# 1

# Calibration Principles and Terminology

## 1.1 What Is Calibration?

Is an instrument reading in the control system "right?" How can we find out whether or not it is right? What is the right reading? Is the reading close enough to the right answer? How close is close enough? What do we do if the reading isn't right?

The purpose of a calibration program is to answer these questions and resolve issues methodically. This book introduces the concepts of calibration and a calibration program from the perspective of a control system technician (CST) and discusses how these concepts can be applied to a few of the most common process measurement instruments as examples. It does not provide examples for all instruments used in control systems, but the concepts can be applied to any instrument.

We decide whether a reading is "right" by comparing it to a measurement we know is very close to right. This process is called *calibration*.

> ***calibration:*** procedure *of checking or adjusting* (*by comparison with a reference standard*) *the accuracy of a measuring instrument*
>
> (*International Society of Automation [ISA],* [1], Clause 3.1.3).

Calibration compares a measuring instrument that has an unknown amount of uncertainty against a standard of higher accuracy that has a known amount of uncertainty. The measurement standard gives an answer within a range of accuracy that, for practical purposes, is the "right" answer.

Calibration is used to detect, correlate, adjust, rectify, and document the accuracy of the instrument being calibrated. In general, the steps are:

1) Find the appropriate measurement standard for comparison.
2) Apply an input to the instrument being checked.
3) Compare the instrument reading to the standard reading.
4) If the instrument reading is within the specified tolerance, record the result.
5) If the instrument reading is not within the specified tolerance, follow the steps detailed in the calibration procedure (e.g., repair, replace, adjust, and record).

Note that calibration is not the same as configuration. A smart instrument can be configured for a specific range of measurement, but that process does not compare the instrument reading to a reference standard.

## 1.2 Calibration-Related Terminology

### 1.2.1 Calibration Range

The *calibration range* is defined by the upper and lower range values, as shown in Figure 1.1.

- *Upper range limit (URL)* is the upper end of the instrument's capability.
- *Lower range limit (LRL)* is the lower end of the instrument's capability.
- *Instrument range* or *full range* is the difference between the upper and lower range limits.
- *Upper range value (URV)* is the upper end of the configured measurement range.
- *Lower range value (LRV)* is the lower end of the configured measurement range and the minimum output of the transmitter. It is also commonly called the *zero value*.
- *Span* or *calibration range* is the difference between the upper and lower range values.

The calibration range may differ from the instrument range, which refers to the instrument's capability. For example, an electronic pressure transmitter may have a nameplate instrument range of 0 to 750 pounds per square inch gauge (psig) and an output of 4 mA to 20 mA. However, the design calls for the instrument to be calibrated for 0 to 300 psig = 4 mA to 20 mA. Therefore, the calibration range (span) would be specified as 0 to 300 psig = 4 mA to 20 mA. In this example:

LRV (zero) = 0 psig input, 4 mA output
URV = 300 psig input, 20 mA output
Input span = 300 − 0 = 300 psig
Output span = 20 mA − 4 mA = 16 mA

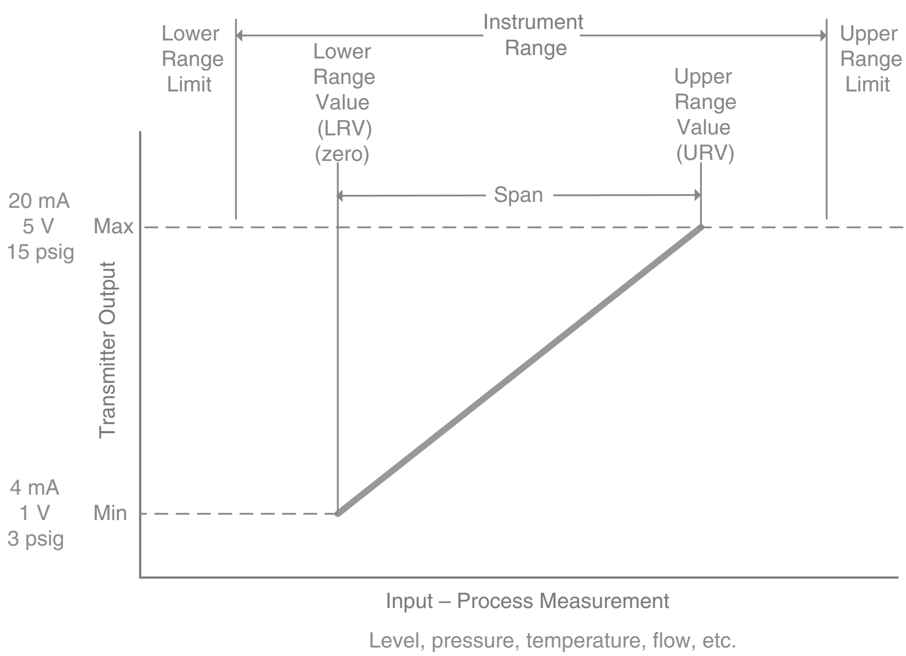


**Figure 1.1** Calibration range terminology. Max, maximum; Min, minimum.

With regard to instrument accuracy, when accuracy is stated as a "percentage of full scale," it is important to know if the manufacturer is referring to the instrument range or the calibrated range.

### 1.2.2 Error and Accuracy

- **Error** – The difference between an indicated value and the actual value. For example, if the instrument reads 90, but the actual value is 100, then the error is 10.
  - **Zero error** – This error is approximately equal over the entire scale.
  - **Span error** – This occurs when the error at full scale differs from the error at zero, often proportional to the input.
  - **Linearity error** – The response is not linear.
  - **Hysteresis error** – The error is different when the input is increasing than when the input is decreasing.
- **Accuracy** – The degree to which an indicated value matches the actual value of the measured variable. The accuracy rating of a device is the limit that errors will not exceed when it is used under specified conditions (i.e., how close to "right" the device can accomplish). Instrument manufacturers typically provide this rating as a percentage of the actual reading or a percentage of full scale (Figure 1.2).

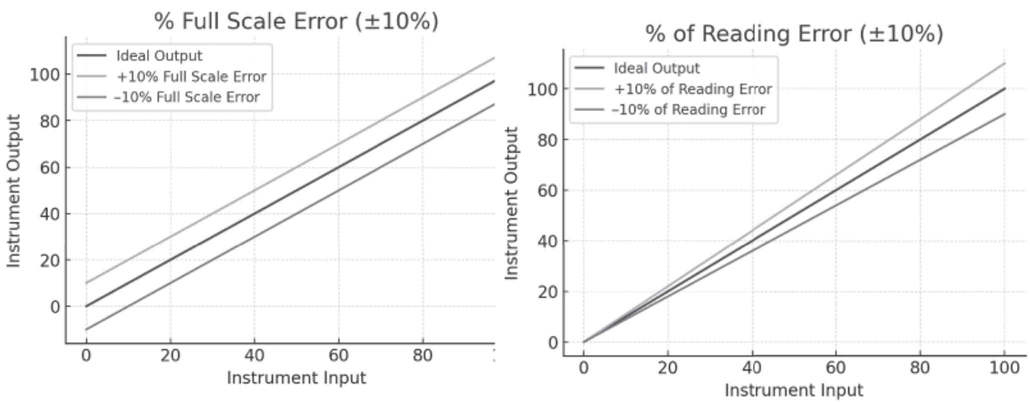


**Figure 1.2** Percentage of full scale versus percentage of reading error.

- **Percentage of full scale** – The difference between the indicated value and the actual value, expressed as a percentage of the device's full range of values (LRL to URL). The error would be the same for readings at the bottom of the scale and the top of the scale.
  Example:
  – Device range: 0 to 200
  – Accuracy: ±1% of *full scale*

| Reading | Error Range | Actual Value Between | |
|---|---|---|---|
| 50 | 1% of 200 = ±2 | 48 | 52 |
| 150 | 1% of 200 = ±2 | 148 | 152 |

- **Percentage of reading** – The difference between the indicated value and the actual value, expressed as a percentage of the actual value. The error would be smaller for readings on the low end of the scale than for readings on the high end.
  Example:
  – Device range: 0 to 200
  – Accuracy ±1% of *reading*

| Reading | Error Range | Actual Value Between | |
|---|---|---|---|
| 50 | 1% of 50 = ±0.5 | 49.5 | 50.5 |
| 150 | 1% of 150 = ±1.5 | 148.5 | 151.5 |

### 1.2.3 Precision and Repeatability

*Precision* represents the repeatability of measurement data. If a measurement is made repeatedly under the same conditions by the same person with the same equipment, the measurement will not always give the same result. Precision (or repeatability) represents how close the repeated measurements are to each other.

It is important to understand the difference between the terms *accuracy* and *precision* because they are often mistakenly used to mean the same thing. Imagine repeatedly trying to hit a target as shown in Figure 1.3.

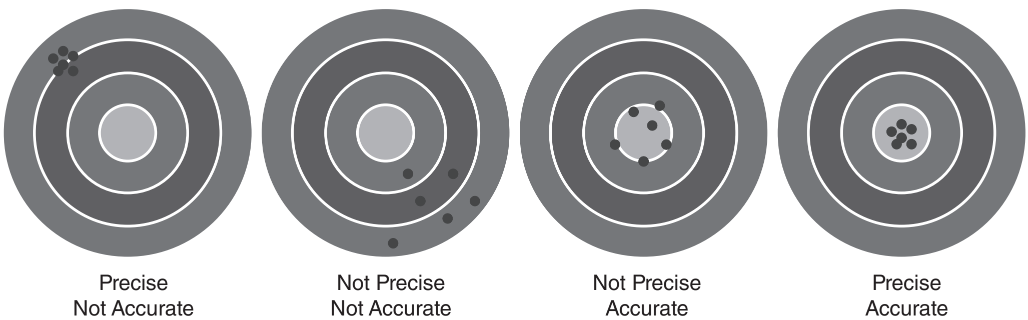


**Figure 1.3** Precision versus accuracy.

With respect to calibration, think of the calibration instrument as the target and the dots representing measurements from the device to be calibrated. If the goal is to get the measuring device to give readings inside the inner circle, that circle represents the tolerance.

### 1.2.4 Tolerance

*Tolerance* is the permissible limit of variation in a measurement with respect to the actual value. Tolerance is "how close is close enough."

Every calibration should be performed to a specified tolerance. The tolerance will be defined by an organization's calibration program and given in the calibration document. It might be given for each device or a device loop. The tolerance will typically be specified in the measurement units of the reading (e.g., psig, °F, V). By specifying an actual value, mistakes caused by calculating the percentages of span or reading are eliminated. Tolerances should be specified in the units of measurement for the calibration.

### 1.2.5 Stability

*Stability* is the maximum change over a time period. The stability of a device is usually given in terms of the maximum expected change in error over a time period, for example, ±0.25% of reading for 5 years. This is how long manufacturers promise that a device will meet the accuracy specifications.

Some manufacturer data sheets also list "zero stability." *Zero stability* is the ability of an instrument to maintain its calibrated zero reading over a specified period of time. For example, it might be given as ±0.1% of URL per year.

### 1.2.6 Test Uncertainty Ratio

*Test uncertainty ratio (TUR)* is the relationship between the accuracy of the test standard and the accuracy of the instrument under test. ISA-RP105.00.01-2017 recommends that standards used for calibration should be at least 4 times more accurate than the required tolerance of the equipment being calibrated (International Society of Automation [ISA], [1]). Therefore, the test equipment (such as a field standard) used to calibrate a process instrument should be 4 times more accurate than the accuracy required of the instrument; the laboratory standard used to calibrate the field standard should be 4 times more accurate than the field standard, and so on. This is a TUR of 4:1.

If multiple calibration equipment components are used to calibrate a loop/component, the aggregate uncertainty of the calibration equipment components should be calculated using the root sum squared (RSS) method, and that aggregate uncertainty should be 4 times greater than the loop/device tolerance ([1], Clause 5.7).

For example, if a loop has been assigned a tolerance of ±1 psig, the calibration standard(s) must have an overall uncertainty of ±0.25 psig.

### 1.2.7 Uncertainty

A calibration technician will sometimes come across these terms in product literature:

- Uncertainty
- Repeatability
- Probability
- Confidence interval

*Uncertainty* is a lack of knowledge of the true value of a variable. For calibration equipment, uncertainty is given by the *probability* that a measurement will fall within a certain range. The range is called the *confidence interval*. A 95% confidence interval means that a reading will fall within the given range 95% of the time.

The terms *repeatability*, *precision*, and *confidence interval* are often seen in analytical equipment specifications.

### 1.2.8 Combined Effects on Uncertainty: Worst-Case Versus Probable

Calibration technicians (especially Level III certified control system technicians [CCSTs]) should be aware of basic uncertainty factors, such as environmental effects, and how to combine multiple calibration equipment accuracies to arrive at a single calibration equipment accuracy. Combining multiple calibration equipment or process instrument accuracies is done by calculating the square root of the sum of the squares.

A device's overall uncertainty is usually a combination of the stated accuracy in addition to influences of factors such as:

- Ambient conditions (temperature, humidity, etc.)
- Process conditions (process pressure, temperature)
- Supply voltage
- Stability (maximum change over a time period)

These errors would be combined for a device to find the total probable error (TPE) for that device (Equation 1.1). To perform this calculation correctly, all errors should be expressed relative to the actual loop/component application measurement span and in the same manner (e.g., percentage of full scale, percentage of reading, or units of measure) ([1], Clause 5.5).

$$\text{TPE} = \sqrt{\text{accuracy}^2 + \text{error1}^2 + \ldots \text{error2}^2} \tag{1.1}$$

The TPE represents the highest error that is likely to be seen for practical purposes. This assumes that not everything is at its worst error at the same time.

The *worst-case error* (WCE) is the sum of all the error components (Equation 1.2):

$$\text{WCE} = \text{accuracy} + \text{error1} + \ldots \text{error2} \tag{1.2}$$

WCE is the worst error that could occur if everything that could go wrong did go wrong all at once for the device.

The same RSS calculation that is given here for a device is also used to calculate the TPE for the combination of all devices in a loop or for combining the uncertainties of multiple calibration equipment.

### 1.2.9 Zero and Span Errors

*Zero error* means that the instrument does not read or output the correct value when the input is at the minimum value. This shifts the entire calibration line up or down by a constant amount (Figure 1.4).

Table 1.1 is an example of a pressure transmitter scaled 0–100 psig = 4–20 mA with a zero error of 1.25 psig.

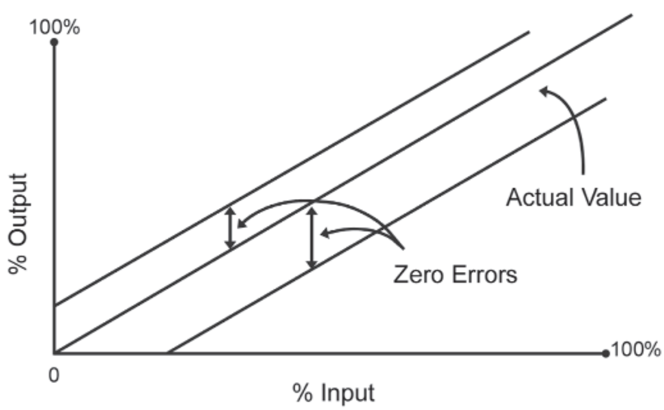


**Figure 1.4** Zero error.

**Table 1.1** Zero error example.

| Input | Expected Output | Actual Output |
|---|---|---|
| 0 psig | 4 mA (0 psig) | 4.2 mA (1.25 psig) |
| 50 psig | 12 mA (50 psig) | 12.2 mA (51.25 psig) |

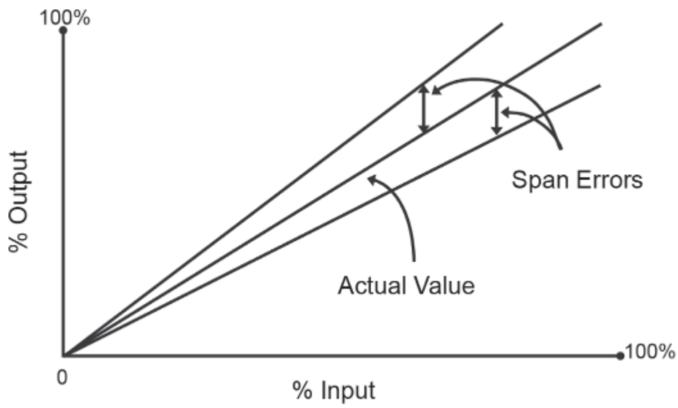


**Figure 1.5** Span error.

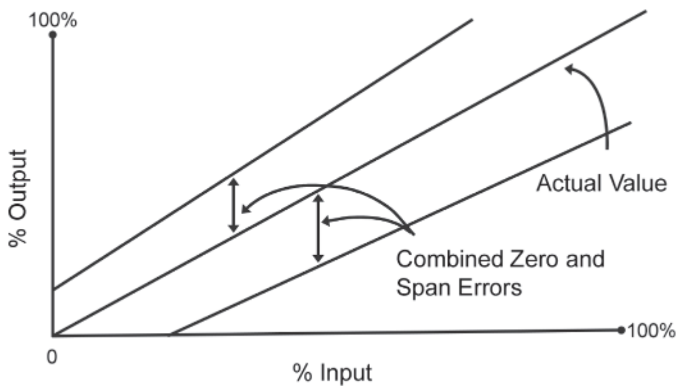


**Figure 1.6** Combined zero and span errors.

*Span error* exists when the error at full scale differs from the error at zero pressure. This error is often proportional to the input, so it affects the slope of the calibration line (Figure 1.5).

If a device has both zero and span errors, they combine to shift the calibration line up or down and also change the slope of the line (Figure 1.6). Zero and span errors can often be corrected by adjusting the transmitter configuration.

### 1.2.10 Linearity and Hysteresis Errors

Typically, an instrument's calibration is checked at several points throughout its calibration range because sometimes the error is not *linear*; that is, the error varies along the range of an instrument, as illustrated in Figure 1.7.

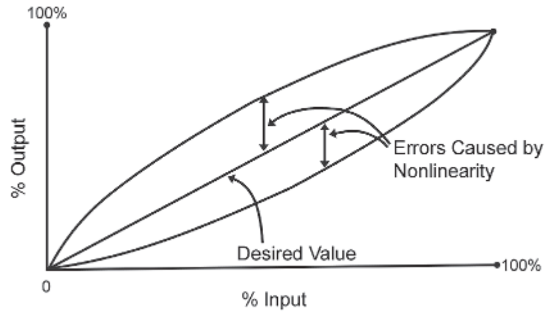


**Figure 1.7** Nonlinear error example.

*Hysteresis* is the measure of the difference in the response of a device as the input signal increases from a minimum to a maximum value and subsequently decreases from maximum to minimum value over the same range, as shown in Figure 1.8. For continuous measurement, the instrument's output is different when the input is going up than when the input is going down. The switch with hysteresis will transition at a different value when the input is going up than when the input is coming down.

Hysteresis can be troublesome on process indicators, sensors, and transmitters. However, a hysteresis feature is built into some process switches to prevent the switch from toggling on and off when the process variable is at the set point. Think of a thermostat in a house that is set at 72 °F. It might come on at 73 °F and turn off at 71 °F.

Hysteresis is expressed in percentage of full scale (%FS).

Instruments with mechanical movements, such as pressure gauges, valve positioners, and current-to-pneumatic (I/P) transducers, develop hysteresis. This is often caused by friction and worn mechanical components. There is no way to adjust for hysteresis during calibration.

Hysteresis can be evaluated by obtaining calibration data with the input applied in both the increasing and decreasing directions, as illustrated in Table 1.2 for a device with a full scale of 100 psig.

When evaluating hysteresis, it is important to approach the target value without overshooting the applied input. If the input value exceeds the increasing target value, decrease the applied input to the previous test point and retry. If the input value passes the decreasing target value, increase the applied input above the previous test point and repeat the test.

**Table 1.2** Example of hysteresis error.

| Applied Input (psig) | As-Found Values (↑) (psig) | As-Found Error (↑) (psig) | As-Found Values (↓) (psig) | As-Found Error (↓) (psig) | Hysteresis (%FS) |
|---|---|---|---|---|---|
| 10 | 9 | –1 | 10 | 0 | 1% |
| 25 | 24 | –1 | 25 | 0 | 1% |
| 50 | 49 | –1 | 51 | 1 | 2% |
| 75 | 74 | –1 | 76 | 1 | 2% |
| 90 | 90 | 0 | 91 | 1 | 1% |

%FS, percentage of full scale.

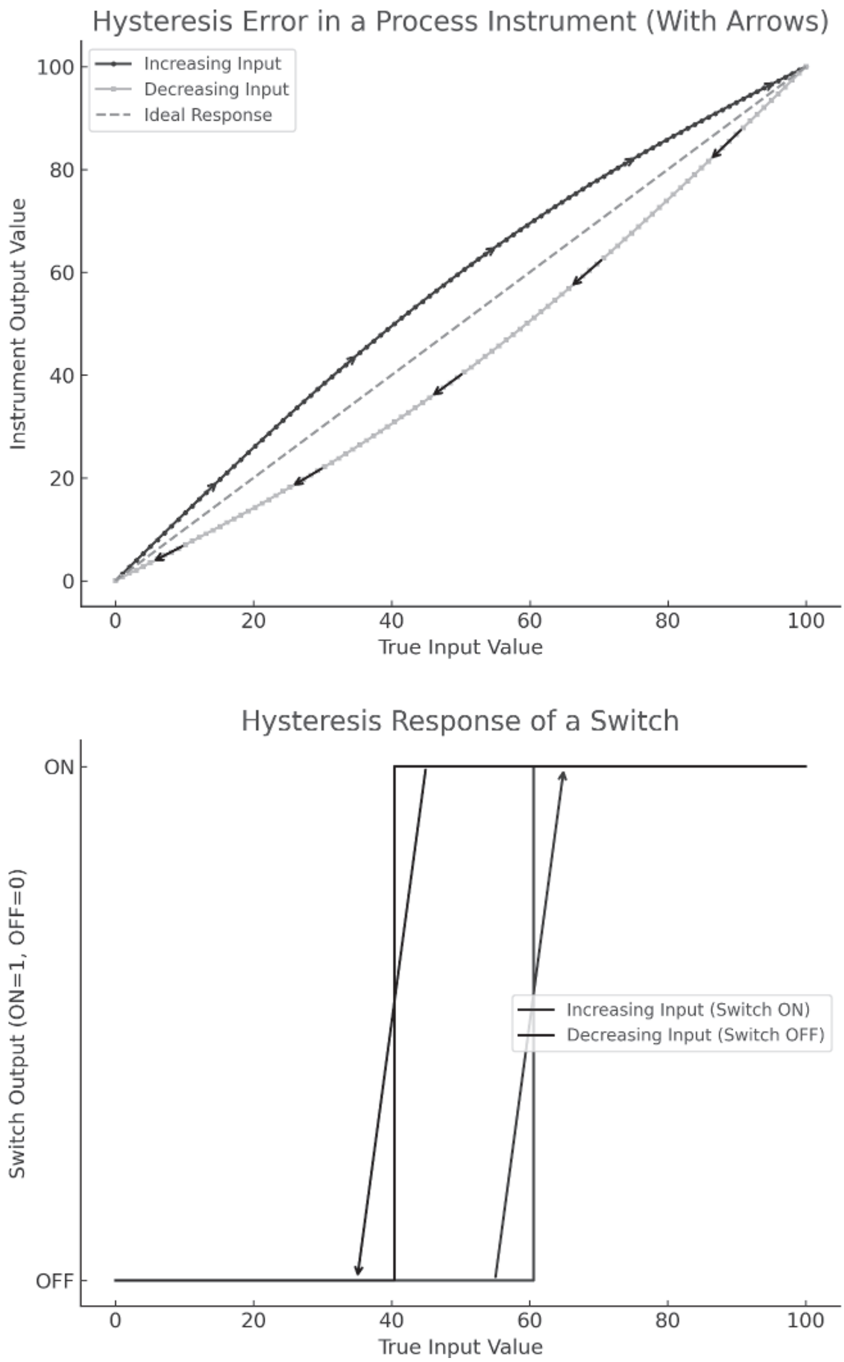


**Figure 1.8** Transmitter and switch hysteresis examples.

## 1.3 Calibration Methods

### 1.3.1 Loop Calibration Versus Device Calibration

*Loop calibration* is performed from the sensor to all loop indications with all the loop components connected, as shown in Figure 1.9. This is the recommended best practice from ISA-RP105.00.01-2017 [1]. This concept is important because it checks the performance of all components working together to measure a process parameter (e.g., sensor, transmitter, and input card). Alarms, controls, and protective functions within the control or safety system might also be verified during a loop calibration.

A source (e.g., pressure or temperature) is applied to the sensor and adjusted to various points through the calibration range. The loop indication (e.g., the operator interface reading) is recorded. The sensor and transmitter outputs might also be recorded. The goal is to determine whether the loop provides a measurement within the stated tolerance.

If the loop is not within tolerance, troubleshooting may be required. The company's procedures for troubleshooting and adjustments should be followed, which might include calibrating individual devices.

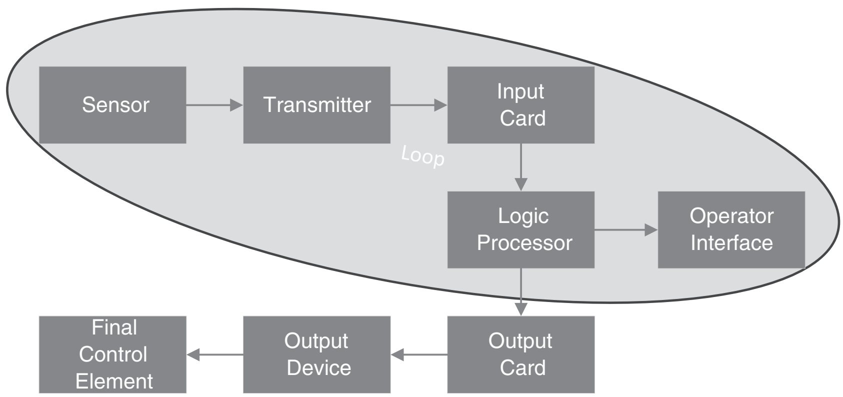


**Figure 1.9** Loop calibration.

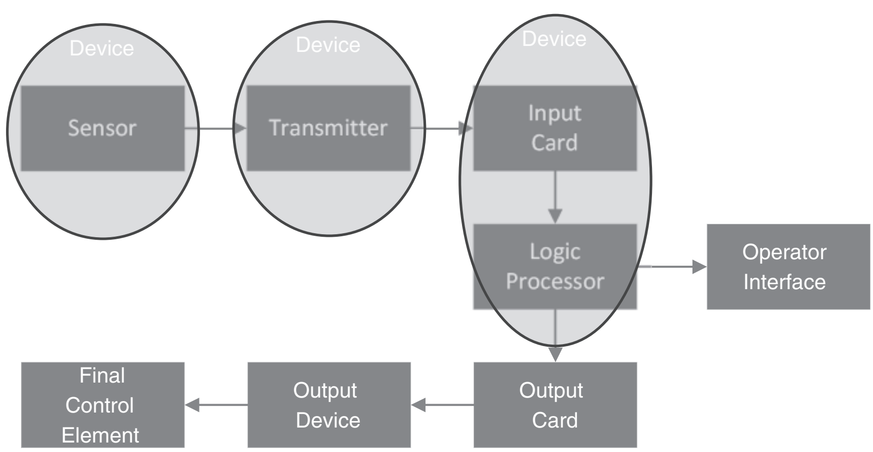


**Figure 1.10** Device calibration.

*Device calibration* is performed only on one device in a loop (Figure 1.10). A known source is applied to the input, and the output is measured at data points throughout the calibration range. If necessary, the instrument is adjusted, and calibration is checked again.

New devices are usually calibrated before installation to confirm that they work correctly. If a loop calibration fails to meet the required tolerance, individual devices in the loop might need to be calibrated to find the cause. Device calibration might also be used when safety or operation considerations prevent testing devices or loops in a running system.

**Expert Advice**

Many companies still individually calibrate each device in a system and pay little attention to the combined effect each device plays in the overall accuracy of the loop. The reason most frequently given by those who oppose loop calibrations is the idea of "de-calibrating" a transmitter to make the reading correct on the data acquisition system, control system, or final indicator. In reality, no sensor is perfect, and the output of some element in the loop is required to bring the loop into calibration.

An example of a measurement error that occurs when loop calibration is not performed is the process of calibrating a temperature device without the sensor in the loop. First, the technician disconnects the temperature element from the device (transmitter or measurement system). Next, the technician connects a temperature simulator to the device to be calibrated. This reduces the potential thermal shock to the temperature element and the time to calibrate the temperature device. However, this process ignores the measurement error of the temperature element. How much of a measurement error is introduced depends on many factors. For a Class B Industrial resistance temperature detector (RTD) operating at 500 °C (932 °F), the accuracy is ±2.8 °C or ±5.04 °F. This approach to calibration does not account for the wiring configuration (two, three, or four-wire), self-heating, or the stability of the RTD. Depending on the process, a measurement error of that magnitude can be costly [2].

### 1.3.2 Bench Versus Field Calibration

A calibration procedure must also indicate whether the calibration is performed in the field or the instrument is uninstalled and calibrated in a shop.

A *bench calibration* (or bench test) is performed in the shop with power supplied from an external source if required. Bench tests are typically performed when new instruments are received, before installation. This provides assurance that the instrument is received in good working condition. This also allows for configuration and calibration in a more favorable environment.

Some periodic calibrations might be performed on the bench when there is no practical way to test the device in place. In this case, the process device is removed from service, disconnected, and taken to the shop for calibration. A calibrated spare might be installed in its place to minimize the process downtime. For example, a critical flow sensor might be sent to a certified flow calibration facility, and a calibrated flow sensor would be installed in its place.

*Field calibrations* are performed in situ, or in place. The instrument being calibrated is not removed from the installed location. Loop calibration is always done in the field.

Field calibrations may be performed after installation to ensure proper connections and configuration. Periodic calibrations are more likely to be performed in the field as part of a loop calibration. Field calibrations are performed in the environment in which the instrument operates. If the instrument is installed in a harsh environment, it is calibrated for that environment. If the instrument is removed for a bench test and returned to service, some error may be introduced because of the ambient conditions, process conditions, power supply, and orientation.

## 1.4 Fundamentals of Metrological Traceability

*Metrology* is the scientific study of measurement. Calibration programs, tools, and methods are rooted in this science. (It is different from meteorology, which is the science of weather forecasting.)

*Traceability* is the property of a measurement result whereby the result can be related to a reference through a documented, unbroken chain of calibrations, each contributing to the measurement uncertainty [3].

Traceability is accomplished by ensuring the test standards are routinely calibrated against higher-level reference standards. Typically, the standards used locally are sent out periodically to a calibration lab that has more accurate test equipment. The standards from the calibration lab are checked regularly for calibration by higher-level standards, and so on until, eventually, the standards are tested against primary standards maintained to an internationally recognized standard. The higher you go on the calibration pyramid (Figure 1.11), the smaller the uncertainty.

All calibrations should be traceable to a nationally or internationally recognized standard. For example, in the United States, the National Institute of Standards and Technology (NIST) maintains nationally recognized standards and certifies calibration labs. This does not mean a calibration shop must have its standards calibrated by a national laboratory. It means that the calibrations performed are traceable to the national standard through all the standards used to calibrate the standards, no matter how many levels exist between the shop and the national standard (Figure 1.12).

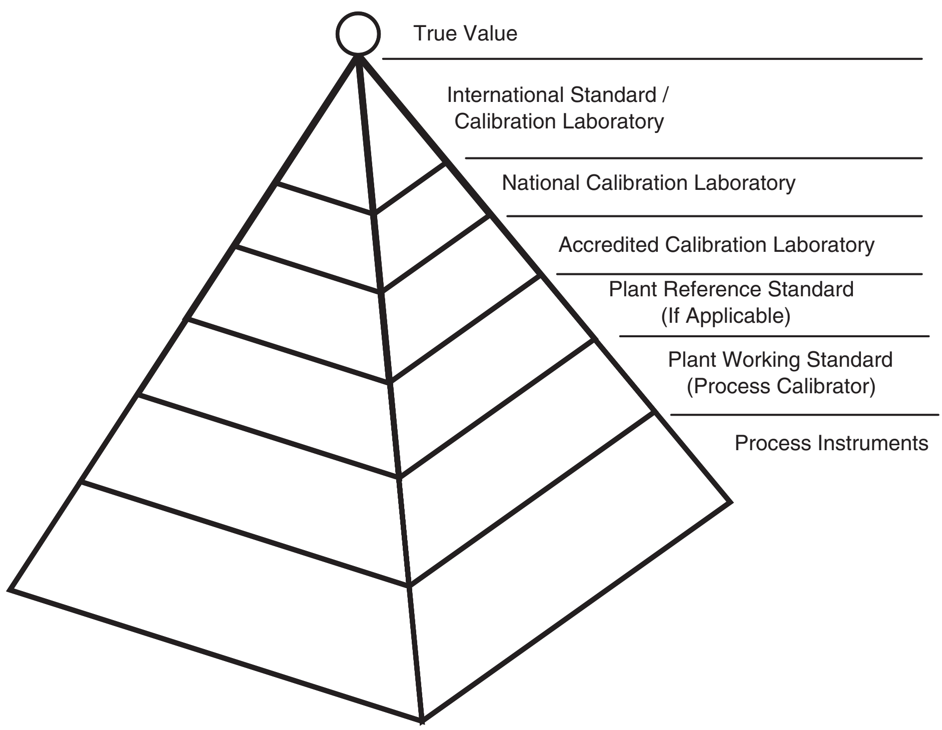


**Figure 1.11** Calibration pyramid.

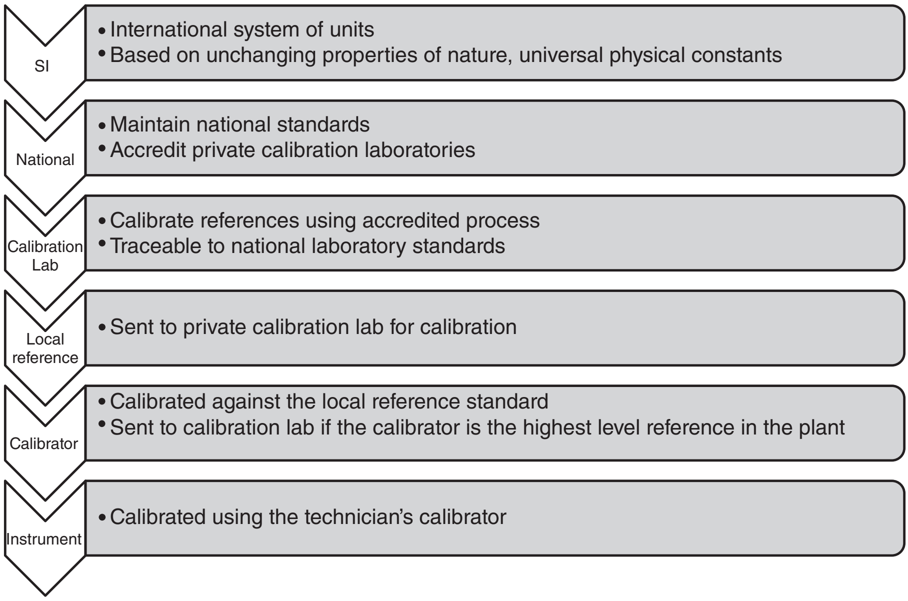


**Figure 1.12** Traceability.

**The Last Artifact**

*(This is not on the CCST exam; it is just neat to know. This author thinks the history of metrology over the centuries is fascinating.)*

In 2018, all reference standards were redefined by the International Bureau of Weights and Measures (BIPM). The references are now defined in terms of fundamental, unchanging properties of nature and can be reproduced by any organization.

For instance, the reference for mass is now based on a combination of physical constants rather than a piece of metal in a vault in Paris. The International Prototype Kilogram, aka "Le Grande K," was officially replaced by the 2018 vote. The platinum cylinder served for 130 years as the international standard for mass. It resided in international territory just outside Paris in a triple-locked underground vault and was the last artifact of metrology to be replaced by the new system.

BIPM's brochure "The International System of Units" is a good reference. It can be downloaded from their website.

An organization's local calibration standards and field calibration devices must be recalibrated on an interval defined in the organization's calibration program. This interval is generally determined based on the device manufacturer's recommendation plus experience (see Section 2.7).

Of course, detailed recordkeeping is necessary to prove traceability. The calibration technician's role in maintaining traceability is to ensure that the test equipment is within its calibration interval and that the unique identifier is recorded on the applicable calibration data sheet when the instrument calibration is performed. Additionally, when test standards are calibrated, the calibration documentation must be reviewed for accuracy and to ensure that a calibration was performed using traceable equipment. Level III technicians will probably have the responsibility for incorporating traceability and recordkeeping into the calibration program.

## 1.5 Summary

This chapter introduces calibration definitions and basic concepts that calibration technicians need to understand. The next chapter presents the structure of a calibration program.

## Review Questions

**1.1** A pressure transmitter's base accuracy is given:
Accuracy = ±0.5% of the *full range*
URL = 200 psig
LRL = 0 psig
a) What is the error when the reading is 50 psig?____________
b) What is the error when the reading is 100 psig?____________

**1.2** Explain the difference between the terms *accuracy* and *precision*.

**1.3** The term *tolerance* means "how close is close enough" or "how good does it need to be?" Is it better to express tolerance in percentage of reading or in actual units of measure?

**1.4** A temperature transmitter is capable of measuring −100 °F to 100 °F, but it is configured to measure 0 °F to 50 °F. Calculate the values for:
URL ____________
LRL ____________
URV ____________
LRV ____________
Range ____________
Span ____________

**1.5** A temperature transmitter with a configuration range of 0 °F to 100 °F is found to have the outputs shown in the following table:

| Input | Expected Output | Actual Output |
|---|---|---|
| 0 °F | 4.0 mA | 4.0 mA |
| 25 °F | 8.0 mA | 8.1 mA |
| 50 °F | 12.0 mA | 12.2 mA |
| 75 °F | 16.0 mA | 16.3 mA |
| 100 °F | 20.0 mA | 20.4 mA |

This is an example of ________________.
a) Zero error
b) Span error
c) Both errors combined
d) Hysteresis

**1.6** A temperature gauge with a range of 0 °F to 100 °F is found to have these readings as the temperature is increased and then decreased:

| Input | Reading | Error |
|---|---|---|
| 0 °F | 0 °F | 0 |
| 25 °F | 25.1 °F | +0.1 |
| 50 °F | 50.3 °F | +0.3 |
| 75 °F | 75.1 °F | +0.1 |
| 100 °F | 100 °F | 0 |
| 75 °F | 74.9 °F | −0.1 |
| 50 °F | 49.7 °F | −0.3 |
| 25 °F | 24.9 °F | −0.1 |
| 0 °F | 0 °F | 0 |


This is an example of ________________.

a) Zero error
b) Span error
c) Both errors combined
d) Hysteresis

**1.7** ISA-RP105.00.01-2017 says the recommended best practice for performing calibrations is:

a) Calibrate just the instrument (device calibration).
b) Calibrate the entire instrument loop, including the instrument to the control system input, to the human-machine interface (HMI; loop calibration).

**1.8** Which of the following best describes the term *traceability* of reference standards used for calibration?

a) The ability to calibrate a device using any available reference standard
b) The capability of a field calibrator to store historical calibration data

c) The ability to track a calibrator's accuracy to a known standard following a clear, documented path of calibrations
d) The use of manufacturer specifications to determine the total probable error (TPE) of a measurement

**1.9** Regarding traceability, the calibration technician should do one or more of the following. Select **all** that apply.
a) Ensure the test equipment is within its calibration interval before using it to perform calibrations.
b) Send test equipment to a certified lab before every use.
c) Record the equipment's unique identifier on the calibration record sheet.
d) Perform bench calibrations on every instrument.

**CCST Level III**

**1.10** A pressure transmitter's specifications include:
Range = 0 psig to 100 psig
Base accuracy: ±1% of range
Temperature effects: ± 0.5% of range
a) Use the RSS equation to calculate the TPE for the device.
b) Calculate the WCE for the device.

## References

*Note:* The dates and editions for standards and other references in this chapter are current as of publication. The reader is encouraged to check for later revisions or editions.

**1** International Society of Automation (ISA), ISA-RP105.00.01-2017, *Management of a Calibration Program for Industrial Automation and Control Systems*. Research Triangle Park, NC: ISA, 2017.
**2** Staples, Leo, "A Standardized Approach to Calibration of Automation Instrumentation and Systems," paper presented at Automation Week, October 2011, Mobile, AL.
**3** National Institute of Standards and Technology (NIST), 2024, June 17, "NIST Policy on Metrological Traceability." NIST. https://www.nist.gov/calibrations/traceability. Accessed December 17, 2024.