Uncertainty Methodology and Application for Instrumentation

Revision 1

Non-Proprietary

February 2017

REVISION HISTORY

Revision	Date	Page	Description
0	November 2014	All	First Issue
1	February 2017	2	Added Reference 1 and 2 documents to indicate that uncertainty methodology for the APR 1400 conforms to Regulatory Guide (RG) 1.105, Revision 3 (RAI 404-8488, Question 6.5-12)
		16	Editorial change by adding Reference 1 and 2
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ABSTRACT

This report provides methodology of identifying and combining the instrument uncertainties to ensure that the important plant protective functions are activated at desired values of critical parameters under normal and accident conditions and that the important plant control functions are performed appropriately under normal operating conditions.

Characteristics of uncertainties affecting the combing uncertainties are analyzed and sources of uncertainties are also identified that cause the errors in the instrument channel. Especially, the environmental attributes such as temperature, humidity, pressure and radiation are identified because they affect the output of instrument and the effects should be considered in calculating the uncertainties.

With the characteristic and sources of uncertainties mentioned above, combining methods of uncertainty terms are provided. For combination of uncertainty terms, one of the methods is applied depending on the characteristics of uncertainty term.

Finally, based on the analysis of characteristics of uncertainties and sources of uncertainties and the considerations of combination method of uncertainties, the methodology for calculating uncertainties of instrumentation channel is provided.

Therefore, it is concluded that the uncertainty methodology provided in this report ensures the important plant protective or control functions are properly operated under the plant conditions that those functions should be required.

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ACRONYMS AND ABBREVIATIONS

A/D	Analog to Digital
ASME	American Society of Mechanical Engineer
ATE	Ambient Temperature Effect
CU	Channel Uncertainty
DP	Differential Pressure
HI	High
HIN	Distance between High and Low Taps
HELB	High Energy Line Break
IR	Insulation Resistance
ISO	International Organization for Standardization
KHNP	Korea Hydro & Nuclear Power Co., Ltd.
LO	Low
M&TE	Measuring and Test Equipment
PTC	Power Test Code
SGR	Specific Gravity of Reference Leg Fluid
SGS	Specific Gravity of Steam at Saturation Temperature
SGW	Specific Gravity of Water at Saturation Temperature
SRSS	Square Root Sum of Squares
TID	Total Integrated Dose
TS	Trade Secret
URL	Upper Range Limit

1. PURPOSE

The systematic method of identifying and combining the instrument uncertainties is necessary to ensure that the important plant protective functions are activated at desired values of critical parameters under normal and accident conditions and that the important plant control functions are performed appropriately under normal operating conditions. It is also necessary to evaluate instrument performance to verify that the instruments work properly between outages.

The purpose of this report is to establish the basis of the general methodology for uncertainty calculation. This report is prepared to set up the consistent methodology for the preparation of uncertainty calculation.

2. SCOPE

This report provides the systematic method to identify the definition, classification, sources, and calculation method of uncertainties in accordance with ISA-S67.04, Part I (Reference 1) and utilizes ISA-RP67.04, Part II (Reference 2) for guidance for the implementation of Reference 1. Setpoint calculation and analysis are covered by a separate technical report (Reference 3).

3. CHARACTERISTICS OF UNCERTAINTIES

3.1 Random and Non-random Uncertainties

Randomness is an important consideration for properly combining uncertainties. Contributors to uncertainty in instrument accuracy can be either random or non-random.

3.1.1 Random Uncertainties

An uncertainty that is not predictable can be classified as random. It has a chance of occurrence defined by its associated probability distribution. A random uncertainty can be predicted by its probability distribution rather than by based on conditions. Random error typically arises from unpredictable variations of influenced quantities. These random effects give rise to variations in repeated observations of the measurement values. The random uncertainties of an analytical result cannot be compensated by correction but it can usually be reduced by increasing the number of observations.

3.1.2 Non-random Uncertainty

An uncertainty that is predictable based on events or conditions can be considered non-random. For example the effects of temperature or radiation dose tend to be predictable.

3.2 Independent and Dependent Uncertainty

3.2.1 Independent Uncertainty

Uncertainty components are independent of each other if their magnitude or algebraic signs are not significantly correlated.

3.2.2 Dependent Uncertainty

Uncertainty components are dependent on each other if they have a significant correlation. Dependent uncertainties are influenced by a common parameter or cause. Within the elements of loop uncertainty, instrument uncertainties subject to the same outside influences are normally treated as dependent terms.

3.3 Distributions

It is important to correctly classify the expected distribution of each uncertainty term in order to appropriately combine with other terms for proper modeling of uncertainty effects.

3.3.1 Normal Distribution

Most uncertainties can be considered to be normally distributed. In cases where technical specification or associated documents to support the type of distribution are not available, it is important that the person who is working on uncertainty calculation carefully considers the uncertainty term to see whether the term has not features of normal distribution or not. Generally, it is not necessary that the term should pass statistical tests to be classified as normally distributed. Approximating a normal distribution is generally sufficient. Small deviations from a classical normal distribution will not normally adversely affect the results when combined with other uncertainty terms.

3.3.2 Uniform Distribution

Uniformly distributed uncertainties are characterized by the value of the term having as equal probability of occurrence over the range of expected values. A common example of a uniformly distributed error term is the step in an analog to digital (A/D) converter. The input has an equal chance of being any of the values over the range of the step width of the A/D.

3.3.3 Other Distribution

Other types of distributions associated with uncertainty terms are uncommon. The uncertainty term which is not normally or uniformly distributed must be carefully considered prior to combining it with other uncertainty terms.

3.3.4 Symmetric and Zero Centered Distribution

Symmetric and zero centered means that an uncertainty term has a mean of zero or near zero and is approximately symmetrical about zero. Any uncertainty term regardless of the distribution of the term requires special consideration if it is not symmetrically centered about zero, even normally distributed terms.

3.4 Bias Term

Bias effects produce a known or predictable offset from zero. Generally the result or output could be corrected to reflect these types of uncertainty terms. The bias term can have a known sign bias or unknown sign bias.

3.4.1 Known Sign Bias

Known sign bias is a systematic uncertainty that is predictable for a given set of conditions because of the existence of a known direction (positive or negative). This term remains constant or changes in a regular fashion in repeated measurements of one and the same quantity.

3.4.2 Unknown Sign Bias

This kind of bias may not have a known sign. Their unpredictable sign should be conservatively treated by algebraically adding the bias in the worst direction.

4. SOURCES OF UNCERTAINTIES

It is important to identify the uncertainty sources for the instrument loop. Uncertainty data are available from the followings:

- Manufacturer
- Model
- Calibration Span and Upper Range Limits of device
- Location
- Operation Conditions
- Static Pressure Corrections
- Reference Leg Configuration

The primary uncertainty sources are manufacturer data. It can be provided through the technical manual. Certain uncertainties which are not provided by the manufacturer or supplier can be extracted from instrument qualification test data. Engineering judgment is to be used to evaluate uncertainties when data are not available, but data are estimated when it exist.

4.1 Instrumentation Effects

4.1.1 Reference Accuracy

The reference accuracy of an instrument is the quantitatively defined limit that errors will not exceed when an instrument is used under specific operating conditions. The reference includes the combined effects of repeatability, linearity, and hysteresis and is almost always specified by the manufacturer. Reference accuracy cannot be adjusted or modified by instrument calibration. Typically the reference accuracy is used as the performance specification which the instrument is tested during calibration. Reference accuracy is available from the manufacturer. In the absence of manufacturer data, a value equal to setting tolerance can be used. The effect of reference accuracy cannot be eliminated by periodic calibration.

4.1.1.1 Repeatability

Repeatability is the closeness of agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions, approaching from the same direction but does not include hysteresis. The concept of repeatability is shown in Figure 4-1.

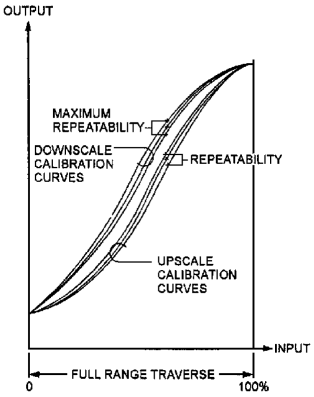


Figure 4-1 Repeatability

4.1.1.2 Linearity

Linearity defines how well the device’s actual performance approximates a straight line across a specified operating range. It can be expressed as independent linearity, zero based linearity or terminal linearity that are basic definition for linearity. When expressed simply as linearity it is assumed to be independent linearity.

4.1.1.2.1 Independent Linearity

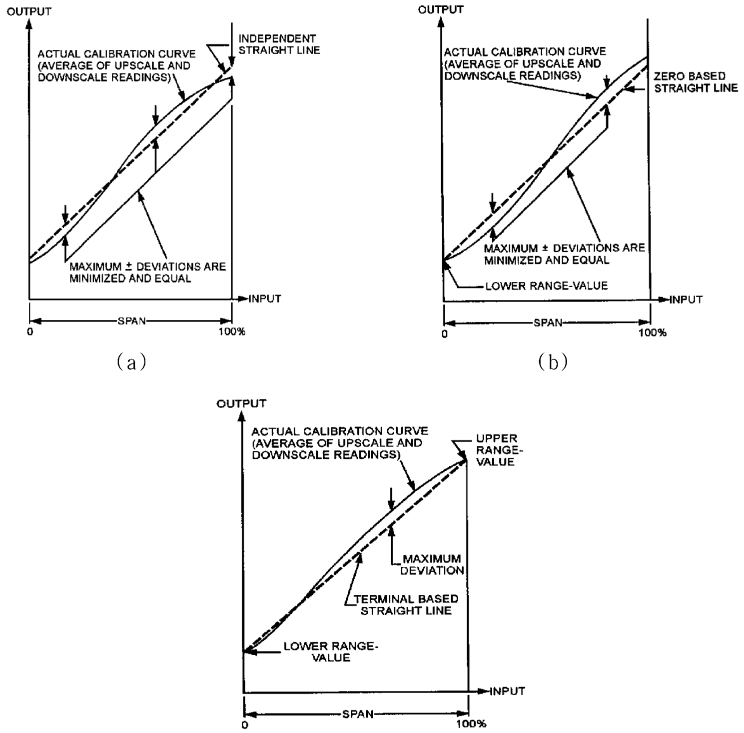
Independent linearity is the most commonly used definition. It is defined as the maximum deviation of the actual performance from a straight line located as to minimize the maximum deviation which is shown in Figure 4-2 (a).

4.1.1.2.2 Zero Based Linearity

Zero based linearity forces the lower range value of the straight line to be equal to the actual lower range value of the device’s characteristic as shown in Figure 4-2 (b), but the straight line is located to minimize the maximum deviation.

4.1.1.2.3 Terminal Linearity

For terminal linearity, the straight line must be located such that each of its end-points coincides with the device’s actual upper and lower range values. Figure 4-2 (c) shows the concept of terminal linearity.



(a) (b)

(c)

Figure 4-2 Linearity (a) Independent linearity

(b) Zero based linearity

(c) Terminal linearity

4.1.1.3 Hysteresis and Dead Band

Hysteresis is the dependence of the output of a system not only on its current input, but also on its history of past input. It is defined as the maximum difference for the same input between the upscale and downscale output value during a full range traverse in each direction. Figure 4-3(a) shows the concept of hysteresis.

Dead band is an interval of a signal domain where no action is occurred. That is shown in Figure 4-3 (b). Figure 4-3(c) also shows the case where both hysteresis and dead band exist.

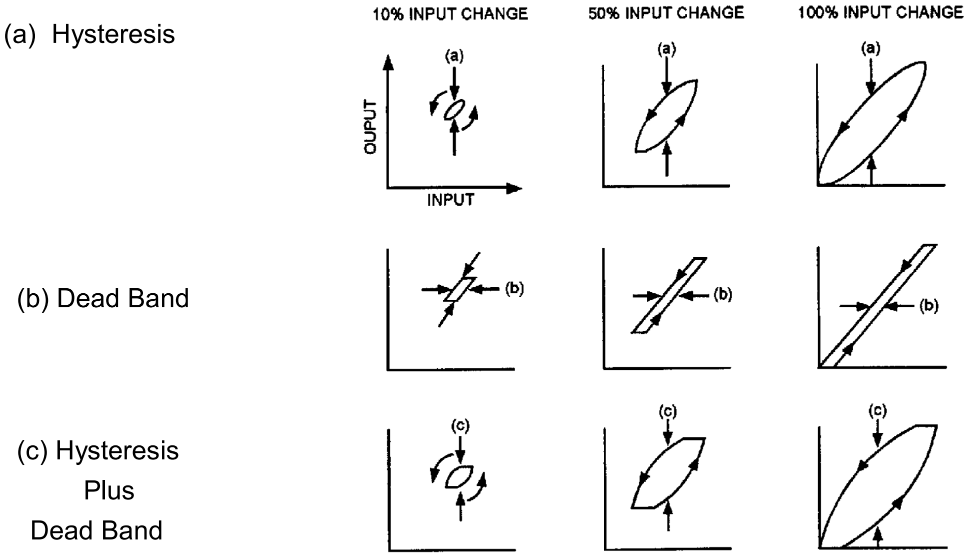


Figure 4-3 Hysteresis and Dead Band

4.1.2 Drift

Drift is an undesired change in the component output over time which is unrelated to the input, environment, or load. Drift is typically specified for a specific time interval by the instrument manufacturer and estimated on the basis of testing instrument in laboratory conditions.

If drift is not available from the manufacturer, a special analysis should be performed to quantify the plant specific experience drifts using as-found/as-left data evaluation. For a special purpose a specific drift analysis can be used instead of the manufacturer's data though manufacturer provides the drift.

The time is a critical parameter in determining the drift. Therefore the drift of instrument will be zero after calibration. It can be assumed that drift is gradually increased up to the manufacturer specified drift value during the manufacturer specified interval. If the calibration interval exceeds the drift interval and the manufacturer cannot supply a new drift value or calibration interval, the drift is justified and calculated considering an extended interval. The most conservative method is linear extrapolation. If plenty of plant specific data are available and an appropriate analysis methodology is used, it is possible to use another method such as SRSS (Square Root Sum of Squares).

Linearly increasing drift can be calculated with the following equation:

- Linear Extrapolation Method

$$\mathrm{Drift_{extended}} = \mathrm{Drift_{specfied}} \times \left(\frac{\mathrm{Time_{extended}}}{\mathrm{Time_{specified}}}\right) \qquad (4.1)$$

Where Drift extended (% span): drift over desired interval

Drift specified (% span): drift specified by manufacturer

Time extended: desired calibration interval

Time specified: drift interval specified by manufacturer

If plant specific drift data based on plant as-found and as-left data are available and drift over each specific interval is assumed to be random, approximately normally distributed and independent, the SRSS method can be used with the following equation:

- SRSS Method

$$\mathrm{Drift}_{\mathrm{extended}} = \sqrt{\mathrm{N} \times \mathrm{Drift}^2_{\mathrm{specified}}} \qquad (4.2)$$

Where N: Next largest integer from $\left(\frac{\mathrm{Time}_{\mathrm{extended}}}{\mathrm{Time}_{\mathrm{specified}}}\right)$

Calibration interval for instrument performance evaluation should be used at refueling interval plus [ ]$^{\mathrm{TS}}$ margin.

4.1.3 Power Supply Effect

Power supply effect is the expected variations in the output of the instrument due to the expected variations in the power of the instrument. Output changes in power supply can affect instrument uncertainty. Typically the relationship between the variation of power supply and the output of the instrument is provided by the manufacturer through instrument performance specification of the technical manual.

4.1.4 Static Pressure Effect

The static effect is an effect caused by the expected variations in the output of the differential pressure (DP) device due to calibrating the device at atmospheric pressure and using the differential pressure in the pressurized system. The term ‘static pressure’ applies to the normal pressure where the differential pressure device functions.

The static pressure can cause both zero and span shift. Generally, the manufacturer supplies the data of static pressure error and error correction procedure for the differential pressure transmitters. If the correction procedure is performed and reflected in the calibration procedure, the variation of process pressure needs to be considered for the error in output of DP transmitters. However, if the correction procedure is not included in the transmitter calibration, the static pressure error provided by the manufacturer is treated as bias because the static error resulting from the difference between normal operating pressure and the pressure in calibrating condition, conservatively assumed, is treated as bias.

4.1.5 Overpressure Effect

Overpressure effect is an error caused from exceeding the design pressure of an instrument. If the instrument has the capability to operate under the design pressure and perform the desired function at any condition, this effect needs not to be considered.

4.1.6 Over-range Effect

Over-range effect is an error which accounts for a sensor or primary element that is exposed to a condition beyond its calibrated span. In the case of the pressure and differential pressure transmitter, the instrument can be exposed to an over range condition though an overpressure condition is not occurred. A typical manufacturer supplies this error through performance specification.

4.1.7 Vibration Effect

Generally the instruments are mounted on a wall, panel or floor-mounted supports. Therefore the vibration error attributed to instrument mounting is assumed to be included in the instrument's calibration and can be negligible for this type of installation. The instruments mounted on components such as pipes, valves or pumps may or may not be exposed to vibrating conditions. In this case a significant amount of vibration can be considered as an error. The error from vibration effects is provided by the manufacturer's technical manual or determined from analysis of plant historical calibration data.

4.1.8 Primary Element Accuracy

The primary element accuracy is the one associated with the component that quantitatively converts the measured process variables into a suitable form for measurement with the instrument. Typical examples of primary elements are orifice plate, venturi, flow nozzle or elbow tap. The primary element accuracy can be obtained from the performance specification, laboratory test report or ASME design requirements.

It is important to identify the plant reference process condition for the primary element accuracy because the differential pressure developed by primary elements can be changed with process density changes which are caused by process fluid temperature changes. Therefore the primary element accuracy is valid for a specific reference process condition, temperature and pressure. The potential difference in process from the primary reference condition is taken into account in determination of process measurement effects.

4.1.9 Temperature Effect

Most instruments are exposed to temperature changes. The magnitude of temperature changes of an instrument is influenced by the change in ambient temperature. The effect of ambient temperature changes on an instrument is transitory. If the amount of temperature change is increased, the temperature effect is increased. This temperature change may have an effect on instrument error. The temperature change of an instrument between the calibration condition and operating condition is a very important parameter. Therefore, it is necessary to identify the following parameters to calculate the temperature effects.

- The physical location of each instrument in instrument loop

- The expected temperature variation between calibration condition and operating condition

- The temperature sensitivity supplied by manufacturer

If the temperature sensitivity data are not available, the conservative value which is equal to the reference accuracy may be used instead. The calibration temperatures of each instrument are determined at site during overhaul or commissioning depending on the situation. The operating temperatures are defined in the design document associated with environmental qualification.

The temperature changes should be treated differently depending on the operating condition, normal environmental condition or accident environmental condition.

Generally the manufacturer supplies the temperature sensitivity with a manufacturer specified range (i.e., per 32.4°C, or per 37.8°C). The user, therefore, can calculate the temperature uncertainty assuming that the temperature effect is assumed to be linear within the specified temperature range. The uncertainty for an ambient temperature effect (ATE) can be calculated as follows:

- Manufacture data

  Temperature sensitivity: ± X% span per Y°C of temperature range

- Maximum temperature difference

  △T = Maximum operating temperature - calibration temperature

  $$ATE = \pm X\left(\frac{\Delta T}{Y}\right)\% \qquad (4.3)$$

4.1.10 Humidity Effect

The magnitude of humidity changes of an instrument is influenced by the change in ambient temperature. The effects of ambient humidity changes on an instrument are transitory. If the amount of humidity change is increased, the amount of humidity effect is increased. This humidity change may have an effect on instrument error. It is necessary to identify the following parameters to calculate the humidity effects.

- The physical location of each instrument in instrument loop
- The expected humidity variation between calibration condition and operating condition
- The humidity sensitivity supplied by manufacturer

Generally recent electronic instruments are very robust for the changes in humidity. If the humidity effect data are not available from the manufacturer, it is assumed that the temperature effect includes the humidity effects. The calibration humidity of each instrument is determined at site during overhaul or commissioning depending on the situation. The operating humidity is identified in the design document associated with environmental qualification.

The humidity changes should be treated differently depending on normal environmental condition or accident environmental condition.

4.1.11 Radiation Effects

The effects of radiation dose on an instrument are cumulative. For example, if radiation dose increases, the amount of instrument radiation effect increases. It is necessary to identify the following parameters to calculate the radiation effects.

- The physical location of each instrument in instrument loop
- The expected total integrated dose (TID) of radiation between calibration intervals

  for each location
- The sensitivity of each instrument to TID which is supplied by manufacturer

The expected radiation level for an operating condition is identified in the design document associated with environmental qualification. Manufacturer's performance specification does not provide the instrument radiation effects regarding specific TID.

4.2 Other effects

4.2.1 Insulation Resistance Effects

Under conditions of high humidity and temperature associated with high energy line break (HELB), cable, splice, connector, and connectors including terminal blocks and penetrations may experience a reduction in insulation resistance (IR). The reduction of IR causes an increase in leakage currents between conductors and between conductors and ground. Leakage currents are assumed negligibly small in normal conditions, which means that if channel calibrations are performed such leakage currents are essentially calibrated out. However, in accident conditions such as HELB, the leakage currents may increase causing errors. Typical instrument loop configuration for the IR effect is shown in Figure 4-4. IR model for an instrument loop in Figure 4-4 is shown in Figure 4-5.

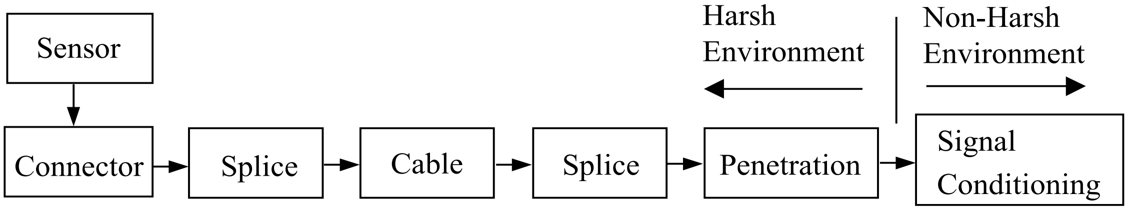
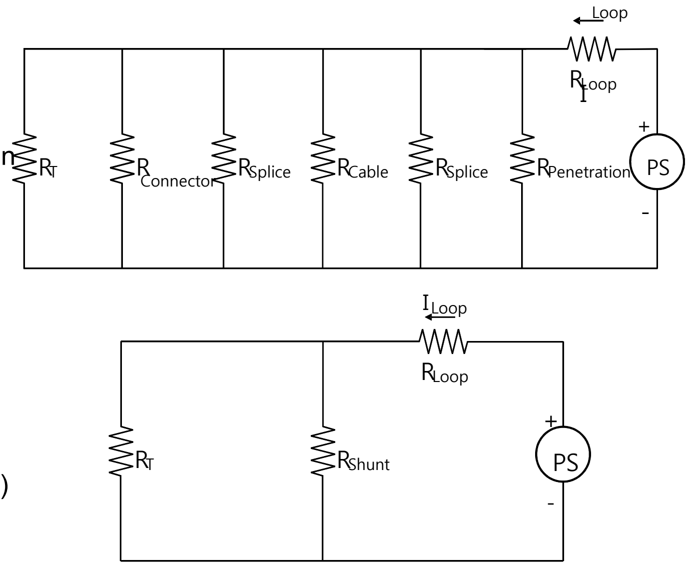


Figure 4-4 Typical instrument loop configuration


(a) Electrical representation of Figure 4-4

(b) Equivalent circuit of (a)

Figure 4-5 Typical IR model for instrument circuit

To determine the IR effect, the following information is required.

- Sensor operation mechanism
- The expected variation in the environmental condition during accident condition
- Configuration and IR of instrument in the accident condition

Typically, the information associated with IR effects for an instrument in the accident condition is provided by a qualification test report. If the qualification report is not available, a qualification test should be performed to show the instrument IR effects in the accident condition. The IR effects should be calculated based on the worst conditions.

IR effects normally impact the output in a single direction. Therefore, IR should be combined using algebraic sum in uncertainty calculation. Since IR values may be randomly distributed over a range of values, it may be possible to justify combining IR terms using a combination of SRSS and algebraic sum.

4.2.2 Seismic Effects

The errors by seismic effects are considered for the impacts of seismic effects both during and after an event. Typically instrument errors for seismic effects are provided by the manufacturer through the technical manual or qualification report. Seismic qualification testing is performed for specific bounding values of acceleration over the range of expected frequencies.

4.2.3 Process Measurement Effects

Process measurement effects are not directly caused by an instrument. These effects are caused by the physical characteristic or the properties of the process which is being measured. Most process measurement effects are induced by the difference between the condition at the point of interest in the process and the condition at the sensor. A few common process measurement error terms can be listed by the following sensor type.

- Pressure sensors

- Static head between the elevation of the tap and the elevation of the sensor

- Differential pressure sensors of level measurement

  . Variation in the reference leg conditions from changes in the temperature and pressure of the fluid or loss of reference leg due to boiling, gas generation, or water accumulation

  . Variation in the variable leg conditions from changes in the temperature and pressure of the fluid

  . Variation of the fluid condition due to boration

  . Changes of vessel height or distance between taps due to the vessel thermal expansion and contraction

- Differential pressure sensors of flow measurement

  . Fluid density effects on the primary elements

  . Thermal expansion or contraction of the primary element

  . Difference in elevation of the upstream and downstream taps

  . Local pressure effect due to the configuration of the upstream and downstream piping

- Temperature sensors

  . Temperature difference between the location of the sensor and the point of interest in the process due to pumps, heat exchangers, etc.

  . Temperature stratification in the process

4.2.3.1 Leg Temperature Effect on DP Transmitters for Level Measurement

When differential pressure transmitters are used to measure the liquid level in vessels, changes in density of the reference leg fluid, vessel fluid or both can cause uncertainties if the level measurement system cannot automatically make compensation for the fluid density changes. This occurs because differential pressure transmitters respond to hydrostatic (head) pressures which are directly proportional to the height of the liquid column multiplied by liquid density. Therefore, measurement uncertainty may be induced in that, while the actual level in the vessel or reference leg remains constant, the liquid density changes are a function of fluid pressure and temperature. It changes the pressure applied to the differential pressure transmitters, which makes the indicated level different from the actual level due to the fact that the transmitter by itself cannot distinguish the difference in pressure caused by the density effect.

The level measuring system is calibrated for assumed normal operating conditions. Typically the vessels are closed. They contain saturated mixture of steam and water with the reference leg filled with water or water with a dry reference leg. Figure 4-6 shows a closed vessel containing a saturated steam/water mixture.

The differential pressure transmitter is calibrated to read the level correctly at specific conditions. As long as the actual vessel and reference leg conditions remain the same as the specific conditions for the system, the indicated level is a linear function of the measured differential pressure and no vessel/reference leg density effects are created. However, when the actual conditions differ from the specific conditions, a level uncertainty is occurred. The following equations are used to show how the temperature changes on vessel or reference leg can cause the level deviation.

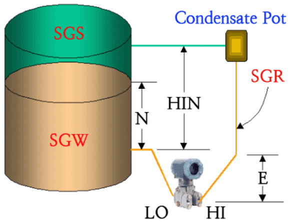


Figure 4-6 Saturated liquid/vapor level measurement

DP = Pressure (HI) - pressure (LO) (4.4)

Pressure (HI) = (HIN + E) SGR + Static Pressure (4.5)

Pressure (LO) = (HIN - N) SGS + (N) SGW + (E) SGR + Static Pressure (4.6)

DP = (HIN) SGR - (N) SGW - (HIN - N) SGS = HIN (SGR - SGS) + N (SGS - SGW) (4.7)

Where, SG = Specific gravity $= \frac{density\ of\ Fluid}{density\ of\ water\ @\ standard\ condition}$

SGW: Specific gravity of water at saturation temperature

SGR: Specific gravity of reference leg fluid

SGS: Specific gravity of steam at saturation temperature

HIN: Vertical distance between upper and lower taps

E: Elevation of lower tap above transmitter

$$L = Zero\ Level + HIN \times \frac{DP@L - DP@0\%}{DP@100\% - DP@0\%} \tag{4.8}$$

$$L \pm e_L = Zero\ Level + HIN \times \frac{DP@L \pm e_{DP} - DP@0\%}{DP@100\% - DP@0\%} \tag{4.9}$$

Substituting equation 4.8 in equation 4.9 and solving e_L yields

$$e_L = HIN \times \frac{e_{DP}}{DP@100\% - DP@0\%} \tag{4.10}$$

$$\begin{aligned} DP &= DP@100\% - DP@0\% \\ &= HIN \times (SGS - SGW) \end{aligned} \tag{4.11}$$

Therefore, substituting equation (4.11) in equation (4.10) yields

$$e_L = \frac{e_{DP}}{SGS - SGW} \tag{4.12}$$

Where, $e_{L:}$ level deviation at water level due to temperature changes

$e_{DP:}$ pressure deviation of differential pressure due to temperature changes

If the conditions are assumed as A and B, the equation for each differential pressure is

$DP\_A = HIN\ (SGR_A - SGS_A) + L\ (SGS_A – SGW_A)$ (4.13)

$DP\_B = HIN\ (SGR_B - SGS_B) + L\ (SGS_B – SGW_B)$ (4.14)

$e_{DP} = DP\_A - DP\_B$ (4.15)

Substituting equation (4.13), (4.14) in equation (4.15) and equation (4.15) in equation (4.12) and solving e_L yields

$$e_L = \frac{HIN(SGRA - SGSA - SGRB + SGSB)}{(SGSB - SGWB)} + \frac{L(SGSA - SGWA - SGSB + SGWB)}{(SGSB - SGWB)} \qquad (4.16)$$

The effect increases with rising vessel temperature because the denominator term decreases with increasing temperature. When the water level is equal to 100% level as per equation (4.16), the effect is maximized. Furthermore, if the vessel condition remains constant, an increasing reference leg temperature above the specific conditions results in a positive effect.

4.2.3.2 Primary Element Effect on Flow Measurement

In general nuclear applications, process fluid flow is measured using primary elements such as orifice, venturi and differential pressure transmitters. It is measured in either mass flow rate or volumetric flow rate. As per ASME Fluid Meters, 6th Edition (Equations for Rates of Flow) (Reference 4), the mass and volumetric flow equations for orifice and venturi at a specific condition are as follows:

Mass flow

$$\dot{m} = 0.041\left(\frac{C\,Y\,d^2\,F_a}{\sqrt{1-\beta^4}}\right) \times \sqrt{\rho h_w} \qquad (4.17)$$

Volumetric flow

$$q_a = 0.0025\left(\frac{C\,Y\,d^2\,F_a}{\sqrt{1-\beta^4}}\right) \times \sqrt{\frac{h_w}{\rho}} \qquad (4.18)$$

Where, $\dot{m}$ = mass flow rate (kg/sec)

q_a = Volumetric flow (m^3/hr)

β = Ratio of throat (primary diameter to pipe diameter)

C = Discharge Coefficient ((actual rate flow)/(theoretical flow rate))

Y = Expansion factor for gas, for case of liquid Y = 1

ρ = Fluid density at specific conditions (kg/m^3)

d = Diameter of Primary element (m)

h_w = Effective differential pressure (kgf/ m^2)

F_a = Thermal expansion factor

The dominant factors for primary element uncertainty are as follows:

- Fluid density changes - ρ
- Thermal expansion factor - F_a
- Discharge coefficient - C

The density is related to differential pressure (h_w) and directly influences an indicated flow rate. Generally, instruments and primary elements relating to flow measurement are calibrated and sized for a normal operating condition. As long as the actual flow conditions match the designed density, process errors cannot be occurred. However, in case of a system which performs dual roles in plant operation and is calibrated for the normal temperature condition, process uncertainties can be induced under a certain different temperature condition.

To identify the effects of fluid density changes assuming other parameters are remaining constant, the equation (4.18) can be simply expressed as follows:

$$q_a = K\sqrt{\frac{h_w}{\rho}} \qquad (4.19)$$

Where, K is a proportional constant.

If the volumetric flow rate (q_a) is kept constant, a decrease in density (ρ) causes a decrease in the differential pressure (h_w). This is occurred because the differential pressure transmitter has been calibrated for a specific differential pressure which corresponds to the designed flow rate. The decreased differential pressure in the transmitter causes the indicated flow rate to be displayed with a lower value. This differential pressure uncertainty is as follows.

Assuming that the flow rate between a specific condition and the actual condition is same, the equality of flow rate is shown in the equation below:

$$Q_1 = Q_2 \qquad (4.20)$$

This equation can be expressed with density and differential pressure.

$$\frac{\Delta P_1}{Density_1} = \frac{\Delta P_2}{Density_2} \qquad (4.21)$$

$$\Delta P_{uncertainty} = \Delta \mathrm{P}_2 - \Delta \mathrm{P}_1 \qquad (4.22)$$

Substituting equation (4.21) in equation (4.22) yields

$$\Delta P_{uncertainty} = \Delta P_1 \times \left[\frac{Density_2}{Density_1} - 1\right] \qquad (4.23)$$

Equation (4.23) shows that density can affect the volumetric flow rate and the absolute effect is maximized when the difference in density is maximized. This occurs at the upper end of the calibrated differential pressure band for the transmitter. The effect varies from negative values for temperatures equal to the specific value (Density2 < Density1) to zero for temperatures equal to the specific value (Density2 = Density1) and finally the positive value for the temperature equal to the specific value (Density2 > Density1). For mass flow rate the equation can be derived in a similar fashion. Note that this method derives from the differential pressure error, which can be converted to a flow rate error using flow versus the differential pressure relationship for the primary element.

Care should be exercised in categorizing uncertainties associated with fluid density changes. Typically these uncertainties are treated as unidirectional biases. Since the effects of density changes may be accurately calculated, it may be possible to reduce and eliminate it as suitable to use SRSS for these uncertainties by proving corrections based on measurement of the density change.

Another potential uncertainty source for primary elements is turbulent flow effects of upstream and downstream. This effect on the sensed differential pressure in transmitters is induced from the pipe configuration. Piping configurations which differ from the one assumed by design or initial calibration testing of primary elements can also alter the pressure profile and affect the sensed differential pressure. ASME PTC 19.5 and ISO 5168 provide the guidance to show the various types of pipe configuration and the pipe straight line requirements for minimum acceptable straightness of upstream and downstream from pipe installations and configurations such as elbow, tee, valve, pump, etc.

4.2.3.3 Line Pressure Loss/Head Pressure Effects

The flow of liquid and gas through piping causes a pressure due to fluid friction. Also, fluid pressure varies as a function of vertical elevation and density in fluid systems. If the point of interest in a process is different in either elevation or point in the flow stream from the sensing location, then uncertainties due to line pressure loss/head pressure effects need to be considered. Most pressure transmitters are calibrated to reflect the pressure at the sensing location, therefore separate consideration of the sensing line head pressure effect is not required.

Figure 4-7 shows an example of a situation which requires consideration of both line pressure loss and head pressure effects. If point A in the figure is the point of interest, then the difference in static head between the sensing tap and the point of interest must be addressed. Likewise any pressure drops due to fluid flow must also be considered. Determination of these effects should take into account the limiting value of the fluid density.

The errors by line pressure loss/head pressure effect are typically bias terms. The effect must be added or subtracted from the analysis limit depending on the particular circumstances to ensure that protective action occurs before exceeding the analysis limit. In figure 4-7, the head pressure would be larger than the one of the pressure sensing location. The line loss would also be negative for the same reason. Since the effects of line loss and head may be accurately calculated, it may be possible to reduce, eliminate or characterize it as suitable to use SRSS for calculating these uncertainties by providing corrections based on measurement of the density changes.

Line pressure loss/head pressure effects generally apply to pressure transmitters. However, the installation of differential pressure devices should be reviewed with respect to the elevation of the high and low pressure taps. For example, if a differential pressure switch is monitoring the pressure drop across a heat exchanger and if the taps are at different elevations, the tap elevation difference will introduce an offset in the sensed differential pressure. This differential pressure may contribute to overall measurement uncertainty.

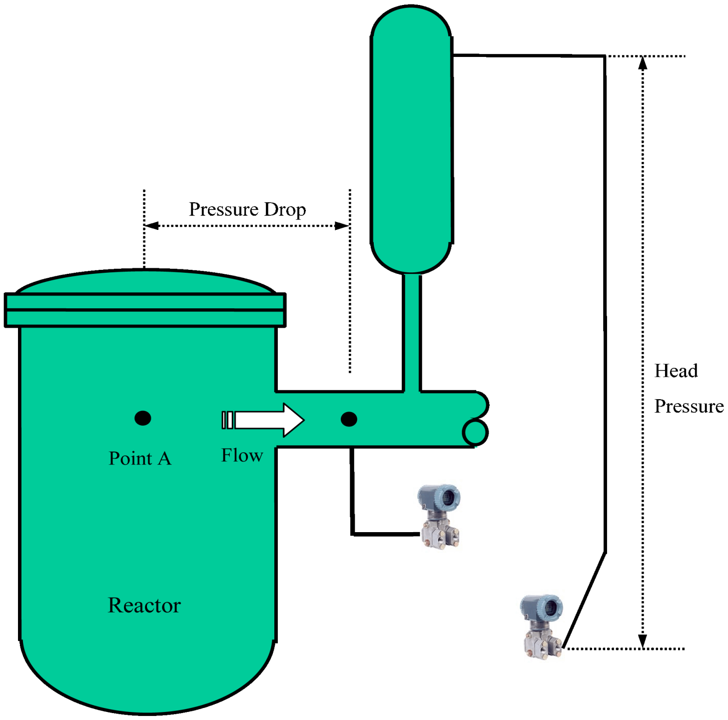


Figure 4-7 Line Pressure Loss and Head Pressure Effects

4.2.4 Measuring and Test Equipment Effects

The Measuring and Test Equipment (M&TE) effect is an error which accounts for the uncertainties related to the M&TE requirements of the periodic calibration of the instrument loop. In order to determine the M&TE effect, the calibration method should be defined. This can be accomplished through review of the calibration procedure.

4.2.4.1 M&TE Accuracy

The accuracy of M&TE shall be less than or equal to the accuracy of the instrument to be calibrated. The accuracy includes the reference accuracy of M&TE, the uncertainty associated with calibration and the readability of M&TE. The reference accuracy of M&TE is available from the M&TE manufacturer.

4.2.4.2 Reference Standard Requirement

A Reference Standard is used for calibrating certain M&TE and the Reference Standard shall have an accuracy which is equal to or better than one-fourth of the M&TE accuracy to meet the guideline of IEEE Standard 498 (Reference 5).

4.2.5 Setting Tolerance Effects

Setting tolerance effects is an error which accounts for the calibration procedure acceptance criteria. Setting tolerance (or calibration tolerance) is the acceptable parameter variation limit above or below the desired output for a given input standard associated with the calibration of the instrument channel. To minimize instrument wear and to provide for human factor considerations, a band rather than a single value should be specified in the calibration procedure. This may be symmetrical band about a setpoint e.g.

[ ]$^{\text{TS}}$, or in some cases a non-symmetrical band about a setpoint e.g. [ ]$^{\text{TS}}$.

This calibration tolerance is usually based on the reference accuracy of the device being calibrated. The size of the calibration tolerance should be established based on the reference accuracy of the instrument, the limitations of the technician in adjusting the instrument and the need to minimize maintenance time.

Depending on the method of calibration, the calibration tolerance may or may not need to be included in channel uncertainty. If the calibration tolerance is less than or equal to the reference accuracy, then the calibration tolerance does not need to be included in total channel uncertainty. If the calibration tolerance is larger than the reference accuracy, then the calibration tolerance may be substituted for the reference accuracy.

4.2.6 Readability Accuracy

An error for the readability of the indicator should be included when the function of the loop or device requires that the indicator be read. For an analog device, the error is generally taken as equal to half of a minor division of the indicator. For digital devices, the error is generally taken as equal to the resolution of the indicator.

5. ENVIRONMENTAL EFFECTS

Environmental effects can cause the expected variations in the output of an instrument that would be attributed to changes in the temperature, humidity, pressure, and radiation at the location of the instrument. The following are the examples of a typical instrument (i.e. transmitter) which can be exposed to a harsh environment to consider the environmental effect and to include these effects to uncertainty calculation.

5.1 Normal Environmental Effects

Normal environmental effects refer to changes in environmental conditions that can be expected when the plant is operating as designed. Normal performance accuracies are calculated by SRSS method by combining the following normal environmental errors (as applicable).

- Reference Accuracy (including applicable linearity, repeatability, and hysteresis)
- Drift (for calibration period)
- M&TE
- Power Supply Effects
- Temperature Effects (Normal Environments)
- Relative Humidity Effects
- Background Radiation (integrated dose and dose rate)

5.2 Accident Environmental Effects

Accident environmental conditions can also significantly affect the output of an instrument channel due to increase in the cable insulation resistance, accident radiation and seismic effects. Accident environmental effects refer to changes in environmental conditions that can be expected when the plant is experiencing an upset condition. Accident performance accuracies are calculated by SRSS method by combining the normal performance accuracy with the following accident environment errors (as applicable).

- HELB Effects (including appropriate chemical spray)
- Accident Radiation (integrated dose and dose rate)
- Seismic Effects

Accident performance accuracies may also be calculated specifically. When excessive conservatisms are present, the redundant error components should be removed. The channel uncertainty is determined by only combining the errors applicable to the condition for which the error calculation is needed. For example, the accident radiation error reported by the manufacturer includes the background radiation; therefore the background radiation component may be removed from the accident performance accuracy calculation when the accident radiation error component is used in a channel accuracy calculation for accident conditions. Another example of errors are associated temperature effects (for example, the effects of a HELB), which include the temperature and humidity rising in accident condition which are much higher than those in the normal condition; therefore the temperature effects in the normal condition need not be included in accident performance accuracy calculation.

6. EXPRESSING UNCERTAINTY

Instrument performance is normally expressed or specified in terms of calibration span. Some instrument manufacturers provide the instrument performance specification in terms of a maximum range of instrument capability (or Upper Range Limit: URL). A typical example is transmitters which are provided with a maximum range and normally used at specific calibrated span. For the uncertainty calculation of an instrument loop which includes sensors and signal conditioning units and display devices, it’s important to use calibration span as unified unit because each instrument can have its unique unit such as kg/cm^2, V, mA or %. In order to evaluate the instrument performance, the unit to express the uncertainty needs to keep the consistency with calibration span. Therefore, it is necessary to use turndown ratio in calculating uncertainty in terms of calibrated span if the manufacturer provides the uncertainties as URL. Turndown ratio is the ratio of the maximum span (or URL) to the calibration span. If the manufacturer supplies the uncertainty as %URL, %span can be obtained by dividing it with the turndown ratio. Where possible, all uncertainty of instruments loops can be calculated in terms of engineering units of the measurement channel output.

7. COMBINATIONS OF UNCERTAINTIES

After the uncertainty terms are defined and classified to the same units or fraction of URL, they can be combined to determine the overall uncertainty of an instrument loop. The combination of the uncertainty terms is generally performed using SRSS and algebraic sums. This combination method provides the way to determine the total uncertainty in a conservative manner.

7.1 Square Root Sum of the Squares

Uncertainty terms are combined using SRSS provided the terms are linear, independent, random and normally distributed about zero, which includes the effects of error propagation. Combining uncertainties using SRSS is done as follows:

$$e_{Mod}^{+} = +[w^2 + x^2 + y^2 + z^2]^{\frac{1}{2}} \tag{7.1}$$

$$e_{Mod}^{-} = -[w^2 + x^2 + y^2 + z^2]^{\frac{1}{2}} \tag{7.2}$$

Where, e^{+}_{mod} and e^{-}_{mod} an uncertainty for a module or instrument loop component (+ sign means positive, - sign means negative) and *w, x, y* and *z* are uncertainty terms.

If two uncertainty terms are dependent on each other, they are combined using different combining methods. For example, if two uncertainty terms *x* and *y* in equation (7.1) and (7.2) are a function of common parameter, they should be combined algebraically first as in the following equations:

$$e_{Mod}^{+} = +[w^2 + (x+y)^2 + z^2]^{\frac{1}{2}} \tag{7.3}$$

$$e_{Mod}^{-} = -[w^2 + (x+y)^2 + z^2]^{\frac{1}{2}} \tag{7.4}$$

All of the individual uncertainty terms which are combined using SRSS should reflect bounding values with a 95% probability. Where a confidence interval can be determined, it should also represent a 95% value. The instrument manufacturer usually provides performance data which reflect bounding values with a probability of at least 95% or a two standard deviation units (sigma) value. The uncertainty estimate resulting from combining the random terms by SRSS will then reflect a value which bounds the total uncertainty with a 95% probability. For conservatism, it is assumed that published manufacturer's specifications are 2 sigma value unless specific information is available to indicate otherwise. In calculating the uncertainty, the individual uncertainty terms should be adjusted to the performance specifications of various instruments of the channel to the same sigma value. If the uncertainty is available to higher sigma (i.e. 3 sigma) value through plant data analysis such as from as-found/as-left analysis or the manufacturer provides some of uncertainties as 3 sigma value, then 3 sigma error value may be multiplied by 2/3 to approximate the 2 sigma value.

7.2 Algebraic Sum

Algebraic sum refers to the determination of maximum loop uncertainty by adding the uncertainties. This method effectively assumes that all uncertainties occur at the same time at their maximum values and all in both positive and negative directions. The uncertainty terms are presumed to have no statistical characteristics. While this method provides a high level of assurance that the derived uncertainty is conservative, it is likely that these results would be overly restrictive from an operational perspective. Uncertainty terms can always be conservatively combined using algebraic sum for linear problems.

$$e_{alg\ sum}^{+} = +[\mathrm{B}_1 + \mathrm{B}_2 + \mathrm{B}_3 + \mathrm{B}_4] \quad (7.5)$$

$$e_{alg\ sum}^{-} = -[\mathrm{B}_1 + \mathrm{B}_2 + \mathrm{B}_3 + \mathrm{B}_4] \quad (7.6)$$

Where, $e^{+}_{\text{alg sum}}$ and $e^{-}_{\text{alg sum}}$ are a total uncertainty by algebraic sum ((+) sign means positive, (-) sign means negative) and *1, 2, 3, and 4* are uncertainty terms.

It is important that only positive terms be combined with positive terms and negative terms only combined with negative terms. Combining positive terms with negative terms effectively represent taking credit for an uncertainty term being at its maximum value which is highly unlikely. Typically any terms which do not meet the requirements for combination using SRSS are combined using algebraic sum. The typical uncertainty term to be combined by algebraic sum is bias. Bias terms which are not approximately normally distributed and not zero-centered are normally combined using algebraic sum. The bounding value associated confidence level for bias, where applied, is the same as SRSS method.

7.3 Non-Linear Functions

Combination of uncertainties for functions which are not linear requires special consideration. This problem is frequently encountered for instrument loops used for flow measurement and radiation monitors. Flow loops typically include a device that produces an output signal proportional to the square root of input signal. Radiation monitors generally include a component which produces an output signal proportional to the log of the input signal.

Using algebraic sum and/or SRSS the total uncertainty at the input to the non-linear instrument can be determined at the particular signal level. The uncertainties are frequently constant over the range of signal level. However situations may be encountered where it is desired to define unique uncertainties for each signal level.

Once the total uncertainty is defined at the input to the non-linear instrument, the uncertainties are propagated across the non-linear instrument. To accomplish this propagation, the signal output of the instrument is determined for three values: 1) without application of uncertainties, 2) with application of positive uncertainties to the nominal input value, and 3) with application of negative uncertainties to the nominal input value. The positive and negative propagated uncertainties are determined by subtracting the propagated value without uncertainties from the positive and negative propagated value. The final step for combining non-linear functions is to combine the downstream uncertainties from the non-linear instrument with the positive and negative propagated uncertainties using SRSS and/or algebraic sum. The treatment of the uncertainties related to the non-linear instrument should be based on how the uncertainties are specified for that instrument. Typically these uncertainties are specified as a function of the output of the non-linear instrument and are treated as downstream uncertainties.

Typical example for non-linear functions is computing uncertainties for using a square root characterizer. Flow signals developed by differential pressure sensors may use square root characterizers to develop a linear flow signal for the control room indication, alarms, and control functions for state change. This uncertainty shall consider the propagation of errors by the non-linear signal characterizer. Using SRSS method should include the error propagation at different signal values to determine the overall SRSS uncertainties. This method assumes that all signal conditioning has unity gain. The followings are summarized steps to compute uncertainties for non-linear function using a square root characterizer.

- The approach first determines the overall process sensor error.
- Then random error, which propagates through the signal conditioning, and dependent error components are identified.

- Next, the errors for the square root characterizer are determined by evaluating the characterizers' effect on errors at specific inputs of interest.
- Then the extent of the propagation of errors is derived.
- Finally the remaining errors associated with additional signal conditioners and indication are considered and random error, propagated error, and dependent error components in each case are considered.

The overall uncertainties for the indication should be stated at specific signal values. The overall uncertainty should be determined by combining the random error, which includes the effects of error propagation, using the SRSS method. Any dependent errors on the SRSS method result are included using algebraic sum.

7.4 Total Channel Uncertainty

It is important to consider the following in calculating the total channel uncertainty.

- The Redundant Terms

The redundant term should be identified to determine if one of redundant terms can be eliminated. For the typical example, if uncertainty terms include both the reference accuracy and the setting tolerance, only the larger of the reference accuracy or the setting tolerance need to be included in total channel uncertainty calculation as per section 5.2.6.

- Unit Consistency

The consistency of units is another important thing to be considered in total channel uncertainty calculation. All of the terms should be expressed in common units, the measurement unit of the channel such as % span.

- Sign Convention

Generally the channel uncertainty can be expressed as follows:

$$Uncertainty = Measurement\,Value - Ideal\,Value \quad (7.7)$$

Equation (7.7) shows that a positive error denotes that the indication of the instrument is greater than the ideal value. It is important that the sign convention be established with respect to the result. This may cause simple problems in case of multiple inputs. One input may have a direct effect while another input may have an indirect effect.

Total channel uncertainty is calculated by first combining uncertainty terms with common dependency and then combining all the terms which meet the conditions for combining terms using SRSS. Any remaining terms are then combined algebraically observing the requirement regarding only combining uncertainties with same signs as follows.

$$CU^{+} = +[e_{Mod1}^{2} + e_{Mod2}^{2} + e_{Mod3}^{2} + \cdots]^{\frac{1}{2}} + B^{+} \quad (7.8)$$

$$CU^{-} = -[e_{Mod1}^{2} + e_{Mod2}^{2} + e_{Mod3}^{2} + \cdots]^{\frac{1}{2}} + B^{-} \quad (7.9)$$

Where, CU^{+} and CU^{-} are channel uncertainty ((+) sign means positive, (-) sign means negative), e_{Mod} is uncertainty for each hardware module and B is a bias term.

8. REFERENCES

1. ISA-S67.04-1994, Part I, Setpoint for Nuclear Safety-Related Instrumentation

2. ISA-RP67.04-1994, Part II, Methodologies for the determination of Setpoints for Nuclear Safety-Related Instrumentation

3. APR1400-Z-J-NR-14005-P, “Setpoint Methodology for Plant Protection System, November, 2014

4. ASME Fluid Meters, 6th Edition (Equations for Rates of Flow)

5. IEEE 498-1985, Standard Requirements for the Calibration and Control of Measuring and Test Equipment Used in Nuclear Facilities

6. ANSI/ISA 51.1-1979 (R1993), Process Instrumentation Terminology, ISA

9. DEFINITIONS [REFERENCE 6]

9.1 Accuracy

The degree of conformity of an indicated value to a recognized accepted standard value or ideal value.

The accuracy rating of the instrument is a number or quantity that defines a limit that errors will not exceed when an instrument is used under specified operating conditions. The accuracy rating includes the combined effects of hysteresis, dead band, linearity and repeatability errors.

9.2 Calibrated Span

The absolute value of the difference between the maximum calibrated upper range value and the minimum calibrated lower range value.

9.3 Drift

The combined errors associated with the stability of the sensor and rack equipment. An undesired change in the component output over time, which is unrelated to the input.

9.4 Humidity Effect

The effect associated with the humidity/steam/chemical spray environment for the specific instrument, as determined for both normal and accident conditions.

9.5 Insulation Resistance Effects

Effects associated with electrical current leakage from the cable, cable splices, cable seal instruments, penetrations and terminal blocks.

9.6 Overpressure Effect

The effect on an electro-mechanical instrument which experiences a pressure transient which exceeds the manufacturer design pressure for the instrument.

9.7 Over-range Effect

The effect on an electro-mechanical instrument resulting from continuous operation in over-ranged conditions.

9.8 Power Supply Effect

The expected variations in the output of an instrument associated with expected variations in the power supply to the instrument.

9.9 Primary Element Effect

The accuracy associated with the primary element that quantitatively converts the measured variable energy into a form suitable for measurement by the associated instrumentation.

9.10 Process Measurement Effect

The effect that accounts for measurement errors between the point of interest in the process and the location of the sensor and process conditions which cause variation in the output of the sensor, i.e. The effect of fluid stratification on temperature measurements and the effect of changing fluid density on level measurements.

9.11 Radiation Effect

The effect associated with possible variations in the output of an instrument as a result of instrument exposure to radiation.

Estimates of these output variations for radiation dose in excess of [ ]^{TS} Rads are generally based in test values obtained during testing of the specific type of instrument that is installed.

9.12 Random error

A random error is one which cannot be attributed to a known cause and as a result is unpredictable. In instrument applications, random error follows a normal distribution.

For such distribution, 95% of all errors fall within ±1.96 standard deviations of the mean value.

9.13 Range

The difference between the minimum and maximum value of the instrument.

9.14 Readability

The effect that accounts for ability to determine the value displayed by an indicator.

9.15 Repeatability

The closeness of agreement among a number of consecutive measurements of the output, for the same value of the input, under the same operating conditions, approaching from the same direction. It does not include hysteresis.

9.16 Seismic Effect

The effect associated with the specific instrument to account for variations in the output of the instrument when subject to seismic activity.

9.17 Setting Tolerance

The acceptance criteria to determine the acceptability of a calibration in performing instrument calibration.

The resulting of an instrument calibration or calibration check within this band requires no further adjustment of the instrument.

9.18 Static Pressure

The nominal process pressure applied to differential pressure transmitter during normal operating conditions.

9.19 Systematic Error

The error which remains constant in absolute value and sign or varies according to a definite law when process conditions change.

These errors may be due to incorrect reference standards, installation evaluation differences, non-linearity or range suppression. This error is not considered to be cause by chance.

9.20 Temperature Effect

The effect that accounts for variations in the output of an instrument as a result of changes in the ambient environmental temperature.

9.21 Turndown Ratio

The ratio of maximum span to calibrated span for an instrument.

9.22 Uncertainty

The amount to which an instrument channel's output is in doubt due to possible errors, either random or systematic, which have not been corrected.

Uncertainty is a parameter associated with the result of a measurement that characterizes the dispersion of the values that could reasonably be attributed to the measured values. The uncertainty is generally identified within a possibility and confidence level.