DOCUMENTATION GUIDE

HART COMMUNICATION PROTOCOL

Calibrating HART Transmitters

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Table of Contents

1. INTRODUCTION

This paper assumes that you want to make use of the digital process values that are available from a HART transmitter. However, before examining calibration requirements, we must first establish a basic understanding in two areas: calibration concepts, and the operation of a HART instrument.

Keywords
Calibration, Digital Communications, Fieldbus, HART Protocol, Instrumentation, Smart Instruments, Transmitters, Quality

Abstract
In order to take advantage of the digital capabilities of HART transmitters, especially for reporting process data values, it is essential that they be calibrated correctly. This paper outlines the differences between calibrating a conventional and a HART transmitter, and gives recommendations for calibration practices.

1.1 Calibration Concepts

The ISA Instrument Calibration Series[6] defines calibration as "Determination of the experimental relationship between the quantity being measured and the output of the device which measures it; where the quantity measured is obtained through a recognized standard of measurement." There are two fundamental operations involved in calibrating any instrument:

- Testing the instrument to determine its performance,
- Adjusting the instrument to perform within specification.

Testing the instrument requires collecting sufficient data to calculate the instrument's operating errors. This is typically accomplished by performing a multiple point test procedure that includes the following steps.

1. Using a process variable simulator that matches the input type of the instrument, set a known input to the instrument.

2. Using an accurate calibrator, read the actual (or reference) value of this input.

3. Read the instrument's interpretation of the value by using an accurate calibrator to measure the instrument output.

By repeating this process for a series of different input values, you can collect sufficient data to determine the instrument's accuracy. Depending upon the intended calibration goals and the error calculations desired, the test procedure may require from 5 to 21 input points.

The first test that is conducted on an instrument before any adjustments are made is called the As-Found test. If the accuracy calculations from the As-Found data are not within the specifications for the instrument, then it must be adjusted.

Adjustment is the process of manipulating some part of the instrument so that its input to output relationship is within specification. For conventional instruments, this may be zero and span screws. For HART instruments, this normally requires the use of a communicator to convey specific information to the instrument. Often you will see the term calibrate used as a synonym for adjust.

After adjusting the instrument, a second multiple point test is required to characterize the instrument and verify that it is within specification over the defined operating range. This is called the As-Left test.

It is absolutely essential that the accuracy of the calibration equipment be matched to the instrument being calibrated. Years ago, a safe rule of thumb stated that the calibrator should be an order of magnitude (10 times) more accurate than the instrument being calibrated. As the accuracy of field instruments increased, the recommendation dropped to a ratio of 4 to 1. Many common calibrators in use today do not even meet this ratio when compared to the rated accuracy of HART instruments.

1.1.1 Error Calculations

Error calculations are the principal analysis performed on the As-Found and As-Left test data. There are several different types of error calculations, most of which are defined in the publication "Process Instrumentation Terminology".[5] All of the ones discussed here are usually expressed in terms of the percent of ideal span which is defined as:

% span =(reading - low range) / (high range - low range) * 100.0

The first step in the data analysis is to convert the engineering unit values for input and output into percent of span. Then for each point, calculate the error, which is the deviation of the actual output from the expected output. Table 1 gives a set of example data and error calculations, while Figure 1 graphically illustrates the resulting errors.

Table 1 - Calibration Data

Input	As Found Output	As Found Error	As Left Output	As Left Error
0.00	0.78	0.78	0.28	0.28
25.00	25.72	0.72	25.13	0.13
50.00	50.59	0.59	50.00	0.00
75.00	75.63	0.63	74.91	-0.09
100.00	100.50	0.50	99.78	-0.22
75.00	75.59	0.59	74.88	-0.13
50.00	50.59	0.59	49.97	-0.03
25.00	25.69	0.69	25.13	0.13
0.00	0.75	0.75	0.28	0.28

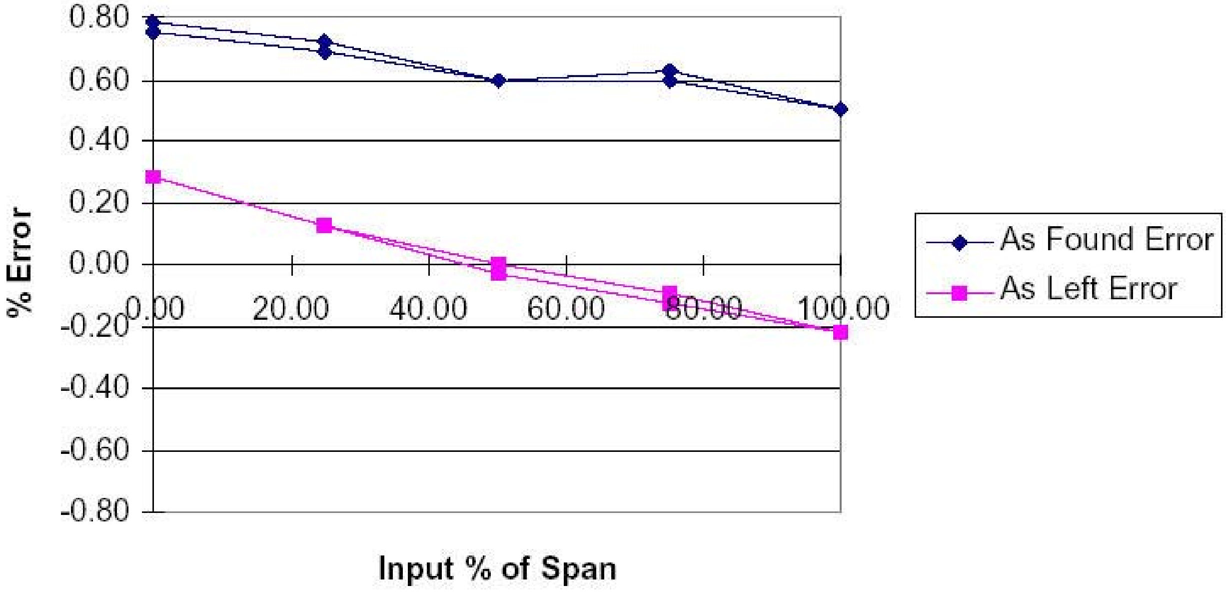

Figure 1 - Graph of Percent Error

It is important to note that the number of data points collected and the order in which they are collected both affect the types of error calculations that can be performed.

The *Maximum* error is the most common value used to evaluate an instrument's performance. If a computer program is not used to analyze the test data, it is often the only error considered and is taken to be the largest deviation from the ideal output. A more accurate value can be obtained by fitting an equation to the error data and calculating the maximum and minimum points on the curve. In practice, this should only be done if there are at least five data points reasonably spaced over the instrument range. Otherwise, it is unlikely that the curve fit will give reasonable values between the data points.

By itself, the maximum error does not give a complete indication of an instrument's performance. With the availability of computer software to facilitate calculations, other error values are gaining popularity including zero error, span error, linearity error, and hysteresis error.

Zero error is defined as the error of a device when the input is at the lower range value. *Span* error is defined as the difference between the actual span and the ideal span, expressed as a percentage of the ideal span.

Linearity error is a measure of how close the error of the instrument over its operating range approaches a straight line. Unfortunately, there are three different methods used to calculate this, resulting in an independent linearity, a terminal based linearity, and a zero based linearity. In practice, it is best to choose one method and apply it consistently. Note that the calculation of linearity error is also greatly facilitated by a curve fit of the error data.

Hysteresis error is a measure of the dependence of the output at a given input value upon the prior history of the input. This is the most difficult error to measure since it requires great care in the collection of data, and it typically requires at least 9 data points to develop reasonable curves for the calculations. Thus a technician must collect at least five data point traversing in one direction, followed by at least four more in the opposite direction, so that each leg has five points, including the inflection point.

If any of these errors is greater than or equal to the desired accuracy for a test, then the instrument has failed and must be adjusted.

1.1.2 Performance over time

In order to adequately assess the long term performance of an instrument, it must be calibrated on a regular schedule. You may also want to determine how often an instrument really needs to be calibrated by examining its change in performance over time. To do this, you must collect both As-Found and As-Left data. By comparing the As-Left data from one calibration to the As-Found of the next calibration, you can determine the instrument's drift. By varying the interval between calibrations, you can determine the optimum calibration interval which allows the instrument to remain within the desired accuracy.

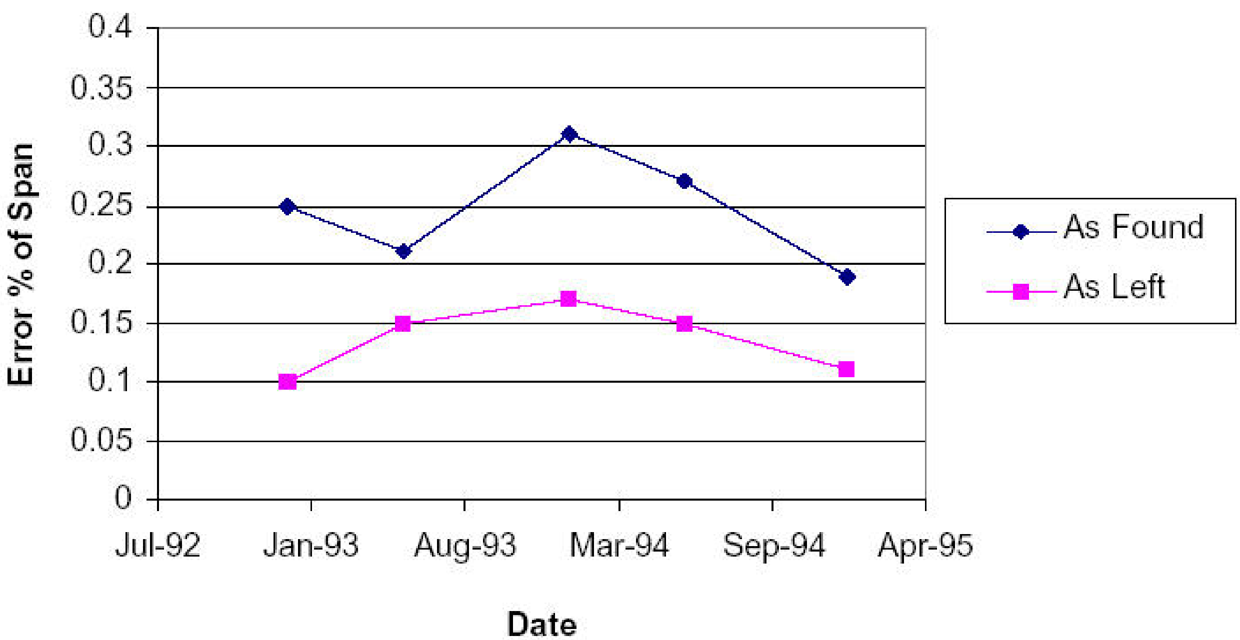

Figure 2 - Performance Over Time

1.2 HART Fundamentals

HART is an acronym for Highway Addressable Remote Transducer. Originally developed by Rosemount in 1986, the HART protocol is now a mature, industry-proven technology. Because Rosemount chose to make HART an open protocol, many manufacturers incorporated it into their products. It has now become a de facto standard for field communication with instruments. In 1993, to insure its continued growth and acceptance, Rosemount transferred ownership of the protocol to the HART Communication Foundation (HCF).

HART products generally fall into one of three categories: field devices, host systems, and communication support hardware. Field devices include transmitters, valves, and controllers. There are HART transmitters for almost any standard process measurement including pressure, temperature, level, flow, and analytical (pH, ORP, density). Host systems range from small handheld communicators to PC based maintenance management software to large scale distributed control systems. Communication support hardware includes simple single loop modems as well as an assortment of multiplexers that allow a host system to communicate with a large number of field devices. In this document, the general term "communicator" will be used to refer to any HART host that can communicate with a field device.

HART is a transition technology that provides for the continued use of the industry standard 4 - 20 mA current loop while also introducing many of the capabilities and benefits associated with a digital field bus system. The complete technical specification is available from the HART Communication Foundation [1]

HART follows the basic Open Systems Interconnection (OSI) reference model. The OSI model describes the structure and elements of a communication system. The HART protocol uses a reduced OSI model, implementing only layers 1, 2 and 7. Since the details for layers 1 (Physical) and 2 (Link) do not directly impact calibration, they are not discussed here.

Layer 7, the Application layer, consists of three classes of HART commands: Universal, Common Practice, and Device Specific. Universal commands are implemented by all HART hosts and field devices. They are primarily used by a host to identify a field device and read process data.

The Common Practice command set defines functions that are generally applicable to many field devices. This includes items such as changing the range, selecting engineering units, and performing self tests. Although each field device implements only those Common Practice commands which are pertinent to its operation, this still provides for a reasonable level of commonality between field devices.

Device Specific commands are different for each field device. It is through these commands that unique calibration and configuration functions are implemented. For example, when configuring an instrument for operation, only temperature transmitters need to be able to change the type of probe attached, while flow meters often need to have information about pipe sizes, calibration factors, and fluid properties. Also, the calibration procedure for a pressure transmitter is obviously different than that for a valve.

It is important to note that in most cases, proper calibration of a HART instrument *requires* the use of a communicator that is capable of issuing device specific commands.

2. CALIBRATING A CONVENTIONAL INSTRUMENT

For a conventional 4-20 mA instrument, a multiple point test that stimulates the input and measures the output is sufficient to characterize the overall accuracy of the transmitter. The normal calibration adjustment involves setting only the zero value and the span value, since there is effectively only one adjustable operation between the input and output as illustrated below.

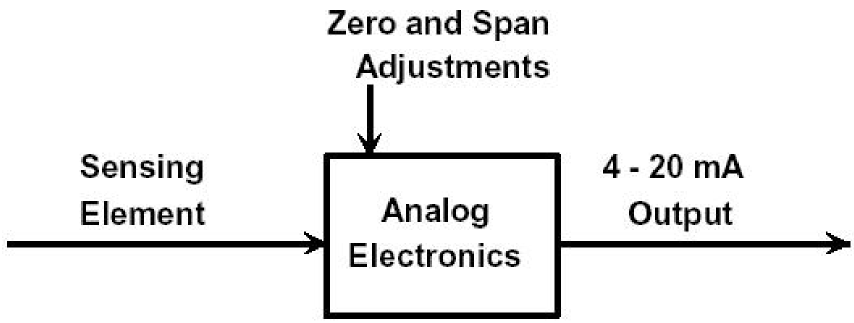

Figure 3 - Conventional Transmitter Block Diagram

This procedure is often referred to as a Zero and Span Calibration. If the relationship between the input and output range of the instrument is not linear, then you must know the transfer function before you can calculate expected outputs for each input value. Without knowing the expected output values, you cannot calculate the performance errors.

3. CALIBRATING A HART INSTRUMENT

3.1 The Parts of a HART Transmitter

For a HART instrument, a multiple point test between input and output does not provide an accurate representation of the transmitter's operation. Just like a conventional transmitter, the measurement process begins with a technology that converts a physical quantity into an electrical signal. However, the similarity ends there. Instead of a purely mechanical or electrical path between the input and the resulting 4-20 mA output signal, a HART transmitter has a microprocessor that manipulates the input data. As shown in Figure 4, there are typically three calculation sections involved, and each of these sections may be individually tested and adjusted.

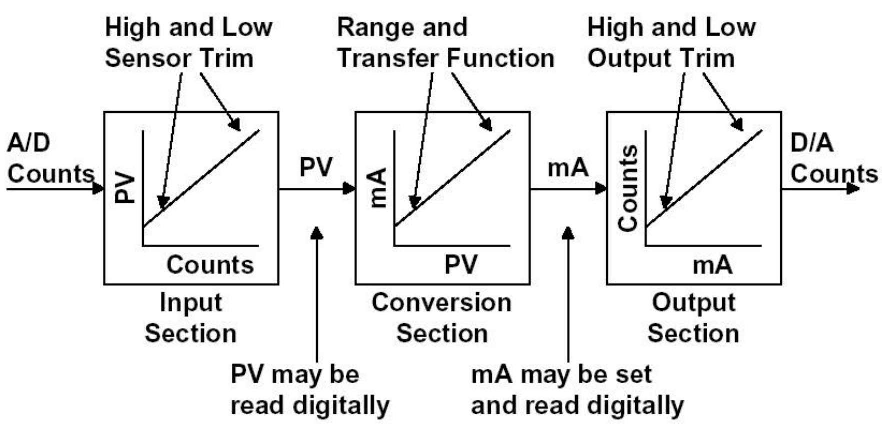

Figure 4 - HART Transmitter Block Diagram

Just prior to the first box, the instrument's microprocessor measures some electrical property that is affected by the process variable of interest. The measured value may be millivolts, capacitance, reluctance, inductance, frequency, or some other property. However, before it can be used by the microprocessor, it must be transformed to a digital count by an analog to digital (A/D) converter.

In the first box, the microprocessor must rely upon some form of equation or table to relate the raw count value of the electrical measurement to the actual property (PV) of interest such as temperature, pressure, or flow. The principle form of this table is usually established by the manufacturer, but most HART instruments include commands to perform field adjustments. This is often referred to as a sensor trim. The output of the first box is a digital representation of the process variable. When you read the process variable using a communicator, this is the value that you see.

The second box is strictly a mathematical conversion from the process variable to the equivalent milliamp representation. The range values of the instrument (related to the zero and span values) are used in conjunction with the transfer function to calculate this value. Although a linear transfer function is the most common, pressure transmitters often have a square root option. Other special instruments may implement common mathematical transformations or user defined break point tables. The output of the second block is a digital representation of the desired instrument output. When you read the loop current using a communicator, this is the value that you see. Many HART instruments support a command which puts the instrument into a fixed output test mode. This overrides the normal output of the second block and substitutes a specified output value.

The third box is the output section where the calculated output value is converted to a count value that can be loaded into a digital to analog converter. This produces the actual analog electrical signal. Once again the microprocessor must rely on some internal calibration factors to get the output correct. Adjusting these factors is often referred to as a current loop trim or 4-20mA trim.

3.2 HART Calibration Requirements

Based on this analysis, you can see why a proper calibration procedure for a HART instrument is significantly different than for a conventional instrument. The specific calibration requirements depend upon the application.

If the application uses the digital representation of the process variable for monitoring or control, then the sensor input section must be explicitly tested and adjusted. Note that this reading is completely independent of the milliamp output, and has nothing to do with the zero or span settings. The PV as read via HART communication continues to be accurate even when it is outside the assigned output range. For example, a range 2 Rosemount 3051c has sensor limits of -250 to +250 inches of water. If you set the range to 0 - 100 inches of water, and then apply a pressure of 150 inches of water, the analog output will saturate at just above 20 milliamps. However, a communicator can still read the correct pressure.

If the current loop output is not used (that is the transmitter is used as a digital only device), then the input section calibration is all that is required. If the application uses the milliamp output, then the output section must be explicitly tested and calibrated. Note that this calibration is independent of the input section, and again, has nothing to do with the zero and span settings.

3.2.1 Calibrating the Input Section

The same basic multiple point test and adjust technique is employed, but with a new definition for output. To run a test, use a calibrator to measure the applied input, but read the associated output (PV) with a communicator. Error calculations are simpler since there is always a linear relationship between the input and output, and both are recorded in the same engineering units. In general, the desired accuracy for this test will be the manufacturer's accuracy specification.

If the test does not pass, then follow the manufacturer's recommended procedure for trimming the input section. This may be called a sensor trim and typically involves one or two trim points. Pressure transmitters also often have a zero trim, where the input calculation is adjusted to read exactly zero (not low range). Do not confuse a trim with any form of re-ranging or any procedure that involves using zero and span buttons.

3.2.2 Calibrating the Output Section

Again, the same basic multiple point test and adjust technique is employed, but with a new definition for input. To run a test, use a communicator to put the transmitter into a fixed current output mode. The input value for the test is the mA value that you instruct the transmitter to produce. The output value is obtained using a calibrator to measure the resulting current. This test also implies a linear relationship between the input and output, and both are recorded in the same engineering units (milliamps). The desired accuracy for this test should also reflect the manufacturer's accuracy specification.

If the test does not pass, then follow the manufacturer's recommended procedure for trimming the output section. This may be called a 4-20 mA trim, a current loop trim, or a D/A trim. The trim procedure should require two trim points close to or just outside of 4 and 20 mA. Do not confuse this with any form of re-ranging or any procedure that involves using zero and span buttons.

3.2.3 Testing Overall Performance

After calibrating both the Input and Output sections, a HART transmitter should operate correctly. The middle block in Figure 4 only involves computations. That is why you can change the range, units, and transfer function without necessarily affecting the calibration. Notice also that even if the instrument has an unusual transfer function, it only operates in the conversion of the input value to a milliamp output value, and therefore is not involved in the testing or calibration of either the input or output sections.

If there is a desire to validate the overall performance of a HART transmitter, run a Zero and Span test just like a conventional instrument. As you will see in a moment, however, passing this test does not necessarily indicate that the transmitter is operating correctly.

3.2.4 Effect of Damping on Test Performance

Many HART instruments support a parameter called damping. If this is not set to zero, it can have an adverse effect on tests and adjustments. Damping induces a delay between a change in the instrument input and the detection of that change in the digital value for the instrument input reading and the corresponding instrument output value. This damping induced delay may exceed the settling time used in the test or calibration. The settling time is the amount of time the test or calibration waits between setting the input and reading the resulting output. It is advisable to adjust the instrument's damping value to zero prior to performing tests or adjustments. After calibration, be sure to return the damping constant to its required value.

4. OPERATIONS THAT ARE NOT PROPER CALIBRATIONS

4.1 Digital Range Change

There is a common misconception that changing the range of a HART instrument by using a communicator somehow calibrates the instrument. Remember that a true calibration requires a reference standard, usually in the form of one or more pieces of calibration equipment to provide an input and measure the resulting output. Therefore, since a range change does not reference any external calibration standards, it is really a configuration change, not a calibration. Notice that in the HART transmitter block diagram (Figure 4), changing the range only affects the second block. It has no effect on the digital process variable as read by a communicator.

4.2 Zero and Span Adjustment

Using only the zero and span adjustments to calibrate a HART transmitter (the standard practice associated with conventional transmitters) often corrupts the internal digital readings. You may not have noticed this if you never use a communicator to read the range or digital process data.
As shown in Figure 4, there is more than one output to consider. The digital PV and milliamp values read by a communicator are also outputs, just like the analog current loop.

Consider what happens when using the external zero and span buttons to adjust a HART instrument. Suppose that an instrument technician installs and tests a differential pressure transmitter that was set at the factory for a range of 0 to 100 inches of water. Testing the transmitter reveals that it now has a 1 inch of water zero shift. Thus with both ports vented (zero), its output is 4.16 mA instead of 4.00 mA, and when applying 100 inches of water, the output is 20.16 mA instead of 20.00 mA. To fix this he vents both ports and presses the zero button on the transmitter. The output goes to 4.00 mA, so it appears that the adjustment was successful.

However, if he now checks the transmitter with a communicator, he will find that the range is 1 to 101 inches of water, and the PV is 1 inch of water instead of 0. The zero and span buttons changed the range (the second block). This is the only action that the instrument can take under these conditions since it does not know the actual value of the reference input. Only by using a digital command which conveys the reference value can the instrument make the appropriate internal adjustments.

The proper way to correct a zero shift condition is to use a zero trim. This adjusts the instrument input block so that the digital PV agrees with the calibration standard. If you intend to use the digital process values for trending, statistical calculations, or maintenance tracking, then you should disable the external zero and span buttons and avoid using them entirely.

4.3 Loop Current Adjustment

Another observed practice among instrument technicians is to use a hand-held communicator to adjust the current loop so that an accurate input to the instrument agrees with some display device on the loop. If you are using a Rosemount model 268 communicator, this is a "current loop trim using other scale." Refer again to the zero drift example just before pressing the zero button.
Suppose there is also a digital indicator in the loop that displays 0.0 at 4 mA, and 100.0 at 20 mA.
During testing, it read 1.0 with both ports vented, and it read 101.0 with 100 inches of water applied. Using the communicator, the technician performs a current loop trim so that the display reads correctly at 0 and 100, essentially correcting the output to be 4 and 20 mA respectively.

While this also appears to be successful, there is a fundamental problem with this procedure. To begin with, the communicator will show that the PV still reads 1 and 101 inches of water at the test points, and the digital reading of the mA output still reads 4.16 and 20.16 mA, even though the actual output is 4 and 20 mA. The calibration problem in the input section has been hidden by introducing a compensating error in the output section, so that neither of the digital readings agrees with the calibration standards.

5. CONCLUSION

While there are many benefits to be gained by using HART transmitters, it is essential that they be calibrated using a procedure that is appropriate to their function. If the transmitter is part of an application that retrieves digital process values for monitoring or control, then the standard calibration procedures for conventional instruments are inadequate. At a minimum, the sensor input section of each instrument must be calibrated. If the application also uses the current loop output, then the output section must also be calibrated.

ANNEX A. REFERENCES

[1] HART Communication Foundation. " HART Field Communication Protocol Specification".

[2] Bell System Technical Reference: PUB 41212, "Data Sets 202S and 202T interface Specification", July 1976.

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[4] Holladay, Kenneth L., "Using the HARTâ Protocol to Manage for Quality", ISA 1994 paper number 94-617.

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ANNEX B. REVISION HISTORY

B1. Changes from 1.0 to 1.1

Document reformatted to a standard “Document Guide” template.

B2. Revision 1.0

Initial Revision