand the verification uncertainty over the transmitter operating range? Since we have the error of each verification divided into zero, slope, hysteresis and linearity, we can create a pivot table of the data that groups the combined verification error into discrete intervals and to then calculate average and standard deviation values for the individual verification errors within these groups.

Figure 9 and Figure 10 show the pivot data graphically. A few notes about these figures will help with their interpretation:

1. The Y-axis show the error contribution of the Zero and Slope plotted against the X-axis combined verification error bins.
2. The line superimposes the bin average and 1 standard deviation error bars.
3. The bars show the # of Verifications in each bin.
4. The top and bottom 5% of the verification data has been omitted to reduce the visual noise it causes due to the low number of verification point in each of the bins. Including the data would not change the trend.

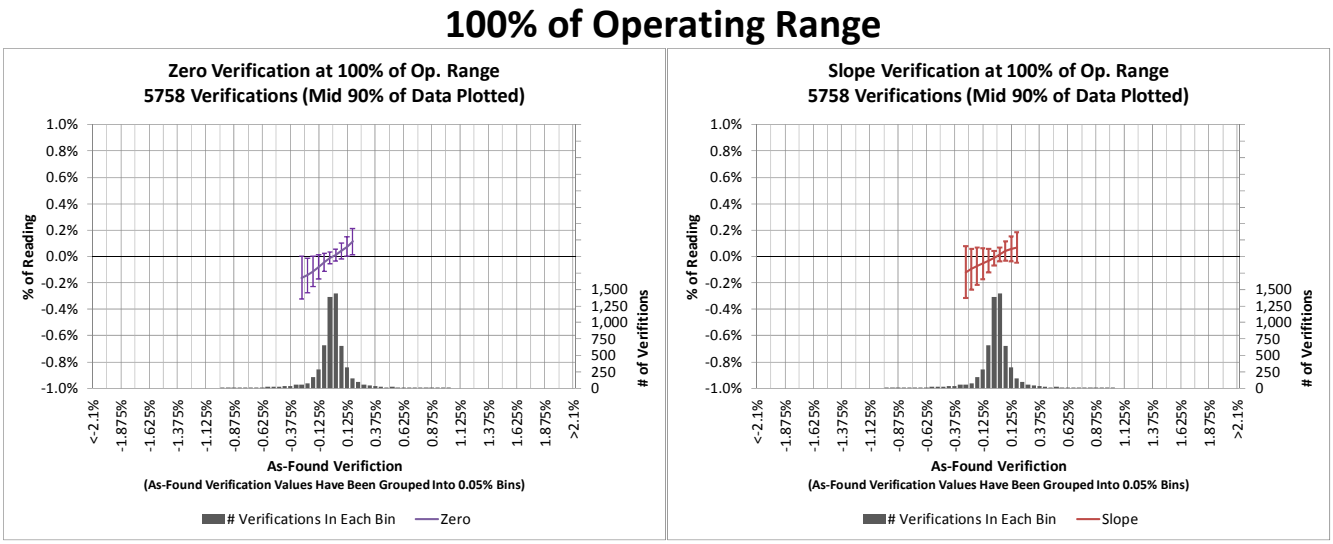


Figure 9 – Graphical Representation of 100% of Span Pivot Table Results

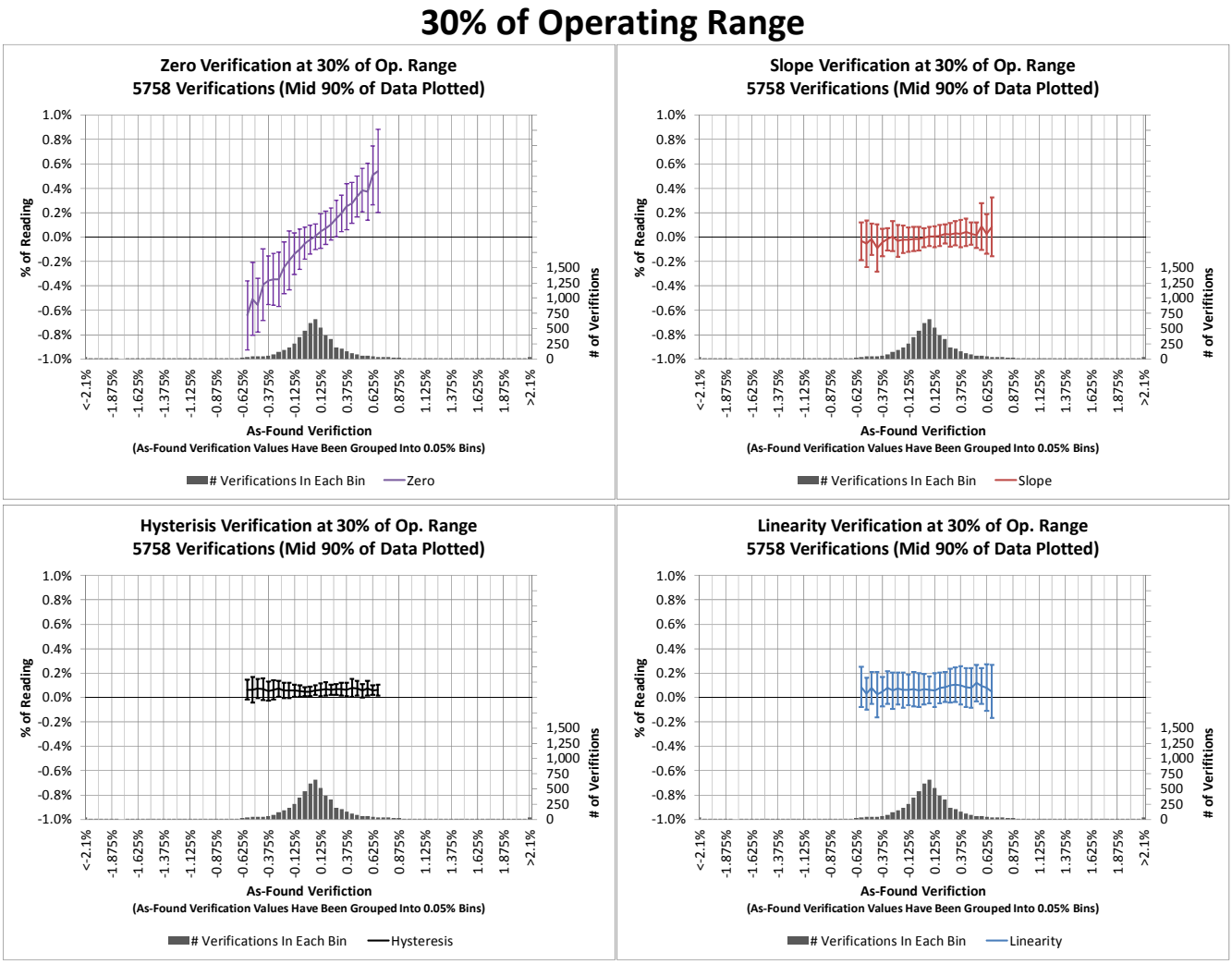


Figure 10 – Graphical Representation of Pivot Table Results at 30% of Operating Range

Although the 100% of operating range data is very tight (±0.4% transmitter error equates to ±0.2% volume error) the picture is quite different in the lower operating range as shown in Figure 10. At 30% of operating range the

% of Reading Zero error contribution as grown by 300% while the % of Reading Slope error is approximately the same as it was at 100%, it just covers a wider Verification Bin range. The wider range of the As-found Verifications Bins is due to the increase in the Zero error contribution to the combined error. Data for all nine verification points can be found in Appendix D.

The data from each of the verification point pivot tables was further summarized by weighting the absolute value of the verification error components in each bin by the number of verifications in the bin to estimate the relative and combined uncertainty contribution of Zero, Slope, Hysteresis and Linearity across the operating range of the transmitter. For example the linearity uncertainty contribution at 50% is:

$$Linearity_{50\%} = \frac{\sum_1^n Bin\ Average\ Linearity \times \#\ of\ Verifications\ in\ each\ Bin}{Total\ \#\ of\ Verifications}$$

Figure 11 show the summary of these calculations for the 9 verification points.

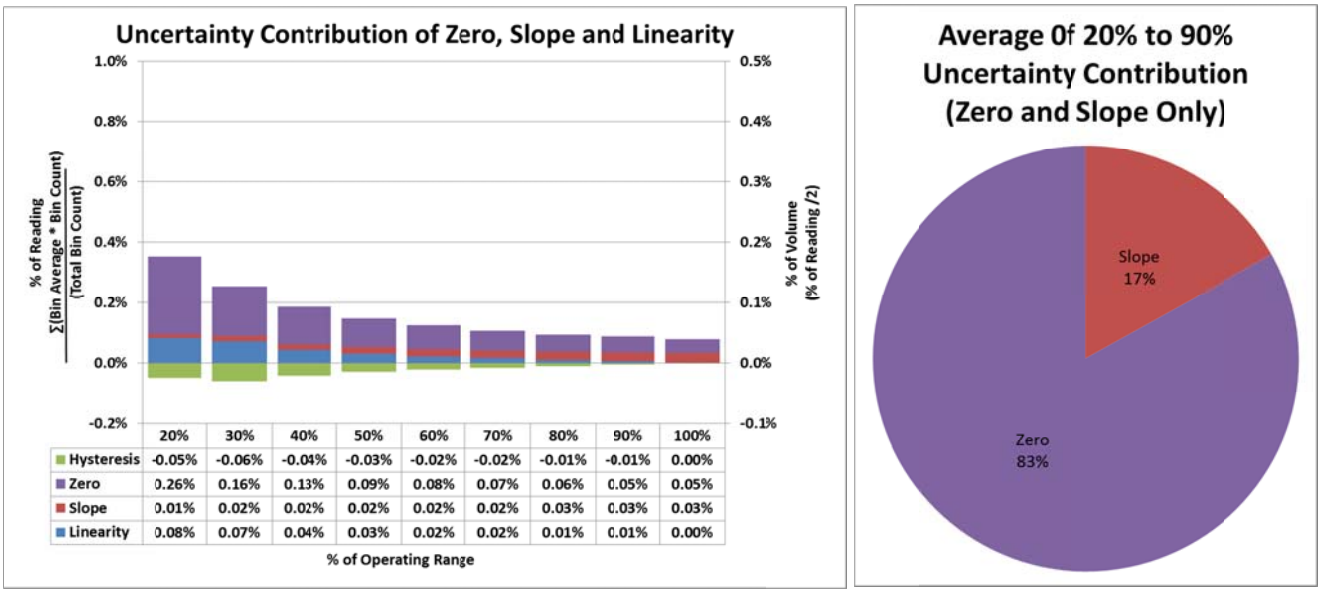


Figure 11 – Uncertainty Contribution of Zero, Slope and Linearity versus Operating Point

Hysteresis has been changed to a negative value to remove its contribution to the % of Reading total. There are two reasons for wanting to remove hysteresis. The first reason is in flow measurement there are usually small fluctuations in the flowing conditions that result in very small hysteresis loops that reduce the hysteresis uncertainty contribution to zero under operating conditions. The second reason for wanting to exclude hysteresis is the increase in the use of electronic verification and the use of volume adjust bottles to create the desired differential pressure. This technique usually results in small under/over adjustment around the desired pressure point which also disables the measurement of hysteresis. So why not just eliminate hysteresis from the graph? Because hysteresis can be used as a diagnostic tool as shown in the next Section - Other Observations.

So what does this information mean?

1. The uncertainty contribution graphs in Figure 11 show that Zero is the major uncertainty contributor.
2. The Zero Verification Distribution graph in Figure 10 shows:
   - If the transmitter is zeroed at its mean operating value, the 95% data limit random variation is approximately ±1.2% of reading/±0.6% of volume. In operation this random variability will introduce flow rate noise to the measurement but its accumulation effect over time will average out to approximately 0%.
   - Zeroing the transmitter at the time of verification can introduce bias. For example if the verification zero is at the lower 95% data limit when the transmitter is zeroed, the 95% data limit random variation will still be approximately ±1.2% of reading/±0.6% of volume but the bias will be -1.2% of reading/-0.6% of volume.
   - Simplistically adjusting the transmitter to zero out random verification error can introduce bias.

- System balance bias, caused by single meter bias when the transmitter is always adjusted to zero, will decrease as the number of meters increase because the single meter biases cancel each other out.

3. To manage metering point bias the transmitter needs to be zeroed to it median value and verification tolerance established.
   - If the transmitter is within the verification tolerance, no adjustment should be made.
   - If the transmitter exceeds the verification tolerance, the cause of the error needs to be determined and corrected.

Other Observations

Now that we understand that calibration drift of high accuracy intelligent transmitters is not be our biggest problem, we can start to change our maintenance practices and to look at the information contained in the data to obtain more insights into how to maintain them.

1. Should this transmitter be slope trimmed at 40% of its operating range to reduce the linearity bias by splitting the operating calibration bias error?
2. Does hysteresis expose transmitter depressuring problems such as transmitter over-range, gas condensation, and temperature changes or has something else changed?
3. Do the two verifications on 2000-07-11 for data set 454 show a temporary zero problem? (These verification were filtered out of the data shown in Appendix B.)
4. What is acceptable zero common cause (random) variation? A ±0.2% of operating span variation can have a ±0.8% of reading effect (±0.4% of volume) at 20 % of operating span.
5. Looks like after much recalibration work this transmitter was replaced or was it gas quality problems?
6. What's happening to the slope? Are there temperature compensation problems with this transmitter?

Appendix E contains analysis graphs which point to the answers to these questions and there are many more questions that can be answered once the verification data is looked at in the context of showing something other than calibration drift.

CONCLUSIONS AND RECOMMENDATIONS

The Analysis Summary at the start of this paper presented the following conclusions:

1. Advances in transmitter technology have resulted in designs with little or no calibration drift.
2. Verification differences have less to do with calibration drift and more to do with verification procedures, test equipment accuracy, routine variations that affect the transmitter output and defective or contaminated transmitters.
3. Calibrating transmitters while under the effect of short term influences introduces systematic bias into individual transmitter calibrations while only introducing noise into system balances. For example: Zeroing for a temporary 0.2% of span random influence can introduce a 1% of reading bias at 20% of operating range. This bias adjustment can introduce an $18,200/year error for a facility measuring $10,000/day of product.
4. Policies are required which establish acceptable verification tolerances and change maintenance procedures.
5. A number of influence factors can be determined from verification data once their results are viewed in context. Calibration cannot fix factors that are not calibration related.

Six additional conclusions and recommendations can be made for high performance transmitters:

1. The as-found in-service zero must be measured and reported to understanding the in-service transmitter accuracy. This data would also be helpful in isolating the cause of atmospheric pressure zero shifts. Unfortunately this data was not available for the data set, making the determination of the cause of transmitter zero shifts more difficult.
2. Random errors cause by ambient temperature appears to have a significant zero effect. Understanding and controlling this effect is critical for not introducing bias adjustments and for supporting the extended verification intervals currently in use.

3. Transmitters require zeroing to eliminate installation effects and to adjust for average operating temperature. A transmitter zero process is required to ensure that they are adjusted to their mean operating value and eliminate calibration bias.
4. Additional analysis of the random and systematic errors contained in the individual data sets is required understand and control their effect on measurement is required. For example: removal of the transmitter zero and slope variability show very good repeatability of the transmitter linearity and work is required on how to use this information to determine the best slope trim process.
5. Although this analysis was done for one type of transmitter, it demonstrates that this type of analysis is required for other manufactures of high performance intelligent transmitters to ensure their proper operation and maintenance.
6. With the elimination of the need to adjust for expected calibration drift an SPC (Statistical Process Control) monitoring and adjustment process is required to effectively identify transmitter problems and to make necessary transmitter adjustments.