

**RECOMMENDED PRACTICE
ISA-RP67.04.02-2010**

**Methodologies for the
Determination of Setpoints for
Nuclear Safety-Related Instrumentation**

Approved 10 December 2010

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ISA-RP67.04.02-2010
Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation

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Introduction

Before utilizing this recommended practice, it is important that the user understand the relevance of instrument channel uncertainty and safety-related setpoint determination for nuclear power plants. Safety-related instrument setpoints are chosen so that potentially unsafe or damaging process excursions (transients) can be avoided and/or terminated prior to exceeding safety limits (process-design limits). The selection of a setpoint requires that consideration be given to much more than just instrumentation.

Experience has shown that an operational limit should be placed on critical process parameters to ensure that, given the most severe operating or accident transient, the plant's design safety limits will not be exceeded. Performance of transient or accident analysis establishes the analytical limits for critical process parameters. Typically, the analysis models include the thermodynamic, hydraulic, and mechanical dynamic response of the processes as well as assumptions regarding the time response of instrumentation. The analytical limits, as established by analysis, do not normally include considerations for the accuracy (uncertainty) of installed instrumentation. To ensure that the actual trip setpoint of an instrument channel is appropriate, additional analyses are generally necessary, including identification of applicable uncertainties.

Instrument channel uncertainty should be determined based on the characteristics of installed instrumentation, the environmental conditions present at the plant locations associated with the instrumentation, and on process conditions. A properly calculated setpoint will initiate a plant protective action before the process parameter exceeds its analytical limit, which, in turn, ensures that the transient will be avoided and/or terminated before the process parameter exceeds the established safety limit.

ISA-67.04 (now ANSI/ISA-67.04.01) was initially developed in the mid-1970s by the industry in response to large numbers of licensee event reports (LER). These LERs were attributed to the lack of adequate consideration of equipment drift characteristics when establishing the trip setpoints for the limiting safety system settings (LSSS) and engineered safety features actuation system (ESFAS) setpoints. These setpoints are included as part of a nuclear power plant's operating license in their technical specifications. Hence, trip setpoints were found beyond the allowable values identified in the Technical Specifications.

The scope of the standard was focused on LSSS and ESFAS setpoints. As the standard evolved, it continued to focus on those key safety-related setpoints noted previously. It should also be noted that as the Technical Specifications have evolved, the values now included in the Technical Specifications may be the trip setpoint, the allowable value, both the trip setpoint and allowable value, or the limiting safety system setting (LSSS), depending on the setpoint methodology philosophy used by the plant and/or the nuclear steam supply system (NSSS) vendor. The methodologies, assumptions, and conservatism associated with performing accident analyses and setpoint determinations, like other nuclear power plant technologies, have also evolved. This evolution has resulted in the present preference for explicit evaluation of instrument channel uncertainties and resulting setpoints rather than implicitly incorporating such uncertainties into the overall safety analyses. Both the explicit and implicit approaches can achieve the same objective of assuring that design safety limits will not be exceeded. During the process of developing the 1988 revision of ISA-67.04 (ANSI/ISA-67.04.01), it was determined that, because of the evolving expectations concerning setpoint documentation, additional guidance was needed concerning methods for implementing the requirements of the standard. In order to address this need, standards Committees ISA67.15 and ISA67.04 were formed and prepared ISA-RP67.04, Part II, 1994. It is the intent of the Committees that the scope of the recommended practice be consistent with the scope of the standard. The recommended practice is to be utilized in conjunction with the standard. The standard is ANSI/ISA-67.04.01, Setpoints for Nuclear Safety-Related Instrumentation, and the recommended practice is ISA-RP67.04.02, Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation.

Previous versions of the standard and the recommended practice focused on the calculation of an allowable value and trip setpoints. In most cases the allowable value represented a limiting surveillance as-found test value. As long as the as-found trip setpoint was conservative to or could be reset conservative to the allowable value, the channel was defined as operable. (From the Technical

Specification's perspective, this meant the channel would protect the safety limit.) These versions in some cases confused the actual operability of the channel (functioning within the confines of the setpoint calculation) with nuclear power plant licensing issues. The use of a single value to verify the channel met all requirements failed to identify any conditions where the channel was not performing within identified expectations. The previous recommended practice also identified three separate methods for the determination of allowable values and trip setpoints to support existing NRC-approved methodologies. These different methods defined variations on statistical methods, and all resulted in conservative setpoints and allowable values when the basic assumptions were evaluated and confirmed.

This revision of the recommended practice focuses on the functioning of the channel within expected limits and requires validation of the assumptions in the calculation when performing periodic surveillance testing to confirm the status of the channel. The limiting trip setpoint is defined as the least conservative value for the setpoint (including the tolerances) before returning the channel to service. The as-left tolerance value ensures that the channel, or any part being evaluated by the test, will be reset to an acceptable value. The as-found tolerance verifies that the channel is functioning within expected variations. Should the channel continually be found outside the as-found tolerance (or found to deviate only a small fraction of the as-found tolerance over multiple cycles) then the channel should be evaluated to ensure that operation is within expectations.

The allowable value (calculated using the methods discussed in previous versions of this document) may still be calculated, or the least conservative as-found value may be used as the allowable value for plants that wish to maintain current plant licensing basis.

During the development of this recommended practice, a level of expectation for setpoint calculations was identified, which, in the absence of any information on application to less critical setpoints, may lead some users to come to expect that all setpoint calculations should contain the same level of rigor and detail. The lack of specific treatment of less critical setpoints has resulted in some potential users expecting the same detailed explicit consideration of all the uncertainty factors described in the recommended practice for all setpoints. It is not the intent of the recommended practice to suggest that the methodology described is applicable to all setpoints. Although it may be used for most setpoint calculations, it is by no means necessary that the recommended practice guidance be used for all setpoints. In fact, in some cases, it may not be appropriate.

Setpoints associated with the analytical limits determined from transient or accident analyses are considered part of the plant's safety-related design since they are critical to protecting the safety limit analytical limits that assure the integrity of the multiple barriers to the release of fission products. This class of setpoints and their determination have historically been the focus of ANSI/ISA-67.04.01 as discussed above.

Also treated as part of many plants' safety-related designs are setpoints that are not determined from the accident analyses and are not required to maintain the integrity of the fission product barriers. These setpoints may provide anticipatory inputs to, or reside in, the reactor protection and/or engineered safeguards initiation functions but are not credited in any accident analysis. Alternatively, there are setpoints that support operation of, not initiation of, the engineered safety features.

In applying the standard and recommended practice to the determination of setpoints, a graduated or "graded" approach may be appropriate for setpoints that are not credited in the accident analyses to initiate automatic reactor shutdown or the engineered safety features.

While it is the intent that the recommended practice provides a basis for consistency in approach and terminology to the determination of setpoint uncertainty, it is acknowledged that the recommended practice is not an all-inclusive document. Other standards exist that contain principles and terminology, which, under certain circumstances, may be useful in estimating instrument uncertainty. It is acknowledged therefore that concerns exist as to whether the recommended practice is complete in its

presentation of acceptable methods. The user is encouraged to review several of the references in the recommended practice that contain other principles and terminology.

The uncertainty and setpoint calculations discussed in this recommended practice may be prepared either manually or with a computer software program. The documentation associated with these calculations is discussed in Section 10; however, the design control and documentation requirements of manual calculations or computer software are outside the scope of the recommended practice.

This recommended practice is intended for use primarily by the owners/operating companies of nuclear power plant facilities or their agents (NSSS suppliers, architects, engineers, etc.) in establishing setpoint methodology programs and preparing safety-related instrument setpoint calculations.

This recommended practice utilizes statistical nomenclature that is customary and familiar to personnel responsible for nuclear power plant setpoint calculations and instrument channel uncertainty evaluations. It should be noted that this nomenclature may have different definitions in other statistical applications and is not universal, nor is it intended to be. Furthermore, in keeping with the conservative philosophy employed in power plant calculations, the combination of uncertainty methodology for both dependent and independent uncertainty components is intended to be bounding. That is, the resultant uncertainty should be correct or overly conservative to ensure safe operation. In cases where precise estimation of measurement uncertainty is required, more sophisticated techniques should be employed.

ISA Standard Committee ISA67.04 operates as a Subcommittee under ISA67, the ISA Nuclear Power Plant Standards Committee, with Robert Queenan as Chairman.

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1 Scope

This recommended practice provides guidance for the implementation of ANSI/ISA-67.04.01-2006 in the following areas:

- a) Methodologies, including sample equations to calculate total channel uncertainty;
- b) Common assumptions and practices in instrument uncertainty calculations;
- c) Equations for estimating uncertainties for commonly used analog and digital modules;
- d) Methods to determine the impact of commonly encountered effects on instrument uncertainty;
- e) Application of instrument channel uncertainty in setpoint determination;
- f) Sources and interpretation of data for uncertainty calculations;
- g) Discussion of the interface between setpoint determination and plant operating procedures, calibration procedures, and accident analysis;
- h) Documentation requirements.

2 Purpose

The purpose of this recommended practice is to present guidelines and examples of methods for the implementation of ANSI/ISA-67.04.01-2006 in order to facilitate the performance of instrument uncertainty calculations and setpoint determination for safety-related instrument setpoints in nuclear power plants.

3 Definitions

3.1 analytical limit (AL):

limit of a measured or calculated variable established by the safety analysis to ensure that a safety limit is not exceeded.

3.2 abnormally distributed uncertainty:

a term used in this recommended practice to denote uncertainties that do not have a normal distribution. See 6.2.1.2.2 for further information.

3.3 as-found value:

the condition in which a channel, or portion of a channel, is found after a period of operation and before recalibration (if necessary).

3.4 as-left value:

the condition in which a channel, or portion of a channel, is left after calibration or final setpoint device setpoint verification.

3.5 bias:

an uncertainty component that consistently has the same arithmetic sign and is expressed as an estimated limit of error.

3.6 dependent uncertainty:

uncertainty components are dependent on each other if they possess a significant correlation, for whatever cause, known or unknown. Typically, dependencies form when effects share a common cause.

3.7 design basis:

the design basis for protection systems is as defined in Part 4, Safety System Design Basis, of IEEE Standard 603-1998. (See IEEE Std. 603.)

3.8 drift:

a variation in sensor or instrument channel output that may occur between calibrations that cannot be related to changes in the process variable or environmental conditions. (ANSI/ISA-67.04.01-2006)

3.9 effect:

a change in output produced by some outside phenomena, such as elevated temperature, pressure, humidity, or radiation.

3.10 error:

the arithmetic difference between the indication or measured value and the ideal value of the measured signal.

3.11 final setpoint device:

a component or assembly of components, that provides input to the process voting logic for actuated equipment.

NOTE — Examples of final setpoint devices are bistables, relays, pressure switches, and level switches.

3.12 independent uncertainty:

uncertainty components are independent of each other if their magnitudes or arithmetic signs are not significantly correlated.

3.13 instrument channel:

an arrangement of components and modules as required to generate a single protective action signal when required by a plant condition. A channel loses its identity where single protective action signals are combined. (See IEEE Standard 603.)

3.14 instrument span:

the region between the limits within which a quantity is measured, received, or transmitted, expressed by stating the lower- and upper-range values.

3.15 limiting safety system setting (LSSS):

limiting safety system settings for nuclear reactors are settings for automatic protective devices related to those variables having significant safety functions. Where a limiting safety system setting is specified for a variable on which a safety limit has been placed, the setting must be so chosen that automatic protective action will correct the abnormal situation before a safety limit is exceeded. (See Title 10 Part 50 Paragraphs 50.36[c][1][i][A] and 50.36[c][1][ii][A]).

3.16 margin:

in setpoint determination, an allowance added to the instrument channel uncertainty. Margin moves the setpoint farther away from the analytical limit.

3.17 module:

any assembly of interconnected components that constitutes an identifiable device, instrument, or piece of equipment. A module can be removed as a unit and replaced with a spare. It has definable performance characteristics that permit it to be tested as a unit. A module can be a card, a drawout circuit breaker, or other subassembly of a larger device, provided it meets the requirements of this definition. (See IEEE Standard 603.)

3.18 nuclear safety-related instrumentation:

that which is essential to

- provide emergency reactor shutdown;
- provide containment isolation;
- provide reactor core cooling;
- provide for containment or reactor heat removal;
- prevent or mitigate a significant release of radioactive material to the environment; or

is otherwise essential to provide reasonable assurance that a nuclear power plant or nuclear reactor facility can be operated without undue risk to the health and safety of the public.

3.19 performance test:

a test that evaluates the performance of equipment against predefined acceptance criteria.

3.20 primary element:

the system element that quantitatively converts the measured variable energy into a form suitable for measurement (e.g., Venturi, orifice plate).

3.21 process measurement instrumentation:

an instrument, or group of instruments, that converts a physical process parameter, such as temperature, pressure, etc., to a usable, measurable parameter, such as current, voltage, etc.

3.22 random:¹

describing a variable whose value at a particular future instant cannot be predicted exactly but can only be estimated by a probability distribution function. (See ANSI C85.1.)

3.23 reference accuracy (also known as "accuracy rating" as defined in ISA-51.1):

a number or quantity that defines a limit that errors will not exceed when a device is used under specified operating conditions.

3.24 safety limit:

a limit on an important process variable that is necessary to reasonably protect the integrity of physical barriers that guard against uncontrolled release of radioactivity. (See 10 CFR 50.36 [c][1][i][A].)

¹ In the context of this document, "random" is an abbreviation for "random, independent, and approximately normally distributed." The arithmetic sign of a random uncertainty is equally likely to be positive or negative with respect to some median value. Thus, random uncertainties are eligible for the square-root-sum-of-squares combination propagated from the process measurement module through the signal conditioning module of the instrument channel to the module that initiates the actuation.

3.25 sensor:

the portion of an instrument channel that responds to changes in a process variable and converts the measured process variable into an instrument signal; e.g., electric or pneumatic. (See IEEE Standard 603.)

3.26 setpoint:

a predetermined process value for actuation of a final trip device, control device or indicated action point. Typically associated with

- trip bistables;
- reactor vessel pressure control;
- verification of technical specifications minimum condensate water storage tank level; and
- operator actions associated with emergency response procedure setpoint.

3.27 signal conditioning:

one or more modules that perform signal conversion, buffering, isolation, or mathematical operations on the signal as needed.

3.28 signal interface:

the physical means (cable, connectors, etc.) by which the process signal is propagated from the process measurement module through the signal conditioning module of the instrument channel to the module that initiates the actuation.

3.29 test interval:

the elapsed time between the initiation (or successful completion) of tests on the same sensor, channel, load group, safety group, safety system, or other specified system or device. (See ANSI C85.1.)

3.30 tolerance:

the allowable variation from a specified or true value. (See IEEE Standard 498.) The tolerance is used to establish acceptance criteria. (See Sections 8.1 and 8.2.)

3.31 trip setpoint – limiting (LTSP):

the limiting value for the nominal trip setpoint so that the trip or actuation will occur before the analytical limit (AL) is reached, regardless of the process or environmental conditions affecting the instrumentation.

3.32 trip setpoint – nominal (NTSP):

a predetermined value for actuation of a final setpoint device to initiate a protective action.

3.33 uncertainty:

the amount to which an instrument channel's output is in doubt (or the allowance made for such doubt) due to possible errors, either random or systematic. The uncertainty is generally identified within a probability and confidence level.

Additional definitions related to setpoints or instrument terminology and uncertainty may be found in ISA-37.1-1975 (R1982), ANSI/ISA-51.1-1979 (R1993), and ANSI/ISA-67.04.01-2006.

4 Using this recommended practice

The recommended practice is primarily focused on calculating a setpoint for a single instrument channel using acceptable statistical methods, where use of these methods is important to assuring the plant operates within the envelope of the accident analyses and maintains the integrity of the fission product release barriers. There are a number of different approaches that are acceptable for use in establishing nuclear safety-related setpoints. The statistical method presented in the recommended practice is the most common approach in use at this time. The recommended practice is intended to identify areas that should be evaluated when one performs a setpoint calculation, to present some examples of present thinking in the area of setpoint calculations, and to provide some recommendations for a setpoint methodology. The methods discussed in the recommended practice are not intended to be all-inclusive. The recommended practice includes many terms used in probability and statistics. Since it is not the purpose of the recommended practice to be a text on these subjects, it is recommended that the user review a text on statistics to establish a knowledge base for some of the terminology in conjunction with the use of the recommended practice.

Additionally, it is recognized that some safety-related setpoints are not explicitly assumed in the safety analyses and do not, even from a system's standpoint, have an explicit limiting value. Thus a graded approach may be applied to the plant's safety-related setpoints. A graded approach might include a method of classifying setpoints according to their contribution to plant safety. Based on the method of classification, the approach would provide guidance on the method to be used to determine the channel uncertainty. Specific criteria for establishing a graded approach or the level of analysis used as part of this type of approach are outside the scope of the recommended practice.

The remainder of the recommended practice is structured to mimic the process in determining an instrument channel setpoint. A method for calculating instrument channel uncertainties is discussed in Section 5, and a method for calculating the trip setpoint is discussed in Section 6 when an analytical limit for the process is defined.

The recommended practice starts in Section 5 with the preparation of a block diagram of the instrument channel being analyzed. Uncertainty equations and discussions on sources of uncertainty and interpretation of uncertainty data are presented in 6.1 and 6.2. The basic equations for calculating total instrument channel uncertainty are presented in 6.3. Methods to determine the performance test acceptance criteria and trip setpoint for an instrument channel are presented in Section 8.

It is prudent to evaluate setpoint calculations to ensure they are not overly conservative. Overly conservative setpoints can be restrictive with respect to normal plant operation or may reduce safety by unnecessarily increasing the frequency of plant trip occurrence or safety system actuation. The evaluation should assure that there are no overlapping, redundant, or inconsistent values or assumptions. Excessive conservatism may result from the many interfaces between organizations that may have an input to the calculation. These interfaces are discussed in Section 9.

Documentation considerations are discussed in Section 10. The appendices provide in-depth discussions concerning the theory and background for the information presented in Sections 5 through 8, as well as extensive and comprehensive examples of setpoint calculations and discussions of unique topics in setpoint determination.

5 Preparation for determining instrument channel setpoints

The following discussion provides a suggested sequence of steps to be performed when developing an instrument channel uncertainty or setpoint analysis. The intent is to guide the reader through the basics of the channel layout, functions provided, sources of uncertainty that may be present, etc., with references to the appropriate section(s) for detailed discussions of particular topics of interest.

5.1 Instrument channel layout diagram

When preparing an uncertainty or setpoint calculation, it is helpful to generate a diagram of the instrument channel being analyzed in a manner similar to that shown in Figure 1. A diagram aids in developing the analysis, classifying the uncertainties that may be present in each portion of the instrument channel, determining the environmental parameters to which each portion of the instrument channel may be exposed, and identifying the appropriate module transfer function.

Figure 1 shows a typical instrument channel that could be used to provide a nuclear safety-related protection function. It also shows interfaces, functions, sources of error, and different environments.

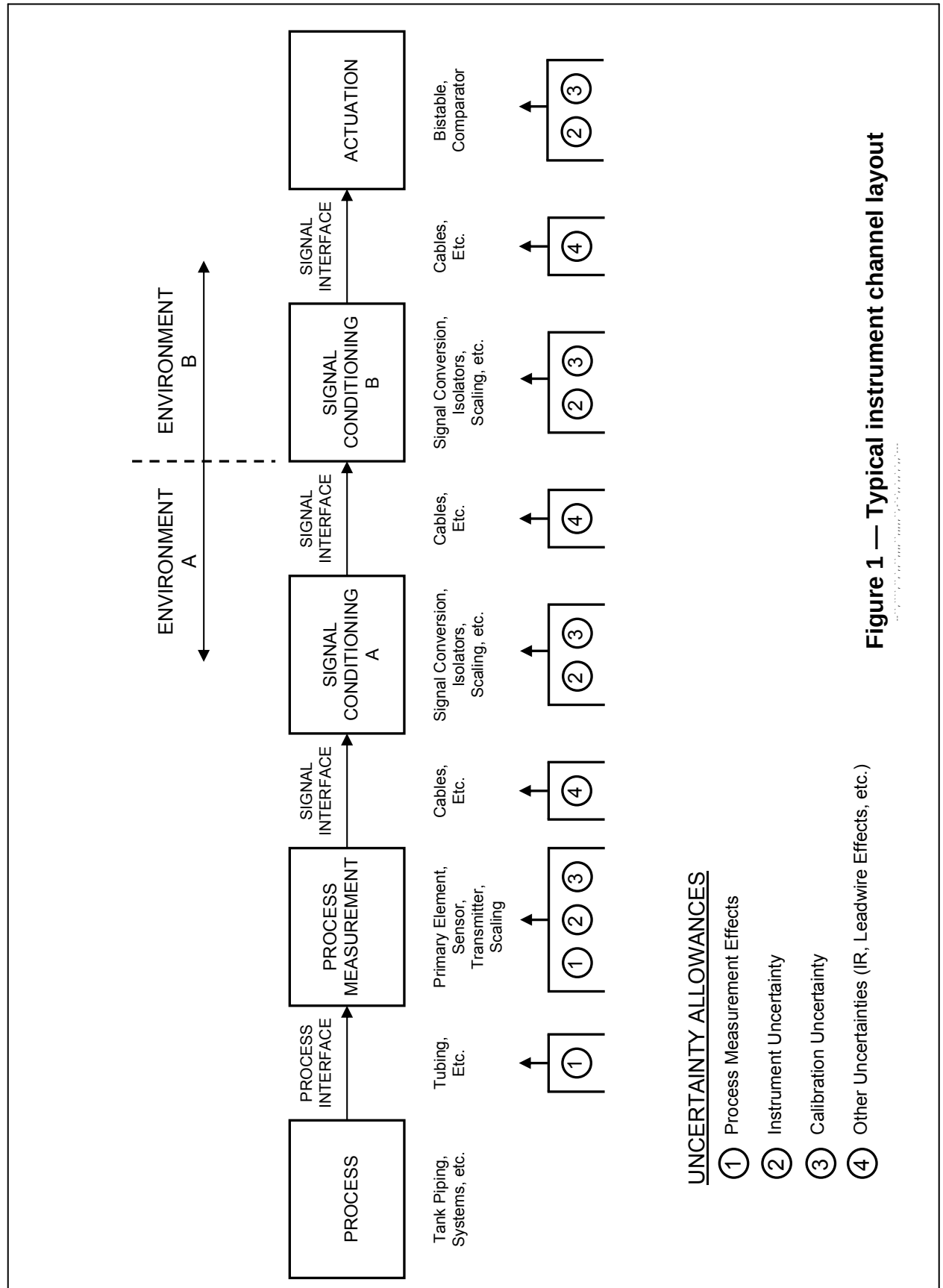


Figure 1 — Typical instrument channel layout

A typical instrument channel consists of the following major sections:

- Process
- Process interface
- Process measurement
- Signal interface
- Signal conditioning
- Actuation

5.2 Identifying design parameters and sources of uncertainty

The functional requirements, actuation functions, and operating times of the instrument channel, as well as the postulated environments that the instrument could be exposed to concurrent with these actuations, should be identified. Many times the instrument channel uncertainty is dependent on a particular system operating mode, operating point (i.e., maximum level, minimum flow, etc.), or a particular sequence of events. A caution that should be considered when the same setpoint is used for more than one actuation function, each with possibly different environmental assumptions, is that the function with the most limiting environmental conditions should be used. Where a single instrument channel has several setpoints, either the most limiting set of conditions should be used or individual calculations for each setpoint should be performed, each with the appropriate set of conditions.

Environmental boundaries can then be drawn for the instrument channel as shown in Figure 1. For simplicity, two sets of environmental conditions are shown. Typically, the process measurement, process interface, some of the signal conditioning (if applicable), and some of the signal interface components are located in areas of the plant that may have a significantly different local environment from the remainder of the instrument channel. Typically, most signal conditioning components and other electronics are located in a controlled environment not subject to significant variations in temperature or to post-accident environments. Therefore, two sets of environmental conditions are defined, with conditions in Environment A normally more harsh than conditions in Environment B. Normally, larger environmental uncertainty allowances will be used with those portions of the instrument channel exposed to Environment A. Environmental effects and assumptions pertaining to environmental conditions are discussed in 6.2.4.

After the environmental conditions are determined, the potential uncertainties affecting each portion of the instrument channel should be determined. For example, the process interface portion is normally affected only by process measurement effects and not by equipment calibration or other uncertainties. Also, cables in the mild conditions of Environment B would not be appreciably affected by insulation resistance (IR) effects.

Figure 1 shows where each major class of uncertainty typically will be present. Each major class is listed below along with a further breakdown into particular types and the particular section(s) in which each is discussed in the recommended practice. This list is not meant to be all-inclusive.

Process measurement effects:

- a) Vessel/reference leg temperature effects (Annex B)
- b) Fluid density effects on flow and level measurement (Annexes B and C)
- c) Piping configuration effects on flow measurement (Annex C)
- d) Line pressure loss/head pressure effects (Annex F)

Instrument uncertainty:

- a) Reference accuracy (6.2.6)
- b) Temperature effects (6.2.2)
- c) Pressure effects (6.2.3)
- d) Drift (6.2.7)
- e) Module power supply variations (6.2.8)
- f) Digital signal processing (6.2.9)
- g) RTD accuracy confirmation (Annex G)
- h) Environmental effects - accident (6.2.4)
- i) Calibration uncertainty (6.2.6)

Other:

- a) Insulation resistance effects (Annex D)
- b) Lead wire effects

The uncertainty allowances must then be identified. These may be obtained from any number of sources such as NSSS vendors' analysis for a process measurement effect, the manufacturer's product specifications and test reports, or actual plant data. Also, various assumptions may need to be made when data are not available and to limit the conditions under which the calculation results may be considered valid. Once identified, the uncertainties should be classified as either random, bias, or abnormally distributed.

When the instrument channel diagram is developed and the uncertainty allowances are known, a mathematical expression of the total instrument channel uncertainty from the process through the bistable can be developed from the individual module input/output relationships. Then the total instrument channel uncertainty can be determined. The methods for combining individual uncertainties into total sensors, modules, and/or instrument channel allowances are discussed extensively in 6.3.

Once the instrument channel uncertainty and analytical limit are known, the trip setpoint and performance test acceptance criteria can be determined. These are discussed in Sections 7 and 8.

A flowchart of the setpoint determination process is provided in Figure 2. Example calculations that depict this process are contained in Annex L.

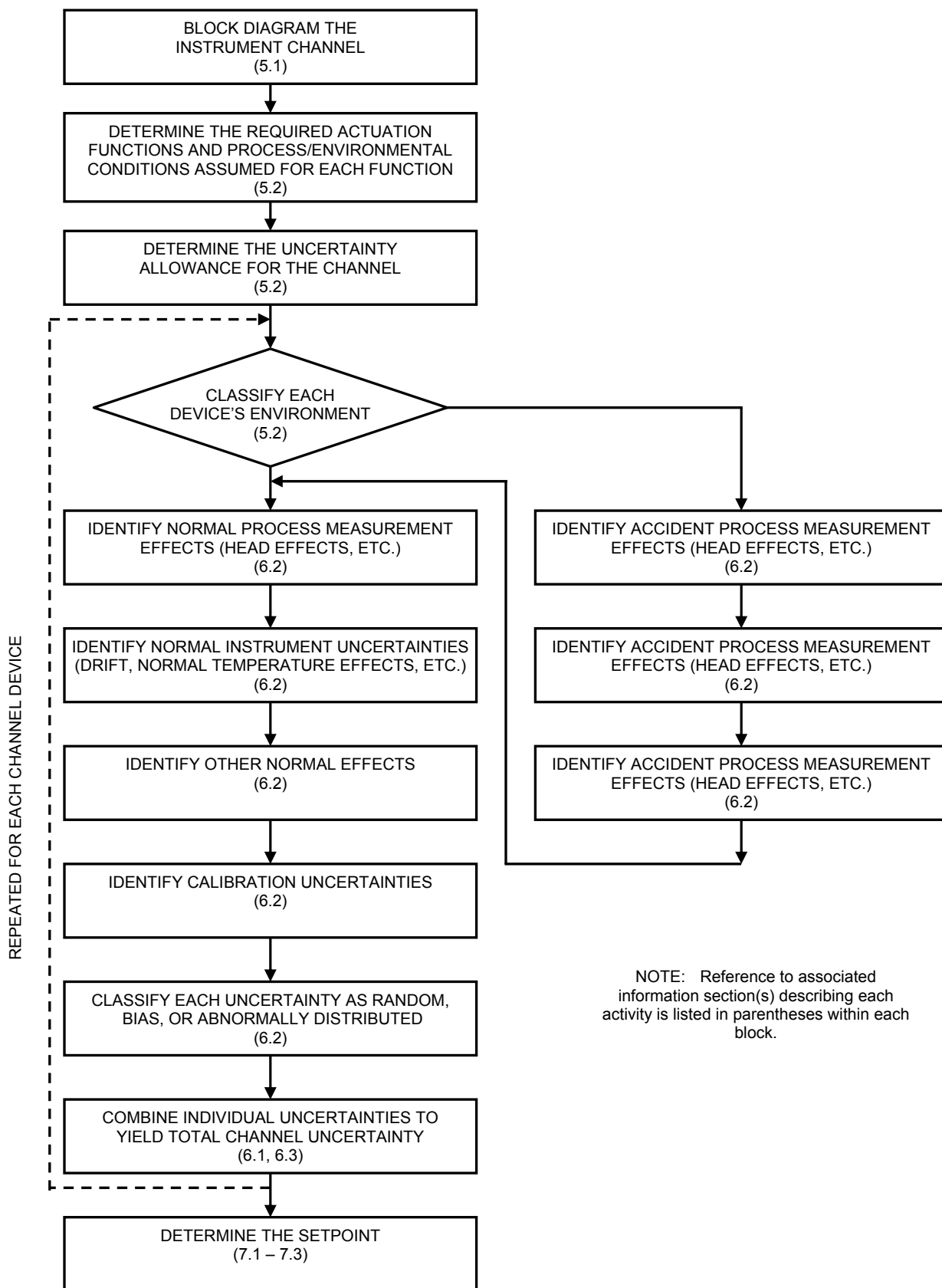


Figure 2 - Setpoint calculation flowchart

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6 Calculating instrument channel uncertainties

6.1 Uncertainty equations

Since all measurements are imperfect attempts to ascertain an exact natural condition, the actual magnitude of the quantity can never be known. Therefore, the actual value of the error in the measurement of a quantity is also unknown. The amount of the error should therefore be discussed only in terms of probabilities (i.e., there may be one probability that a measurement is correct to within a certain specified amount and another probability for correctness to within another specified amount). For the purpose of this recommended practice, the term "uncertainty" will be utilized to reflect the distribution of possible errors.

There are a number of recognized methods for combining instrumentation uncertainties. The method discussed by this recommended practice is a combination of statistical and arithmetic methods that uses statistical square root sum of squares (SRSS) methods to combine random uncertainties and then arithmetically combine the nonrandom terms with the result. The formulas and discussion below present the basic principles of this methodology. Another recognized methodology to estimate instrument measurement uncertainty is described in ANSI/ASME PTC 19.1, Measurement Uncertainty, Part I. Additional discussion of this methodology is provided in J.1 of Annex J.

The basic formula for uncertainty calculation takes the form:

$$(Eq. 6.1) \quad Z = \pm[(A^2 + B^2 + C^2)]^{1/2} \pm |F| + L - M$$

where:

- A,B,C = random and independent terms. The terms are zero-centered, approximately normally distributed, and indicated by a $\pm$ sign.
- F = abnormally distributed uncertainties and/or biases (unknown sign). The term is used to represent limits of error associated with uncertainties that are not normally distributed and do not have known direction. The magnitude of this term (absolute value) is assumed to contribute to the total uncertainty in a worst-case direction and is also indicated by a $\pm$ sign.
- L & M = biases with known sign. The terms can impact an uncertainty in a specific direction and, therefore, have a specific + or - contribution to the total uncertainty.
- Z = resultant uncertainty. The resultant uncertainty combines the random uncertainty with the positive and negative components of the nonrandom terms separately to give a final uncertainty. The positive and negative nonrandom terms are not arithmetically combined before combination with the random component.

The addition of the F, L, and M terms to the A, B, and C uncertainty terms allows the formula to account for influences on total uncertainty that are not random or independent. For biases with known direction, represented by L and M, the terms are combined with only the applicable portion (+ or -) of the random uncertainty. For the uncertainty represented by F, the terms are combined with both portions of the random uncertainty. Since these terms are uncertainties themselves, the positive and negative components of the terms cannot be arithmetically combined into a single term. The positive terms of the nonrandom uncertainties should be summed separately, and the negative terms of the nonrandom uncertainties should be summed separately and then individually combined with the random uncertainty to yield a final value.

Individual nonrandom uncertainties are independent probabilities and may not be present simultaneously. Therefore, the individual terms cannot be assumed to offset each other.²

If R equals the resultant random uncertainty $(A^2 + B^2 + C^2)^{1/2}$, the maximum positive uncertainty is:

$$Z^+ = +R + |F| + L$$

and the maximum negative uncertainty is

$$Z^- = -R - |F| - M$$

SRSS combination for bias uncertainties is inappropriate since by their nature they do not satisfy the prerequisites for SRSS. Bias uncertainties are not random and are not characterized by a normal probability distribution. Since the number of known biases is typically small, and they may or may not be present simultaneously, the recommended practice conservatively endorses arithmetic summation for bias uncertainties.

In the determination of the random portion of an uncertainty, situations may arise where two or more random terms are not totally independent of each other but are independent of the other random terms. This dependent relationship can be accommodated within the SRSS methodology by arithmetically summing the dependent random terms prior to performing the SRSS determination. The formula takes the following form:

$$\text{(Eq. 6.2)} \quad Z = \pm [A^2 + B^2 + C^2 + (D + E)^2]^{1/2} \pm |F| + L - M$$

where

D and E = random dependent uncertainty terms that are independent of terms A, B, and C.

The uncertainty terms of equation 6.2 and their associated relationships are depicted in Figure 3.

² The purpose of the setpoint calculation is to ensure that protective actions occur 95 percent of the time with a high degree of confidence before the analytical limit is reached. The desired level of confidence should attempt to incorporate 95/95 tolerance limit, where there is a 95% probability that the constructed limits contain 95% of the population of interest for the surveillance interval selected. A conservative philosophy applies the SRSS technique only to those uncertainties that are characterized as independent, random, and approximately normally distributed (or otherwise allowed by versions of the central-limit theorem). All other uncertainty components are combined using the maximum possible uncertainty treatment, i.e., arithmetic summation of absolute values as necessary.

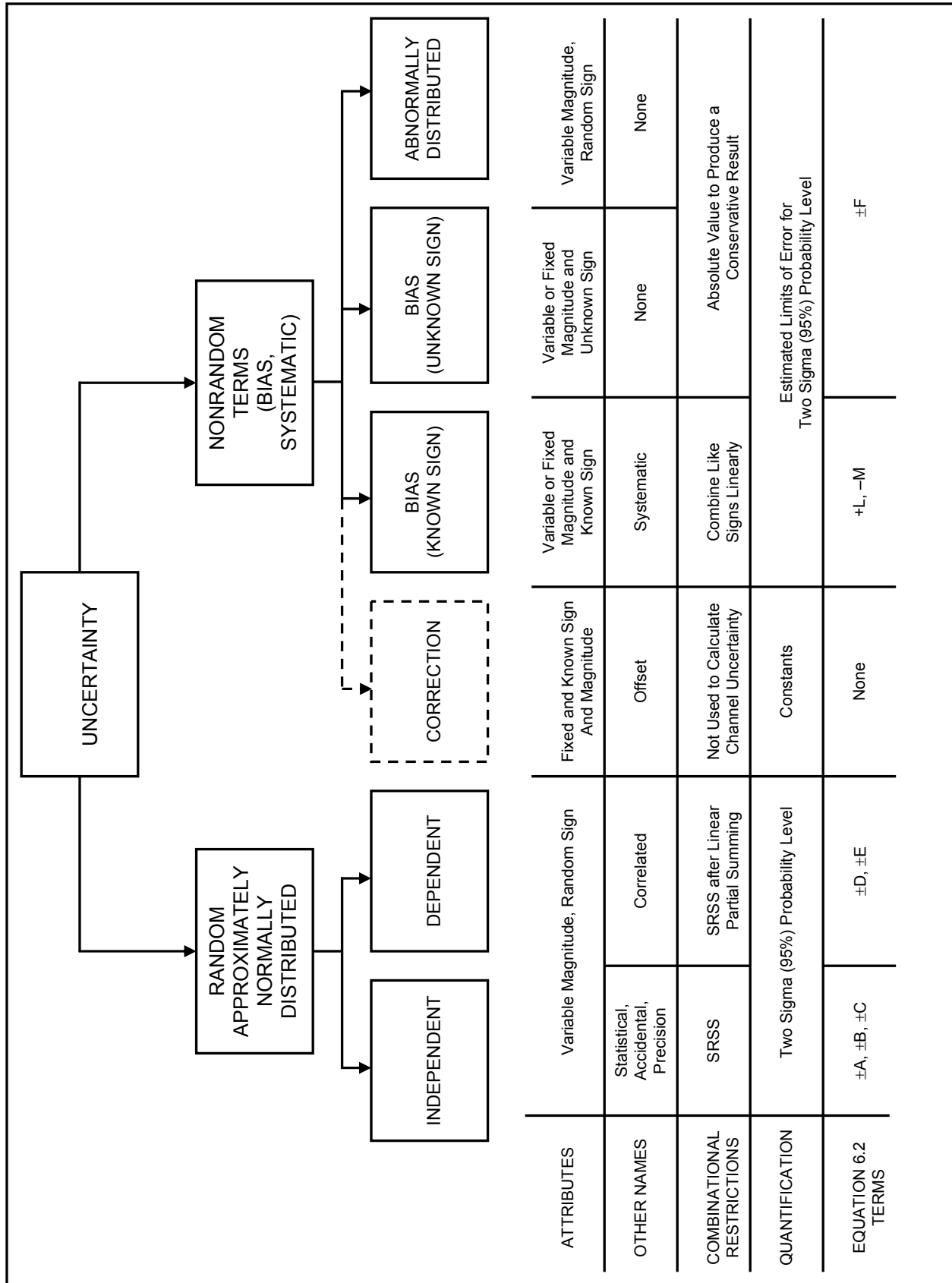


Figure 3 — Uncertainty model

While the basic uncertainty formula can be used for any instrumentation application, care should be taken when applying the formula in applications containing nonlinear modules or functions. While the term can still be random and independent, its magnitude is a function of the input and the transfer function of the module. This requires the calculation of uncertainty for instrument channels containing nonlinear modules to be performed for specific values of the input signal.

The most common of these in instrumentation and control systems is the square root extractor in a flow channel. For these channels, the uncertainty value changes with the value of flow; therefore, it should be determined for each specific flow of interest.

The basic uncertainty combination formula can be applied to the determination of either a module uncertainty or a total instrument channel uncertainty. The results are independent of the order of combination as long as the dependent terms and bias terms are accounted for properly. For example, the uncertainty of a module can be determined from its individual terms and then combined with other module uncertainties to provide an instrument channel uncertainty, or all of the individual module terms can be combined in one instrument channel uncertainty formula. The result will be the same. The specific groupings and breakdown of an uncertainty formula can be varied for convenience of understanding.

6.2 Uncertainty data

The basic model used in this methodology requires that the user categorize instrument uncertainties as random, bias, or abnormally distributed bias. Guidelines for combining these categories of uncertainties to determine the module or overall instrument channel uncertainty are provided in 6.3. It is the purpose of this section to provide an understanding of categories of instrument uncertainty and some insight into the process of categorizing instrumentation based on performance specifications, test reports, and the utility's own calibration data.

The determination of uncertainty estimates is an iterative process that requires the development of assumptions and, where possible, verification of assumptions based on actual data. Ultimately, the user is responsible for defending the assumptions that affect the basis of the uncertainty estimates.

It should not be assumed that, since this methodology addresses three categories of uncertainty, all three should be used in each uncertainty determination. Additionally, it should not be assumed that instrument characteristics should fit neatly into a single category. Data may require, for example, that an instrument's static pressure effect be represented as a random uncertainty with an associated bias (random error not zero centered).

6.2.1 Categories of uncertainty

6.2.1.1 Random uncertainties

In ANSI/ISA-51.1-1979, random uncertainties are referred to as a quantitative statement of the reliability of a single measurement or of a parameter, such as the arithmetic mean value, determined from a number of random trial measurements. This is often called the statistical uncertainty and is one of the so-called precision indices. The most commonly used indices, usually in reference to the reliability of the mean, are the standard deviation, the standard error (also called the standard deviation of the mean), and the probable error.

It is usually expected that those instrument uncertainties a manufacturer specifies as having a $\pm$ magnitude are random uncertainties. However, the uncertainty must be zero-centered and approximately normally distributed to be considered random. The hazards of assuming the $\pm$ in vendor data implies that the instrument's performance represents a normal statistical distribution

are addressed in 6.2.12. After uncertainties have been categorized as random, any dependencies between the random uncertainties should be identified.

6.2.1.1.1 Independent uncertainties

Independent uncertainties are those uncertainties for which no common root cause exists. It is generally accepted that most instrument channel uncertainties are independent of each other.

6.2.1.1.2 Dependent uncertainties

Because of the complicated relationships that may exist between the instrument channels and various instrument uncertainties, a dependency may exist between some uncertainties. The methodology presented here provides a conservative means for addressing these dependencies. If, in the user's evaluation, two or more uncertainties are believed to be dependent, then, under this methodology, these uncertainties should be added arithmetically to create a new, larger independent uncertainty.

Dependent uncertainties are those for which the user knows or suspects that a common root cause exists that influences two or more of the uncertainties with a known relationship.

6.2.1.2 Nonrandom uncertainties

6.2.1.2.1 Bias (known sign)

A bias is a systematic instrument uncertainty that is predictable for a given set of conditions because of the existence of a known direction (positive or negative).

For example, the static pressure effect of differential pressure transmitters, which exhibits a predictable zero shift because of changes in static pressure, is considered a bias. Additional examples of bias include head effects, range offsets, reference leg heatup or flashing, and changes in flow element differential pressure because of process temperature changes. A bias error may have an uncertainty associated with the magnitude.

6.2.1.2.2 Abnormally distributed uncertainties

Some uncertainties are not normally distributed. Such uncertainties are not eligible for SRSS combinations and are categorized as abnormally distributed uncertainties. Such uncertainties may be random (equally likely to be positive or negative with respect to some value), but extremely non-normal.

This type of uncertainty is treated as a bias against both the positive and negative components of a module's uncertainty. Refer to Annex J on the use of the central limit theorem. Because they are equally likely to have a positive or a negative deviation, worst-case treatment should be used.

6.2.1.2.3 Bias (unknown sign)

Some bias effects may not have a known sign. Their unpredictable sign should be conservatively treated by arithmetically adding the bias in the worse direction.

6.2.1.2.4 Correction

Errors or offsets that are of a known direction and magnitude should be corrected for in the calibration of the module and do not need to be included in the setpoint calculation. (See also 6.2.6.4.)

6.2.2 Module temperature effects

Most instruments exhibit a change in output as the ambient temperature to which they are exposed varies during normal plant operation above or below the temperature at which they were last calibrated. As this change or temperature effect is an uncertainty, it should be accounted for in instrument uncertainty calculations. To estimate the magnitude of the effect, the operating temperature (OT) extremes above or below the calibration temperature (CT) should be defined. Many times these temperatures should be assumed, based on conservative insight or guidance, if documented operating experience or design-basis room temperature calculations are not available. For example, it would be conservative to assume the maximum OT coincident with the minimum CT to maximize the temperature shift.

Once the temperatures are defined, the temperature effect (TE) uncertainty for each module can be calculated using the manufacturer's published temperature effect specification. Commonly, the temperature effect is stated in vendor literature in one of the following two ways (expression in parentheses is an example). In each expression the temperature component (i.e., per 100°F) is a change in temperature within the vendor's specified range.

Either

- a) $TE = \pm X\% \text{ span per } Y^{\circ}\text{F}$
(for example, $\pm 1.0\% \text{ span per } 100^{\circ}\text{F}$)

or

- b) $TE = \pm X_1\% \text{ span at minimum span per } Y^{\circ}\text{F}$
(for example, $\pm 5.0\% \text{ span at minimum span per } 100^{\circ}\text{F}$)

and

$$TE = \pm X_2 \text{ } Y\% \text{ span at maximum span per } Y^{\circ}\text{F}$$

(for example, $\pm 1.0\% \text{ span at maximum span per } 100^{\circ}\text{F}$)

If the temperature effect cannot be approximated by a linear relationship with temperature, a conservative approach is to use the bounding value for a temperature shift less than $Y^{\circ}\text{F}$. If the relationship is linear, then the uncertainty can be calculated as shown below. For the TE as expressed in (a),

$$(\text{Eq. 6.3}) \quad TE = \pm X\% (\Delta T)/Y$$

where

$$\Delta T = OT_{\max} - CT \text{ or } \Delta T = CT - OT_{\min}, \text{ whichever is greater.}$$

For example, using Equation 6.3 and the example value of TE of (a) above, if OT varies from 50°F to 120°F and CT = 70°F,

$$\begin{aligned} \text{TE} &= \pm (1.0\%) (120 - 70)/100 \\ &= \pm 0.5\% \text{ span} \end{aligned}$$

Note that in the example above, the maximum operating temperature that the module will see (120°F) is a conservative value.

or (b), the uncertainty is not only temperature-dependent but span-dependent as well. To find the temperature effect for the span of interest, assuming the temperature effect is a linear function of span and temperature, it is necessary to interpolate using the following expression:

$$\text{(Eq. 6.4)} \quad \frac{X - X_1}{X_2 - X_1} = \frac{(\text{Span} - \text{Min Span})}{(\text{Max Span} - \text{Min Span})}$$

Solving Equation 6.4 for X,

$$\text{(Eq. 6.5)} \quad X = \frac{(\text{Span} - \text{Min Span})}{(\text{Max Span} - \text{Min Span})} (X_2 - X_1) + X_1$$

If, for example, the span is 55 psi for a transmitter with an adjustable span range of 10-100 psi, the uncertainty in (b) for the same temperature conditions assumed in the previous example can be calculated using Equation 6.5 and then Equation 6.3 as follows. In this case, however, X_1 and X_2 should be converted to process units so that units are the same.

$$\begin{aligned} X_1 &= (\pm 5.0\% \text{ span per } 100^\circ\text{F})(10 \text{ psi/span}) \\ &= \pm 0.5 \text{ psi per } 100^\circ\text{F} \end{aligned}$$

$$\begin{aligned} X_2 &= (\pm 1.0\% \text{ span per } 100^\circ\text{F})(100 \text{ psi/span}) \\ &= \pm 1.0 \text{ psi per } 100^\circ\text{F} \end{aligned}$$

$$X = \frac{(55 - 10)(1.0 - 0.5)}{(100 - 10)} + 0.5$$

$$= \frac{(45)(0.5)}{90} + 0.5$$

$$= \pm 0.75 \text{ psi per } 100^\circ\text{F}$$

$$\begin{aligned} \text{TE} &= (0.75)(120 - 70)/100 \\ &= \pm 0.375 \text{ psi} \end{aligned}$$

Or in percent span

$$\begin{aligned} \text{TE} &= \pm 0.375 \text{ psi}/55 \text{ psi} \times 100\% \\ &= \pm 0.68\% \text{ span.} \end{aligned}$$

This section dealt with module ambient temperature influence under normal conditions. Accident effects and ambient-induced process uncertainties (such as reference leg heatup) are discussed in 6.2.4 and Annex B. If the particular instrument exhibits uncertainties under varying process temperatures, a range of expected process temperatures needs to be included as an assumption and the actual uncertainty calculated.

6.2.3 Module pressure effects

Some devices exhibit a change in output because of changes in process or ambient pressure. A typical static pressure effect expression applicable to a differential pressure transmitter, where the listed pressure specification is the change in process pressure, may look like

$\pm 0.5\%$ span per 1000 psi within the vendor's specified range.

This effect can occur when an instrument measuring differential pressure (dP) is calibrated at low-static pressure conditions but operated at high-static pressure conditions. The manufacturer gives instructions for calibrating the instrument to read correctly at the normal expected operating pressure, assuming calibration was performed at low-static pressure. This normally involves offsetting the span and zero adjustments by a manufacturer-supplied correction factor at the low-pressure (calibration) conditions so that the instrument will output the desired signal at the high-pressure (operating) conditions. To calculate the static pressure effect uncertainty (SP), an operating pressure (OP) for which the unit was calibrated to read correctly and a pressure variation (PV) above or below the OP should be determined. Once these points are defined, an expression similar to Equation 6.3 can be used to calculate the static pressure effect (assuming the effect is linear). Normally, the manufacturer lists separate span and zero effects.

A caution needs to be discussed concerning proper use of this uncertainty in calculations. The effect shown above is random. However, additional bias effects may need to be included due to the way the static pressure calibration correction is done. For example, some instruments read low at high-static pressure conditions. If they have not been corrected for static pressure effects, a negative bias would need to be included in the uncertainty calculation.

Another effect related to pressure extremes is the overpressure effect. This uncertainty is due to over-ranging the pressure sensor.

Ambient pressure variations will cause gage pressure instruments to shift upscale or downscale depending on whether the ambient pressure at the instrument location decreases or increases without a related change in the measured (process) variable. This occurs if the reference side of the process instrument is open to ambient pressure and the process is a closed system or if the process is open to atmosphere in an area with a different ambient pressure. This effect is a bias. The magnitude and direction will depend upon the variations in atmospheric pressure at the instrument location. This may be a concern for gage pressure instruments in enclosed areas such as reactor containment or containment enclosures.

6.2.4 Environmental effects - accident

For accident conditions, additional uncertainties associated with the high temperature, pressure, humidity, and radiation environment, along with the seismic response, may be included in the instrument uncertainty calculations as required.

Qualification reports for safety-related instruments normally contain tables, graphs, or both of accuracy before, during, and after radiation and steam/pressure environmental and seismic testing. Many times, manufacturers summarize the results of the qualification testing in their

product specification sheets. More detailed information is normally available in the equipment qualification report.

Because of the limited sample size typically used in qualification testing, the conservative approach to assigning uncertainty limits is to use the worst-case uncertainties. Discussions with the vendor may be helpful to gain insight into the behavior of the uncertainty (i.e., should it be considered random, bias, or abnormally distributed).

Using data from the qualification report (or module-specific temperature compensation data) in place of design performance specifications, it is often possible to justify the use of lower uncertainty values that may occur at reduced temperature or radiation dose levels. Typically, qualification tests are conducted at the upper extremes of simulated DBE environments so that the results apply to as many plants as possible, each with different requirements. Therefore, it is not always practical or necessary to use the results at the bounding environmental extremes when the actual requirements are not as limiting. Some cautions are needed, however, to preclude possible misapplication of the data.

- a) In the absence of a statistically valid sample size, the highest uncertainties of the units tested at the reduced temperature or dose should be used. This is to ensure that bounding uncertainties are used in the absence of a statistically valid sample size. When extrapolating test data to lower-than-tested environmental data, a margin may need to be applied. Again, discussions with the vendor may provide helpful insight for performing these extrapolations.
- b) The units tested should have been tested under identical or equivalent conditions and test sequences.
- c) If a reduced temperature is used, ensure that sufficient "soak time" existed prior to the readings at that temperature to ensure sufficient thermal equilibrium was reached within the instrument case. In other words, if a transmitter case takes one minute to reach thermal equilibrium, ensure that the transmitter was held at the reduced temperature at least one minute prior to taking readings.

Finally, it is sometimes possible to delete or reduce accident uncertainties from calculations based on the timing of the actuation function. For example, accident effects would not have to be considered for a primary reactor trip on low-reactor coolant pressure if the trip function is credited for the design-basis, large-break, loss-of-coolant accident (LOCA) only. This is true because the trip signal occurs very rapidly during the large immediate pressure decrease. Therefore, the trip function will be accomplished before the environment becomes harsh enough to begin to affect equipment performance significantly or affect the analysis results. Care should be taken in using this technique. Specifically, the user must verify that the most limiting conditions for all of the applicable safety analyses are used.

6.2.5 Process measurement effects (PM)

Another source of instrument channel uncertainty that is not directly caused by equipment is process measurement effects. These are uncertainties induced by the physical characteristics or properties of the process that is being measured. The decisions related to classifying process measurement uncertainties as random or bias should follow the guidance presented in 6.2.1.

Several types of process uncertainties may be encountered in instrumentation design. A few of the most common process uncertainty terms are discussed in the appendices. The applicability of all possible process measurement effects should be considered when preparing uncertainty calculations.

6.2.6 Calibration uncertainty (CU)

Calibration is performed to verify that equipment performs to its specifications and, to the extent possible, to eliminate bias uncertainties associated with installation and service; for example, head effects and density compensations. Calibration uncertainty refers to the uncertainties

introduced into the instrument channel during the calibration process. This includes uncertainties introduced by test equipment, procedures, and personnel.

This section deals only with calibration uncertainties and how they should be included in the total instrument channel uncertainty calculation. However, other effects, such as installation effects (if the instrument is removed from the field for calibration and then reinstalled), should be accounted for. Also, this recommended practice assumes that the calibration of a module is performed at approximately the same temperature, whether in situ or remote, so that temperature effects between calibrations are minimized.

6.2.6.1 Measuring and test equipment (M&TE) uncertainty

Several effects should be considered in establishing the overall magnitude of the M&TE uncertainty. These include the reference accuracy of the M&TE, the uncertainty associated with the calibration of the M&TE, and the readability of the M&TE by the technician. Frequently, a standard M&TE uncertainty (such as $\pm 0.5\%$) is assumed. This approach is acceptable provided care is taken to ensure the M&TE is bounded by the standard number.

The reference accuracy (RA) of the M&TE is generally available from the M&TE vendor. Note that the RA may be different for different scales on the M&TE.

M&TE should be periodically calibrated to controlled standards to maintain its accuracy. Typically, the RA of these standards is such that there is an insignificant effect on the overall channel uncertainty. However, if a standard does not meet the guidelines of IEEE Standard 498 (i.e., 4 to 1 better than the M&TE), this effect may need to be evaluated. If the RA of the standard is included in the uncertainty calculation, it may be combined with the RA of the M&TE using the SRSS techniques to establish a single value for the uncertainty of that piece of M&TE.

For example,

$$(Eq. 6.6) \quad MTE = (RA_{MTE}^2 + RA_{STD}^2)^{1/2}$$

where

MTE = uncertainty of the M&TE

RA_{MTE} = reference accuracy of the M&TE

RA_{STD} = reference accuracy of the controlled standard

The technician performing an instrument calibration (or the periodic calibration of M&TE) introduces additional uncertainty into the instrument loop. This uncertainty is introduced from reading the instruments used in the calibration process. If the piece of M&TE has an analog scale, in addition to the movement uncertainty, the specific use of the scale should be considered to assess the uncertainty. If the calibration process is arranged such that the scale divisions are always used and there is no parallax, it is reasonable to assume no technician uncertainty since the pointer can be easily aligned with the fixed markings. If the points to be read lie between divisions, it is reasonable to assign an uncertainty. This turns into a judgment call on the part of the preparer. For example, if the scale spacing is "wide," $\pm 20\%$ of the difference between divisions could be assigned to the technician's uncertainty. Where the divisions are more closely spaced, $\pm 50\%$ of the difference may be a better choice.

As before, any uncertainty assigned because of uncertainties in reading during the calibration process should be converted to the appropriate units and combined with the M&TE uncertainty to obtain a more correct representation of the calibration process uncertainty. SRSS techniques may be used.

For example,

$$(Eq. 6.7) \quad MTE = (RA_{MTE}^2 + RD^2)^{1/2}$$

where

RD = reading uncertainty

If the M&TE has an uncertainty due to the standard used in its calibration and has a reading uncertainty, the uncertainty of the M&TE would be

$$(Eq. 6.8) \quad MTE = (RA_{MTE}^2 + RA_{STD}^2 + RD^2)^{1/2}$$

The same units used to calculate the overall M&TE uncertainty should be used to calculate the instrument channel uncertainty. If the instrument channel uncertainty calculation uses units of percent span, the M&TE uncertainty should be converted to percent span of the instrument channel. For example, if a piece of M&TE has a reference accuracy of 0.025 percent of its span, if its span is 0 to 3,000 psi, and if it is used in an instrument channel with a span of 1,000 psi, the M&TE reference accuracy is

$$(3,000 \text{ psi}) / (1,000 \text{ psi}) \times 0.025\% = 0.075\% \text{ span of the instrument channel.}$$

The M&TE uncertainty for a module should include the uncertainty of both the input and the output test equipment. Typically, both the input and output calibration test equipment are considered independent. These individual uncertainties may be combined by the SRSS method to establish the overall M&TE uncertainty.

For example, using the diagram of Figure 4, the sensor M&TE uncertainty (SMTE) may be calculated as follows:

$$(Eq. 6.9) \quad SMTE = [(MTE_1)^2 + (MTE_2)^2]^{1/2}$$

where

MTE₁ = the uncertainty associated with the sensor input test equipment (M&TE labeled Number 1 in Figure 4)

and

MTE₂ = the uncertainty associated with the sensor output test equipment (M&TE labeled Number 2 in Figure 4).³

³ The module transfer function is assumed to be linear. Refer to 6.3.1 for the treatment of nonlinear modules.

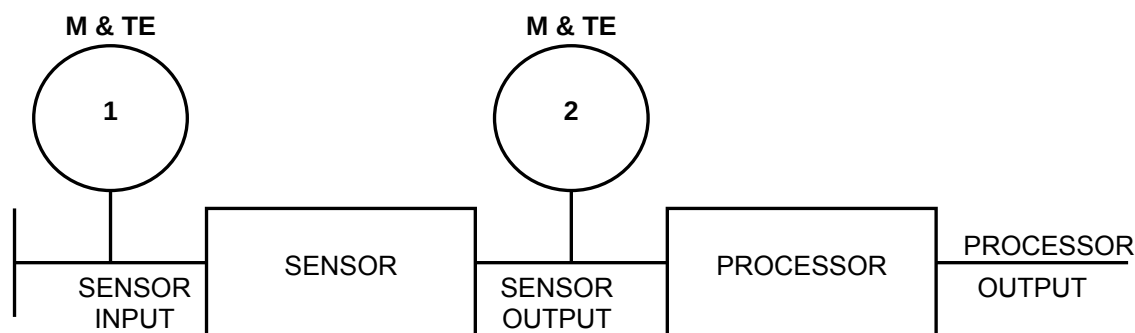


Figure 4 - Combining measuring and test equipment uncertainty

If the overall uncertainty of the M&TE used in a calibration of a module is less than 1/10th of the reference accuracy of the module being tested, the uncertainty associated with the M&TE is negligible and may be disregarded.⁴

For example, if the reference accuracy of a sensor is ± 0.5 percent of span, the overall accuracy of the M&TE may be disregarded if it is better than $+0.05$ percent of the sensor span. If the M&TE is not that accurate, the uncertainty should be taken into account.

M&TE uncertainty should be considered for each separate calibration in an instrument channel. If an entire instrument channel is calibrated at one time, sometimes called a "string calibration," only one M&TE uncertainty value need be included. However, if each individual module in an instrument channel is calibrated separately without a channel verification, an M&TE uncertainty should be associated with each module.

The M&TE uncertainties used in the calculation should consider the M&TE module reference accuracy, the M&TE calibration standard, uncertainties associated with reading the M&TE, and any additional uncertainties introduced during the calibration process. The values should be consistent with the uncertainties associated with the actual M&TE specified in the calibration procedure. This is to allow the technicians performing instrument calibrations to remain within the assumptions of the setpoint uncertainty calculation. In practice, this may mean specifying in the procedures and in the calculation the specific model of test equipment to be used and the scale on which the test equipment is to be read. An alternative to this would be to establish a bounding reference accuracy for the M&TE in the calibration procedure and then establish a bounding assumption with appropriate justification for the M&TE uncertainty in the setpoint uncertainty calculation.

6.2.6.2 Calibration tolerance

Calibration tolerance is the acceptable parameter variation limits above or below the desired output for a given input standard associated with the calibration of the instrument channel. Typically, this is referred to as the setting tolerance of the width of the "as-left" band adjacent to the desired response. It is recommended that a band rather than a single value should be

⁴ This recommended practice does not establish accuracy requirements for M&TE. This discussion simply identifies an accuracy for M&TE that is mathematically insignificant.

specified in the calibration procedure. This may be a symmetrical band about a setpoint (e.g., $109\% \pm 1\%$), or in some cases, an asymmetrical band about a setpoint (e.g., $110\% +0\%, -2\%$). This calibration tolerance is usually based on the reference accuracy of the module being calibrated. However, individual plant calibration philosophies may specify a smaller or larger calibration tolerance. The size of the calibration tolerance should be established based on the reference accuracy of the module, the limitations of the technician in adjusting the module, and the need to minimize maintenance time.

Depending on the method of calibration or performance verification, an allowance for the calibration tolerance may need to be included in the setpoint uncertainty calculation. If the method of calibration or performance verification verifies all attributes of reference accuracy,^{5, 6} and the calibration tolerance is less than or equal to the reference accuracy, then the calibration tolerance does not need to be included in the total instrument channel uncertainty. In this case, the calibration or performance verification has explicitly verified the instrument channel performance to be within the allowance for the instrument channel's reference accuracy in the setpoint uncertainty calculation. If the method of calibration or performance monitoring verifies all attributes of the reference accuracy, and the calibration tolerance is larger than the reference accuracy, the larger value for the calibration tolerance may be substituted for the reference accuracy in the setpoint uncertainty calculation as opposed to inclusion of the calibration tolerance as a separate term. For example, if the vendor's stated reference accuracy for a particular module is 0.25%, but the calibration tolerance used in the procedure is 0.5%, the value of 0.5% may be used for the reference accuracy of the module in the setpoint uncertainty calculation with no additional allowance for calibration tolerance. In these cases, the calibration tolerance is simply the term used to represent reference accuracy in the test's performance, and it does not represent a separate uncertainty term in the setpoint uncertainty calculation.

If the method of calibration or performance verification does not verify all attributes of the reference accuracy, the potential exists to introduce an offset in the instrument channel's performance characteristics that is not identified in the calibration or performance verification of the instrument channel. Usually, the offset is very small; however, the upper limit would be the calibration tolerance. In this case, the reference accuracy and calibration tolerance are separate terms, and, therefore, both should be accounted for in the setpoint uncertainty calculation. Several methods are possible to account for the combination of reference and calibration tolerance. The following discussion provides some examples of these methods but is not intended to be all-inclusive.

One bounding method is to account for not verifying all attributes of reference accuracy by the calibration or performance verification by including allowances for both in the setpoint uncertainty calculation as explicit terms.

Another method is to establish a calibration tolerance that is less than the reference accuracy. If the difference between calibration tolerance and reference accuracy accounts for the uncertainty of the various attributes that are not verified during calibration or performance verification, only reference accuracy would be included in the setpoint uncertainty calculation.

The third method is to include a specific allowance in the setpoint uncertainty calculation for the attributes of reference accuracy that are not verified in the calibration or performance verification. For example, if the calibration or performance verification does not exercise an instrument channel more than once to demonstrate repeatability, it may be appropriate to include

⁵ Reference accuracy is typically assumed to have four attributes: linearity, hysteresis, dead band, and repeatability.

⁶ ANSI/ISA–51.1 indicates that an instrument channel should be exercised up and down a number of times to verify reference accuracy.

an allowance for repeatability in the setpoint uncertainty calculation. If a channel performs functions in both the increasing and decreasing directions, and the calibration or performance verification does not check the accuracy in both directions, it may be appropriate to provide an allowance for hysteresis in the setpoint uncertainty calculation. If the calibration or performance verification does not check accuracy in the area of the trip functions, it may be appropriate to provide an allowance for linearity in the setpoint uncertainty calculation.

6.2.6.3 As-found/as-left calibration values

During calibration of a module, as-found and as-left data are typically obtained and recorded. If possible, the as-found data shall be taken without previously exercising the module, thereby providing a better indication of how the module would have performed if called upon by changes in the process. The difference between the as-found data of the current calibration and the as-left data from the previous calibration represents the net effects of several uncertainties, including the repeatability (reference accuracy) and drift of the module over the calibration interval. If the ambient temperature in the area of the module was not the same for the two calibrations, part of the difference between the as-found and as-left data may be due to temperature effects. As-found and as-left data may be analyzed to estimate a value for drift for the module, recognizing that variations in environmental conditions and other uncertainties may be present at the time of the calibration and, if appropriate, accounted for when analyzing as-found and as-left data.

Nominal values and generic module performance data may be used for calculating module uncertainties to establish setpoints for initial plant operation. These nominal values should be refined after sufficient operating experiences and plant-specific data are available. Plant-specific data are more representative of each module's performance within its unique installation and application characteristics and should be used to calculate module drift uncertainties. Reducing module drift uncertainties identifies performance expectations and allows one to revise setpoints to provide increased margin between the setpoint and expected process conditions during normal plant operating conditions. However, care should be taken to ensure that the use of plant-specific data is based on generally accepted statistical principles since limited sample sets may not be representative.

6.2.6.4 Calibration corrections

Frequently, calibration procedures include corrections to account for the difference in instrument performance or readings between calibration conditions and normal operating conditions, such as static pressure and head pressure corrections. If these corrections have been made, the setpoint uncertainty calculation does not need to include them (however, the uncertainty of these corrections should be included). The fact that these corrections are made during calibration should be identified in the setpoint uncertainty calculation.

6.2.7 Drift

If all known effects are accounted for and eliminated, the output of instrumentation still changes over time. These remaining effects are collectively described as “drift” or “stability”. Vendors typically specify some amount of drift as a value for a given time period, such as “1% span per six months.” These values are typically based on the results of long-term monitoring of samples of the instrumentation.

In most applications, the drift value provided by the vendor must be adjusted to cover the time interval of interest. This time interval should be the limiting case time between calibrations, which often includes both the nominal time and some grace period used by maintenance planning. For example, if the calibration interval is 18 months with a 25% grace period, the drift should be adjusted to account for at least a 22.5-month interval.

Evidence to date indicates that not all drift is linear with time; that is, the drift may happen at the beginning of the interval, in the middle, or at the end. Therefore, unless there is data supporting linear drift, it is inappropriate to adjust the drift value downward for a smaller time interval than specified by the vendor. Continuing the example above, if the vendor stated “1% span per six months” and you want to have a drift value for three months, the 1% value should be used.

It is always conservative to adjust the drift value upward to cover enough time periods to envelop the time interval of interest. Again continuing the above example, even increments of the vendor specified drift should be used. Therefore, for a 22.5-month test interval, four six-month periods of vendor-specified drift would be applicable. Thus, a conservative drift value would be $4 \times 1\% = 4\%$ in 24 months.

However, industry experience has shown that this is a very conservative estimate of drift. A more realistic estimate can be made by combining enough time periods to envelop the time interval of interest using an SRSS technique. This assumes that the drift term is random and sufficiently independent for each specified interval. For the example, this more realistic drift would be the SRSS of four six-month drifts, or $\text{SRSS}(1\%, 1\%, 1\%, 1\%) = 2\%$ in 24 months.

If more realistic data on actual changes in instrumentation accuracy over time are desired, it can be determined by analysis of plant as-found and as-left data; see Annex E for the development of such techniques.

When using any method for the extrapolation of drift, it should be listed as an assumption in the uncertainty calculation with justification provided.

6.2.8 Module power supply variations

Most electronic instruments exhibit a change in output because of variations in power supply voltage. A typical manufacturer's specifications may read

$\pm 0.01\%$ span per volt variation.

To calculate the uncertainty associated with the power supply (PS) effect, a normal operating voltage (OV) and voltage variation (VV) should be determined. Once these points are defined, if the effect is linear, an expression similar to equation 6.3 can be used to calculate the uncertainty associated with the power supply effect. Typically, this uncertainty is very small in comparison to other instrument channel uncertainties.

6.2.9 Additional considerations for digital signal processing

In channels using digital processing equipment, uncertainties are introduced by hardware for conversions between analog and digital domains and by the algorithms for digital arithmetic operations. Values for analog-to-digital (A/D) and digital-to-analog (D/A) conversion uncertainties may be obtained from the module manufacturers or through testing. Sources of uncertainty may include: precision of computation, rounding or truncation uncertainties, process variable changes during the deadband between data acquisition sampling scans, and inaccuracies of algorithms for transcendental functions or empirical curve fitting. The nature of the uncertainties contributed by the software (that is, whether they are statistical or arithmetic) should be identified by the software designer. When the uncertainties are characterized and quantified, they can be combined with propagated uncertainties by the methods described in 6.3. Further discussion is provided in Annex H.

6.2.10 Insulation resistance effects

Under the conditions of high humidity and temperature associated with high-energy line breaks (HELB), cables, splices, connectors, terminal blocks, and penetrations experience a reduction in insulation resistance (IR). Reduction in IR causes an increase in leakage currents between conductors and from individual conductors to ground. Leakage currents are negligibly small under normal conditions. These currents are essentially calibrated out during instrument channel calibrations. However, under the HELB event, the leakage currents may increase to a level that causes significant error in measurement. The effect is particularly a concern for sensitive, low-signal-level circuits, such as current transmitters, RTDs, and thermocouples. For a more detailed discussion on determining the IR effect, see Annex D.

6.2.11 Sources of uncertainty data

The most reliable method of developing and substantiating uncertainty data is to perform controlled tests on the devices that impose the conditions that have the potential to cause uncertainties in the device, or to analyze the performance data gained from operation and maintenance of the equipment. This method has been widely applied to determine the uncertainties due to extreme temperature, pressure, and radiation levels. The allowances derived from the test should consider the ability of the test to replicate the conditions and the accuracy and thoroughness of the test as discussed in 6.2.4.

A more common source of data is from the instrument supplier. Performance specifications should be provided by instrument or reactor vendors. Data should include reference accuracy, drift (stability), environmental effects, and reference conditions. Since performance specifications often describe a product line, any single instrument may perform significantly better than the group specification. Performance specifications may be obtained through the review of published information or through communication with the vendor. Test data may or may not be available to support the performance specifications since this data is generally applied to conditions under which the device routinely operates. Therefore, the performance specifications may have been informally validated through the use and maintenance of the equipment.

If performance summary data are not available, or if it does not satisfy the needs of the users, raw test data may need to be reevaluated or created from additional testing.

Occasionally, the situation arises when the data necessary for a setpoint calculation are not readily available; that is, test results or vendor literature do not exist. Several approaches may be taken in these cases. If possible, it is usually best to obtain a recommendation from the manufacturer or other utility/customer based on its experience with the instrumentation. Another approach might include performing circuit analysis of electronic circuits and/or using data associated with an instrument with similar principles of operation, made by another manufacturer. In some cases there may be no prudent alternative but the common practice of using engineering judgment in lieu of vendor literature or test data. The use of engineering judgment in these cases must be tempered by the importance of the setpoint, which can be defined in a graded-approach setpoint program. With any of these approaches, it is appropriate to apply some conservatism to the uncertainty values and to provide written justification for the values utilized.

6.2.12 Interpretation of uncertainty data

The proper interpretation of uncertainty information is necessary to ensure the validity of the setpoint calculation. Historically, there have been many different methods of representing numerical uncertainty. Almost all suffer from the ambiguity associated with shorthand notation. The symbol $\pm$, for example, without further explanation, is often interpreted as the symmetric probability interval associated with a random, normally distributed uncertainty. Further, the

probability level may represent 50% (probable error), 68.27% (one sigma), 95.45% (two sigma), or 99.73% (three sigma). Still others may assume that the $\pm$ symbol defines the limits of error (reasonable bounds) of bias or non-normally distributed uncertainties. Discussions with the vendor may provide helpful insight for interpreting performance specifications or test results.

It is the user's responsibility to avoid improper use of the vendor performance data. If a vendor-published value of an uncertainty term (source) is believed to contain a significant bias uncertainty, then the $\pm$ value should be treated as an estimated limit of error. Simple field tests (repeated measurement) by the user can give an indication of the random component of the published value, if separation of components is desirable. If based on engineering judgment, the term is believed to represent only random uncertainties (no significant bias uncertainties), then the $\pm$ value may be treated as a value suitable for inclusion in the SRSS combination.

One source of performance data that requires careful interpretation is that obtained during harsh environment testing. Often such tests are conducted only to demonstrate functional capability of a particular instrument in a particular harsh environment. This usually requires only a small sample size and invokes inappropriate rejection criteria for a probabilistic determination of instrument uncertainties. This type of data base typically results in limits of error (reasonable bounds) associated with bias or non-normally distributed uncertainties.

The sample size should be considered prior to adjusting the measured net effects for normal environmental uncertainties, reference accuracies, etc. The results of such tests describe several mutually exclusive categories of uncertainty. For example, the results of a severe environment test contain uncertainty contributions from the instrument reference accuracy, M&TE uncertainty, calibration uncertainty, and others, in addition to the severe environment effects. A conservative practice is to treat the measured net effects as only uncertainty contributions due to the harsh environment.

Occasionally, select test data may appear inconsistent with the majority of the test data collected. In this situation it may be possible to justify the inconsistent data as outliers. Analytical techniques for this purpose are discussed in ANSI N15.15, ANSI/ASME PTC 19.1, and ANSI/ASTM E 178. Annex J provides further discussion on statistical analysis.

6.3 Calculating total channel uncertainty

The calculation of an instrument channel uncertainty should be done in a clear, straightforward process. The actual calculation can be done with a single-loop equation that contains all potential uncertainty values or by a series of related term equations. Either way, a specific instrument channel calculation should be laid out to coincide with a channel's layout from process measurement to final output module or modules.

The actual technique and layout of the calculation are influenced by the type of instrument channel being analyzed. While many channels can be analyzed using the basic formulas defined in 6.1, channels that contain modules with transfer functions, such as an amplifier, summer, square root extractor, etc., require special consideration. This is due to the effect the transfer function can have on the incoming signal and its associated uncertainty. The module's transfer function will act on both the true signal and its uncertainty to develop an output. Thus, the uncertainty within a signal may be increased or decreased by a module's transfer function, with respect to the true signal.

A detailed look at the propagation of uncertainty through functional modules is provided in 6.3.1. Both the equations developed using the techniques of 6.3.1 and the basic equations of 6.1 must be used to analyze a channel's uncertainty. A discussion on the application of the basic statistical equations for an instrument channel that does not contain modules with transfer

functions is provided in 6.3.2, while 6.3.3 provides a discussion on the application of the uncertainty propagation equations.

6.3.1 Equations for the propagation of uncertainties through functional modules

If signal conditioning modules, such as scalars, amplifiers, summers, square root extractors, multipliers, etc., are used in the instrument channel, the module's transfer function should be accounted for in the instrument setpoint/uncertainty calculation. The uncertainty of a signal conditioning module's output can be determined when the uncertainty of the input signal and the uncertainty associated with the module, as well as the module's transfer function, are known. Using partial derivatives or perturbation techniques (refer to Annex K for a detailed discussion of these techniques), equations have been developed to determine the output signal uncertainties for several common types of signal conditioning modules and are presented in Table 1. The equations are applicable to all signal conditioning modules of that type, regardless of the manufacturer.

The attributes of uncertainties such as randomness or independence are discussed in detail in 6.2.1. For simplicity, the equations presented in Table 1 are based on the assumption that the input uncertainties consist of either all random or all bias uncertainties. The user must take care in applying these equations to individual instrument channel uncertainty calculations to ensure that the probability and confidence levels of the data and resulting uncertainty values are maintained. In balancing the requirements of calculation conservatism, probabilities, and operating margins, it may be beneficial to optimize the uncertainty determination by computer simulation techniques. The more general case of uncertainties with both random and bias components is addressed in Annex K.

It is important to note that the method of calibration or testing may directly affect the use of the information presented in this section. If, for example, a group of the modules for a particular instrument channel is always tested and calibrated together, it may be treated as a single module. The uncertainties associated with the output of the group treated as a single module would be equal to or less than the uncertainties calculated by combining the uncertainty of the individual modules.

6.3.2 Application of basic uncertainty propagation equations

For single instrument channels that do not have transfer functions or that have linear transfer functions, the formulas of 6.1 can be used directly to calculate instrument channel uncertainty. The basic formulas may also be applied to multiple signal channels that have linear transfer functions, as long as the transfer functions have a unity gain. The instrument channel equation would take the form:

$$(Eq. 6.10a) \quad CU^+ = + [PM^2 + PE^2 + module_1^2 + module_2^2 + module_n^2]^{1/2} + B_t^+$$

$$(Eq. 6.10b) \quad CU^- = - [PM^2 + PE^2 + module_1^2 + module_2^2 + module_n^2]^{1/2} - B_t^-$$

where

CU = channel uncertainty. The CU is the total uncertainty at a designated point in the channel. The CU can be calculated for any point in a channel from module 1 to module n, as needed.

- PM = process measurement uncertainty. PM accounts for the variation in actual process conditions that influence the measurement, such as temperature stratification, density variations, pressure variations, etc.
- PE = primary element accuracy. PE is the accuracy of a component, piece of equipment, or installation used as a primary element to obtain a given process measurement. The PE includes the accuracy of flow nozzle and/or the accuracy achievable in a specific flow metering run.
- Module_n = total random uncertainty of each module that makes up the loop from module 1 through module n. The modules may include field sensors and transmitters, signal process circuits, and rack-mounted circuits.
- B_t⁺ = total of all positive biases associated with an instrument channel, including any uncertainties from PM, PE, or the modules that could not be combined as a random term (biases and abnormally distributed uncertainties as discussed in 6.1).
- B_t[−] = total of all negative biases associated with an instrument channel, including any uncertainties from PM, PE, or the modules that could not be combined as a random term (biases and abnormally distributed uncertainties as discussed in 6.1).

The individual module random uncertainties are themselves a statistical combination of uncertainties. Depending on the type of module, its location, and the specific factors that can affect its accuracy, the determination of the module uncertainty will vary. For example, the module uncertainty may be calculated as

$$(Eq. 6.11a) \quad e^+ = + [RA^2 + DR^2 + TE^2 + RE^2 + SE^2 + HE^2 + SP^2 + MTE^2]^{1/2} + B^+$$

$$(Eq. 6.11b) \quad e^- = - [RA^2 + DR^2 + TE^2 + RE^2 + SE^2 + HE^2 + SP^2 + MTE^2]^{1/2} - B^-$$

where

- e = uncertainty of module.
- RA = module reference accuracy (usually specified by the manufacturer).
- DR = drift of the module over a specific period.
- TE = temperature effect for the module; the effect of ambient temperature variations on module accuracy; the TE may be a normal operating TE or an accident TE, as required.
- RE = radiation effect for the module; the effect of radiation exposure on module accuracy; the RE may be a normal operating RE, an accident RE, or time-of-trip RE as required.
- SE = seismic effect or vibration effect for the module; the effect of seismic or operational vibration on the module accuracy.
- HE = humidity effect for the module; the effect of changes in ambient humidity on module accuracy, if any.

SP = static pressure effects for the module; the effect of changes in process static pressure on module accuracy.

MTE = measurement and test equipment effect for the module; this accounts for the uncertainties in the equipment utilized for calibration of the module.

B = biases associated with the module, if any.

For the purposes of the previous example, most of the uncertainties have been considered as random and independent. However, the user must determine the actual characteristics of each uncertainty term and combine them based on the criteria discussed in 6.1. Additional terms may have to be included for a particular application. The terms shown are the most common ones encountered for a module.

The individual module uncertainty formulas would contain all appropriate terms for a specific module including any bias terms. The final instrument channel formula bias terms, B^+ and B^- , would be the sum of the individual biases. For example, for the total instrument channel, if PM contained a +3.0%, -0.0% reference leg bias, module 1 contained a $\pm 0.5\%$ calibration abnormally distributed uncertainty, and the instrument channel could experience a +1.0% insulation resistance (IR) degradation effect, then

$$B^+ = B_{PM}^+ + B_{IR}^+ + B_1^+ = 3.0\% + 1.0\% + 0.5\% = + 4.5\%$$

$$B^- = B_1^- = - 0.5\%$$

Table 1 — Equations for propagation of input uncertainties through modules for various mathematical functions

FUNCTION/EQUATION (Notes 1, 2, 3, 4, and 7)

Fixed Gain Amp $C = K * A$

Eq. (6.12)	$e_{C(ALG)} = K * e_{A(B)}$
Eq. (6.13) Note 5	$e_{C(SRSS)} = K * e_{A(R)}$

Summation $C = (K1 * A) + (K2 * B)$

Eq. (6.14)	$e_{C(ALG)} = (K1 * e_{A(B)}) + (K2 * e_{B(B)})$
Eq. (6.15)	$e_{C(SRSS)} = [(K1 * e_{A(R)})^2 + (K2 * e_{B(R)})^2]^{1/2}$

Multiplication $C = (K1 * A) * (K2 * B)$

Eq. (6.16)	$e_{C(ALG)} = (K1 * K2) * [(A * e_{B(B)}) + (B * e_{A(B)}) + (e_{A(B)} * e_{B(B)})]$ $\approx (K1 * K2) * [(A * e_{B(B)}) + (B * e_{A(B)})]$
Eq. (6.17)	$e_{C(SRSS)} = (K1 * K2) * [(A * e_{B(R)})^2 + (B * e_{A(R)})^2 + (e_{A(R)} * e_{B(R)})^2]^{1/2}$ $\approx (K1 * K2) * [(A * e_{B(R)})^2 + (B * e_{A(R)})^2]^{1/2}$

Division $C = (K1 * A) / (K2 * B)$

Eq. (6.18)	$e_{C(ALG)} \approx \frac{K1}{K2} * \left(\frac{(B * e_{A(B)}) - (A * e_{B(B)})}{B^2} \right)$
Eq. (6.19)	$e_{C(SRSS)} \approx \frac{K1}{K2} * \left(\frac{[(B * e_{A(R)})^2 + (A * e_{B(R)})^2]^{1/2}}{B^2} \right)$

Logarithmic Amplification $C = K1 + (K2 * \text{Log } A)$

Eq. (6.20)	$e_{C(\text{ALG})} \approx \left(\frac{K2 * \text{Log}(e)}{A} \right) * e_{A(B)}$
Eq. (6.21) Note 6	$e_{C(\text{SRSS})} \approx \left(\frac{K2 * \text{Log}(e)}{A} \right) * e_{A(R)}$

Squaring $C = A^2$

Eq. (6.22)	$e_{C(\text{ALG})} \quad A = (2A * e_{A(B)}) + (e_{A(B)})^2$ $\text{for } \frac{e_{A(B)}}{A} < 1, \quad e_{C(\text{ALG})} \approx 2(A * e_{A(B)})$
Eq. (6.23) Note 6	$e_{C(\text{SRSS})} \approx 2A * e_{A(R)}$

Multiplication with Division $C = (K * A * B) / D$

Eq. (6.24)	$e_{C(\text{ALG})} \approx K * \left(\left(\frac{B}{D} * e_{A(B)} \right) + \left(\frac{A}{D} * e_{B(B)} \right) - \left(\frac{A * B}{D^2} * e_{D(B)} \right) \right)$
Eq. (6.25)	$e_{C(\text{SRSS})} \approx K * \left(\left(\frac{B}{D} * e_{A(R)} \right)^2 + \left(\frac{A}{D} * e_{B(R)} \right)^2 + \left(\frac{A * B}{D^2} * e_{D(R)} \right)^2 \right)^{1/2}$

Square Root Extraction $C = (A)^{1/2}$

Eq. (6.26)	$e_{C(\text{ALG})} = (A + e_{A(B)})^{1/2} - (A)^{1/2}$ $\text{for } \frac{e_{A(B)}}{A} < 1, \quad e_{C(\text{ALG})} \approx \frac{e_{A(B)}}{2(A)^{1/2}}$
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Eq. (6.27) Note 6	$e_{C(SRSS)} \approx \frac{e_{A(R)}}{2(A)^{1/2}}$
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Square Root with Multiplier C = K * (A * B)^{1/2}

Eq. (6.28)	$e_{C(ALG)} \approx \frac{K}{2} * \frac{(B * e_{A(B)}) + (A * e_{B(B)})}{(A * B)^{1/2}}$
Eq. (6.29)	$e_{C(SRSS)} \approx \frac{K}{2} * \frac{[(B * e_{A(R)})^2 + (A * e_{B(R)})^2]^{1/2}}{(A * B)^{1/2}}$

LEGEND

- A, B, D = input signals (in signal units).
- C = output signals (in signal units).
- e_{A(R)}, e_{B(R)}, e_{D(R)} = random-normal input uncertainties (in signal units).
- e_{A(B)}, e_{B(B)}, e_{D(B)} = bias input uncertainties (in signal units).
- e_{C(ALG)} = algebraic (bias) output uncertainty (in signal units).
- e_{C(SRSS)} = random-normal (or nearly normal) distributed output uncertainty (in signal units).
- K, K1, K2 = arbitrary multipliers of input signals (dimensionless gains or attenuations).

NOTE 1 — The equations in this table describe the propagation of one or more input signal errors through functional modules. Where multiple inputs are involved, the equation also accounts for combination of the input errors. For the derivation of the equations for error propagation through multiple variable functions, see Section 6 of ANSI/ASME PTC 19.1.

NOTE 2 — Equations marked (ALG) must be used for bias errors or for errors with non-normal distributions when the SRSS method would yield non-conservative results.

NOTE 3 — Equations marked (SRSS) may be used when input signal errors are random with a normal distribution. When input signal error distributions are not normal, these equations should not be used unless it can be demonstrated that results are conservative.

NOTE 4 — For single-input functions (e.g., fixed gain amplifier), the SRSS designation means that a normal-input error distribution results in a normal- (or nearly normal) output error that can be combined with other random, normally distributed error terms using the SRSS method.

For multiple-input functions (e.g., multiplier), the SRSS designation means that the output error is calculated using the SRSS method for combining the random, normally distributed input errors, and that output errors with this designation may be combined with other random, normally distributed error terms using the SRSS method.

NOTE 5 — Equation 6.13 is valid for input errors of any magnitude. The output distribution will be the same as the input distribution because the transfer function is linear. The output error can be combined with other normally distributed error terms using the SRSS method.

NOTE 6 — Equations 6.21, 6.23, and 6.27 are valid if input errors are sufficiently small so that the output error distribution is nearly normal. Output errors can then be combined with other normally distributed error terms using the SRSS method.

NOTE 7 — In some cases it may be more convenient to use the relative form of the error propagation equations, that is e_o/C . Since the derivation of these equations is beyond the scope of this recommended practice, refer to ANSI/ASME PTC 19.1 for more information.

An instrument channel calculation should account for the effects of each module in the channel on total uncertainty as well as the external (non-instrument-induced) effects that act on the total uncertainty.

The individual instrument channel module terms would be derived based on the module type. These terms account for both the effect a module has on instrument channel uncertainty due to its own inaccuracies as well as its effect on instrument channel uncertainty due to its manipulation of incoming uncertainty values.

As with any engineering calculation, proper determination and accounting of engineering units is essential. This can become a major stumbling block to an analysis due to the myriad ways uncertainty is specified. The basic formula is not affected by units as long as they are consistent. Either actual process measurement units or a representative unit such as percent span may be used. This document uses percent span as the base unit (except for error propagation which uses the actual signal units to minimize confusion). This affords a universal appeal to the examples and provides for ease of comparison between different types of instrument channels. Specific examples of calculating total instrument channel uncertainty are provided in Annex L.

6.3.3 Application of uncertainty propagation equations for multiple signals or non-linear channels

For channels that contain multiple signals that interact or for channels that contain nonlinear transfer function modules, the instrument channel uncertainty may be calculated using the equations of Table 1. The instrument channel uncertainty calculation uses the equations of 6.1 to combine all uncertainties prior to and downstream of the transfer function module and the equations of Table 1 to determine the uncertainty through the function.

A typical instrument channel calculation for an instrument channel containing a square root module could take the form:

$$a = (PM^2 + PE^2)^{1/2}$$

$$CU^+ = + \left\{ \left[\frac{a}{(2 * A^{1/2})} \right]^2 + \text{module}_1^2 + \text{module}_2^2 + \text{module}_N^2 \right\}^{1/2} + \left[(A + B_i^+)^{1/2} - A^{1/2} \right] + B_{TD}^+$$

$$CU^- = - \left\{ \left[\frac{a}{(2 * A^{1/2})} \right]^2 + \text{module}_1^2 + \text{module}_2^2 + \text{module}_N^2 \right\}^{1/2} - \left[A^{1/2} - (A - B_i^-)^{1/2} \right] - B_{TD}^-$$

where

- PM, PE, & CU = are as defined in 6.3.2.
- module 1 = random uncertainty of the square root module.
- module 2, N = total random uncertainties of each of the remaining modules that make up the loop.
- a = random uncertainty in the input signal entering the square root module (module 1).
- A = magnitude of the input signal to the square root module.
- B_I^+, B_I^- = positive and negative biases associated with the input signal, if any.
- B_{TD}^+, B_{TD}^- = total positive and negative biases associated with the modules downstream of square root module, if any.

In dealing with channels that contain nonlinear transfer functions, the uncertainty value is dependent on the relative magnitude of the input signal. This can be seen in the above equations. With the input uncertainty held constant, the instrument channel uncertainty will increase as the input signal decreases and vice versa. As a result, it is generally advantageous to calculate the uncertainty of loops containing nonlinear modules in terms of specific readings and not percent span. The above square root extractor equation assumes an input magnitude of at least 50 percent. For smaller values, a more rigid equation must be used to maintain the probability and confidence levels of the data. Care must be taken in establishing the proper uncertainty transfer function for nonlinear devices since the nonlinear devices can skew both the probability levels and the confidence levels of the resulting uncertainty value.

One common method used in engineering calculations is to linearize a nonlinear function over a relatively small range of interest. Then errors can be propagated through the device using relatively simple linear techniques. When using this method, care must be taken to account for any modeling uncertainties generated by the linear approximation. One must also ensure that the uncertainty to be propagated is contained in the linearized range.

7 Establishment of setpoints

7.1 Trip setpoint relationships

The requirements for establishing setpoints and the relationships between the nominal trip setpoint, limiting trip setpoint, analytical limit, and safety limit are discussed in ANSI/ISA-67.04.01-2006. A thorough understanding of these terms is important in order to properly utilize the total instrument channel uncertainty in the establishment of setpoints. Figure 5 presents the relative position of the safety limit, analytical limit, limiting trip setpoint, and the nominal trip setpoint with respect to the normal operating point for an increasing process parameter.

Safety limits are established to protect the integrity of physical barriers that guard against the uncontrolled release of radioactivity. The safety limits are typically provided in the plant technical specifications and safety analyses.

The analytical limits are the assumed trip setpoints modeled in the safety analyses. The values are chosen to ensure that the safety limits are not exceeded. The analytical limits are developed with consideration for parameters such as process delays, rod insertion times, reactivity changes, instrument response times, etc. The development of the analytical limit is outside the scope of this recommended practice.

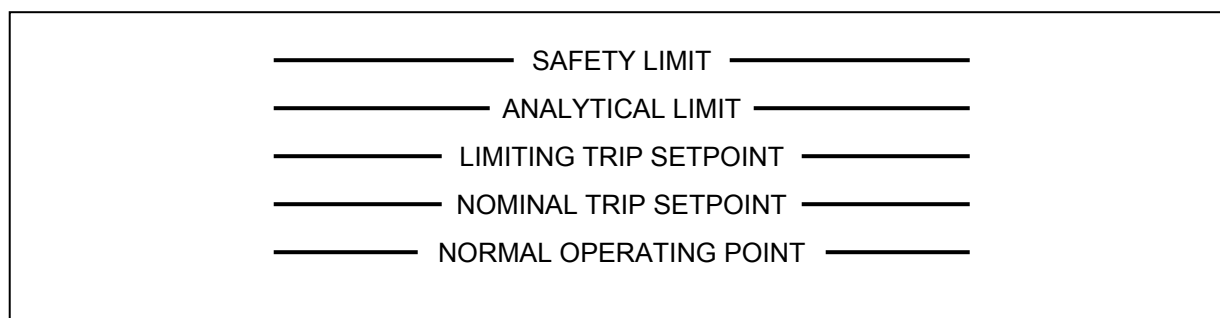


Figure 5 - Setpoint relationships

The nominal trip setpoint is the predetermined value where a final setpoint device changes state. The nominal trip setpoint is derived by scaling calculations and implemented by plant calibration procedures. The limiting trip setpoint is the limiting value for the nominal trip setpoint, and it is established to ensure that an instrument channel trip signal is generated before the analytical limit is reached. The limiting trip setpoint is derived by instrument channel uncertainty calculations that define the total channel uncertainty, including process, environmental, and M&TE effects. The nominal trip setpoint should not result in spurious trips or actuations due to transients that may occur during normal operations.

7.2 Trip setpoint determination

The following section will discuss the methods used to determine limiting trip setpoint (LTSP) and nominal trip setpoint (NTSP). Alternative methods for calculating the NTSP can be used whenever documented justification is provided. The method for calculating the LTSP is by adding or subtracting the instrument channel uncertainties to the analytical limit, dependent upon the conservative direction of the process variable with respect to the analytical limit:

$$\text{(Eq. 7.1) } \text{LTSP} = \text{AL} \pm (\text{CU})$$

$$\text{(Eq. 7.2) } \text{NTSP} = \text{AL} \pm (\text{CU} \pm \text{trip margin})$$