ENCLOSURE B TO NL-04-156

Engineering Standards Manual IES-3B, Revision 0;
Instrument Loop Accuracy and Setpoint Calculation Methodology (IP3)

ENTERGY NUCLEAR OPERATIONS, INC.
INDIAN POINT NUCLEAR GENERATING UNIT NO. 3
DOCKET NO. 50-286

New York Power Authority

IES-3B
Revision 0

ENGINEERING STANDARDS MANUAL

CONTROLLED

COPY # 3/

INSTRUMENT LOOP ACCURACY AND SETPOINT CALCULATION METHODOLOGY (IP3)

■ Full Revision ☐ Limited Revision ☐ Limited Revision

EFFECTIVE DATE:	PERIODIC REVIEW DATE:	
6/1/98	6/1/2003	

APPROVAL	
Responsible Procedure Owner SWPetrosi [signature] 5/6/98 print name_signature_date	Director QA M. [signature] for R.L. PATCH 5-6-98 print name_signature_date

☐ TSR ■ NTSR INFORMATIONAL USE

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IES-3B Revision 0 Implementation Plan

ITEM	Description	Responsibility	ACTS	DUE
1	Approve IES-3B	J. DeRoy	N/A	5/5/98
2	Complete training all affected Personnel (Design Engineering, Contractors, I&C Engineering) who perform Instrument Loop Accuracy and Setpoint Calculations.	S. D'Auria	N/A	5/29/98
3	Instrument Loop Accuracy and Setpoints Calculations completed after 6/1/98 require use of this standard's requirements except as allowed by the transition stipulations identified in item 4 below.	S. D'Auria	N/A	6/1/98
4	Transition to Revision 0 of IES-3B from Revision 1 of IES-3: The methodology and requirements of this revision are to be used on any calculation (Preparation or Revision) started on or after the effective date of IES-3B. Work in progress (to the Checker) on calculation preparation or revision on 6/1/98 may be completed in accordance with the requirements of IES-3 Revision 1 or IES-3B Revision 0 until 7/1/98.		N/A	

1.0 PURPOSE

The purpose of this engineering standard is to provide a methodology for the determination of instrument loop uncertainties and setpoints. The methodology described in this standard applies to uncertainty calculations for setpoint, control, and indication applications.

Numerous attachments are provided to assist the user with the application of the methodology. The extensive use of attachments was deliberate to improve the user's ability to find information and use this document. For this reason, the attachments are considered part of the engineering standard.

2.0 APPLICABILITY

This engineering standard provides an acceptable method to calculate instrument loop accuracies and setpoints, and applies to Nuclear Generation personnel as well as any technical staff members involved in the modification of instrument loops at Indian Point 3. The results of an uncertainty analysis might be applied to the following types of calculations:

- New safety-related setpoints
- Evaluation or justification of previously established setpoints
- Nonsafety-related setpoints
- Determination of instrument indication uncertainties

A systematic method of identifying and combining instrument uncertainties is necessary to ensure that vital plant protective features are actuated at the appropriate time during transient and accident conditions. Analytical Limits have been established through the process of accident analysis, which assumed that plant protective features would intervene to limit the magnitude of a transient. Limiting safety system settings (LSSS) are established in accordance with 10 CFR 50.36. Ensuring that these protective features actuate as they were assumed in the accident analysis provides assurance that safety limits will not be exceeded. This engineering standard is to be used as the methodology for uncertainty analysis and setpoint determination for safety-related instrumentation calculations performed in accordance with DCM-2.

Non-safety system setpoints are important for reliable power generation and equipment protection. Because these setpoints may not have safety limits that tie back to an accident analysis, the basis for the setpoint calculation becomes equipment protection and maintaining generation capacity. The criteria in this engineering standard may also be used as a guide for nonsafety-related setpoints to improve plant reliability, but is not a strict requirement.

The uncertainty associated with process parameter indication is also important for safe and reliable plant operation. Allowing for indication uncertainty supports compliance with the Technical Specifications and the various operating procedures, including the emergency operating procedures (EOP). The methodology presented in this engineering standard is applicable to determining indication uncertainty.

This engineering standard was developed specifically for instrumentation components and loops. This engineering standard does not specifically apply to mechanical equipment setpoints (i.e, safety and relief valve setpoints) or protective relay applications. However, guidance presented herein may be useful to predict the performance of other non-instrumentation-type devices.

This engineering standard is to be used for all applicable calculations issued 90 days after the approval date listed on the cover page of this standard. IES-3B Revision 0 documents the methodology which evolved as a result of preparation, review and approval of calculations in accordance with IES-3 Revision 1. Therefore, IES-3B does not require existing calculations to be upgraded to comply with this engineering standard. However, any future revision of existing calculation, prepared in accordance with IES-3, shall be evaluated to provide additional assurance that the requirements of this engineering standard are complied with.

3.0 REFERENCES

References that apply to the methodology presented in this engineering standard are listed in this section. The references are included here for the user's benefit. Commitments associated with certain references are also explained.

3.1 Industry Standards and Documents

3.1.1 Instrument Society of America (ISA) S67.04, Part I, ***Setpoints for Nuclear Safety-Related Instrumentation*****, September 1994**

ISA-S67.04 establishes basic criteria for nuclear safety-related setpoints. Although IP3 is not explicitly committed to the 1994 standard, the methodology provided in this engineering standard does follow its guidance. Refer to Section 3.4.2 for commitments to Regulatory Guide 1.105 and its qualified endorsement of the 1982 version of this standard. NYPA Design Basis Licensing Data Base, Log No. 93-115, provides the following commitment:

> *TITLE*
>
> *License Amendment 140 - 24 Month Surveillance Changes - Reactor Protection System*
>
> *COMMITMENT*
>
> *The loop accuracy/setpoint calculations for the Reactor Protection System (RPS) components or instrumentation channels were updated to include conservative values for 30-month calibration uncertainties (vendor specified uncertainties or MED30, whichever is larger) by accounting for instrument inaccuracies consistent with industry methods described in ISA RP67.04.*

3.1.2 ISA-RP67.04, Part II, *Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation*, September 1994

This Recommended Practice is a companion document to ISA-S67.04, Part 1. Its purpose is to assist with the implementation of ISA-S67.04. Refer to Section 3.4.2 for a commitment.

3.1.3 ANSI/ASME PTC 19.1-1985, ***Measurement Uncertainty***

ANSI/ASME PTC 19.1 establishes a basis for the principles of uncertainty analysis.

3.1.4 ASME MFC-3M-1989, ***Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi***

ASME MFC-3M provides information regarding expected uncertainties and errors associated with flow measurement.

3.1.5 ASME Steam Tables, Fourth Edition

The ASME Steam Tables provide the basis for water density as a function of temperature and pressure.

3.1.6 ANSI N42.18, *American National Standard for Specification and Performance of On-Site Instrumentation for Continuously Monitoring Radioactivity in Effluents*

This standard establishes minimum expected performance standards for certain types of radiation monitoring equipment.

3.2 Procedures

3.2.1 DCM 2, Design Control Manual, *Preparation and Control of Manual Calculations and Analyses*

DCM 2 establishes generic requirements and controls for preparation, review, documentation, and approval of manual (not computerized) design calculations.

3.2.2 DCM 4, Design Control Manual, *Design Verification*

DCM 4 establishes requirements and controls design review and verification. This DCM should be utilized for any design review and verification activity.

3.2.3 MCM 8, Modification Control Manual, *IP3 Setpoint Control*

MCM 8 defines the setpoint control process for IP3. Applicable setpoint changes are performed in accordance with its instructions. This MCM also establishes the boundaries and responsibilities of the IP3 setpoint control program.

3.2.4 Instrument and Control Department Administrative Directive IC-AD-2, *Calibration & Control of Measuring and Test Equipment*

IC-AD-2 establishes the minimum requirements for M&TE control. This engineering standard assumes that M&TE is controlled in accordance with this directive.

3.2.5 Instrument and Control Department Administrative Directive IC-AD-34, *Drift Monitoring Program*

A Drift Monitoring Program is required by Generic Letter 91-04 to support the 24-month calibration interval for certain safety related instruments. The program monitors and assess the effects of increased calibration intervals on instrument drift. The program also verifies that actual drift values are within project limits and identifies any instruments whose drift is outside the specified limits. This procedure is listed as a reference primarily because the drift monitoring program results can have an impact on setpoint calculations.

3.2.6 EOP Setpoint Manual IP3-EOP-SPM, or EOP Setpoint Database IP3 EOP

This database documents the EOP setpoints (supplemental to the PEDB) and is the configuration control database for these setpoints.

3.3 Calculations, Reports, and Internal Correspondence

3.3.1 NYPA Report IP3-RPT-MULT-00763, Revision 1, *24 Month Operating Cycle Technical Specification Operability and Acceptance Criteria*

This report forms the basis for the allowable values listed in Table 3.5-1 of the Technical Specifications. The report also describes the methodology for determining the allowable value.

3.3.2 NSE 95-3-032, Evaluation of IP3 CCR Regulatory Guide 1.97 instrumentation and Cabinet Temperature Rise, Revision 1 (including Reference 5 of the NSE, "Cataract Report No. S94-62322, Evaluation of IP3 Central Control Room Instrumentation & Cabinet Temperature Rise, Dated 1/4/95, Heat Run Test Data")

This report provides information regarding the interior ambient temperature of selected cabinets and is the basis for the expected temperature variation for the determination of temperature effects on instrumentation.

3.3.3 Memorandum IP-DEE-97-033MC, J. Odendahl to J. Wheeler, *Recommendation for Channel Check Acceptance Criteria*

This memorandum provides the Design Engineering Electrical initial recommendations for channel check limits. To assurance that these recommendations remain current; the Calculations Preparer should review and reissue this memorandum if the calculation results indicate a change is necessary.

3.3.4 Technical Specification Interpretation 24 and NYPA Report IP3-RPT-MULT-00981, *Alarms and Trips Required for IP3 Technical Specification Operability*

This Technical Specification Interpretation and associated NYPA Report provides an extensive list of alarms and trips that have Technical Specification requirements. This document should be reviewed when completing an uncertainty or setpoint calculation to ensure that any associated Technical Specification issues are addressed.

3.3.5 NYPA Report IP3-RPT-RPC-01355, *120 VAC Instrument Buses Condition Evaluation*

This report establishes the power supply effect contribution to an uncertainty analysis to be considered as a result of harmonic distortion.

3.4 Miscellaneous Documents

3.4.1 Code of Federal Regulations, Title 10, Part 50, Appendix A, Design Criteria 13, 20, and 29

General Design Criteria (GDC) 13, 20, and 29 require that instrumentation and controls be provided to monitor and control plant variables in process and protection systems for normal operation, all anticipated operational occurrences, and accident conditions. The GDC establishes the base requirements that must be met by the instrument setpoint process.

3.4.2 Regulatory Guide 1.105, *Instrument Setpoints*, Revision 2, February 1986

Regulatory Guide 1.105 endorses, with some discussion and clarification, ISA-67.04-1982, *Setpoints for Nuclear Safety-Related Instrumentation Used in Nuclear Power Plants*. NYPA Design Basis Licensing Data Base, Log No. 93-012-A, provides the following commitment:

TITLE
Extension of Reactor Surveillance Intervals Required for 24 Month Refueling Cycle
COMMITMENT
NRC requested that NYPA formally commit to Reg. Guide 1.105, Rev. 2, and ISA-RP67.04, Part II, Draft 9, dated 03/22/91 for instruments whose calibration interval was to be extended to accommodate a 24 month fuel cycle. NYPA stated that these documents had been part of the NYPA engineering process for some time, and that they would incorporate the use of the documents as a formal commitment to the NRC.

3.4.3 Proposed Revision 3 to Regulatory Guide 1.105 - Draft Regulatory Guide DG-1045, *Setpoints for Safety-Related Instrumentation*

This draft revision to Regulatory Guide 1.105 is referenced here because it establishes the NRC's proposed endorsement of the 1994 revision of ISA-67.04. The discussion in the NRC draft also provides the NRC's perspective on various technical areas related to setpoint methodologies and statistical analysis.

3.4.4 NRC Information Notice 92-12, *Effects of Cable Leakage Currents on Instrument Settings and Indications*

Information Notice 92-12 describes a potential problem related to instrument loop current leakage. During the high humidity and temperature conditions of a LOCA or HELB, insulation resistance can be degraded, thereby contributing to the measurement uncertainty of affected instrument loops. Attachment C of this engineering standard provides a method of assessing current leakage effects to resolve the issues raised by this Information Notice.

3.4.5 NRC Generic Letter 91-04, *Changes in Technical Specification Surveillance Intervals to Accommodate a 24-Month Fuel Cycle*

This NRC Generic Letter establishes the expected process of evaluating and monitoring instrument drift in support of 24-month fuel cycle extensions. It is listed as a reference here because of the relationship between instrument drift and setpoint calculations.

3.4.6 NYPA Letter to NRC IPN-86-05 dated January 7, 1986, *Regulatory Guide 1.97 Implementation Process*

This NRC submittal establishes the basis for Regulatory Guide 1.97 post-accident monitoring instruments that can require evaluation for indication uncertainty. Regulatory Guide 1.97 specifies the instruments and design qualification criteria considered necessary for post-accident monitoring. Supplement 1 to NUREG-0737, *Clarification of TMI Action Plan Requirements*, required that each plant assess the degree to which it would comply with the Regulatory Guide 1.97 criteria. NYPA Letter IPN-86-05 establishes IP3's commitments to Regulatory Guide 1.97. The NRC provided their safety evaluation of the IP3 submittal in their letter to IP3 dated April 3, 1991.

3.4.7 Indian Point 3 Emergency Operating Procedures (EOP)

The emergency operating procedures and associated Westinghouse and Westinghouse Owner's Group documents form the bases for those instruments requiring an evaluation for indication uncertainty. The Calculation Preparer should refer to Reference 3.2.6 to identify applicability.

3.4.8 NYPA Design Basis Licensing Data Base, Log No. 88-037

NYPA Design Basis Licensing Data Base, Log No. 88-037, provides the following commitment:

TITLE
IER 87-22
COMMITMENT
NYPA is in the process of developing its own methodology for performing loop accuracy calculations in house. The methodology proposed is intended to provide a general approach that is applicable to a wide range of problems. Loop diagrams will be prepared for each loop under consideration.

3.4.9 NYPA Design Basis Licensing Data Base, Log No. 90-008-D

NYPA Design Basis Licensing Data Base, Log No. 88-037, provides the following commitment:

TITLE
IER 89-26
COMMITMENT
NYPA has initiated a detailed loop calculation program. The first phase of this effort involves EQ components. This effort is expected to be expanded to encompass all safety related instruments. NYPA has also implemented a program for trending instrument drift from calibration data for input into loop accuracy calculations. These calculations will include measuring and test equipment (M&TE).

3.4.10 EPRI TR-103335, *Guidelines for Instrument Calibration Extension/Reduction Programs*

This EPRI report provides a methodology for evaluating instrument calibration data to estimate instrument drift. The methodology has been used as part of 24-month fuel cycle extension submittals.

3.4.11 EPRI TR-102644, *Calibration of Radiation Monitors at Nuclear Power Plants*

This EPRI report provides calibration information related to radiation monitoring systems and is a reference source for radiation monitor errors and uncertainties.

4.0 ATTACHMENTS

This engineering standard has been organized to provide all required supporting technical information as references or attachments. Refer to the Table of Contents for a complete listing.

5.0 DEFINITIONS

All definitions acronyms and abbreviations are contained in Attachment A, Glossary.

6.0 PROCEDURE

Before the instrument channel uncertainty can be calculated, a considerable amount of information has to be obtained. The Calculation Preparer should refer to the checklist in Table B-1 for issues to be considered when performing an uncertainty calculation. Figure 6-1 shows the overall uncertainty analysis and setpoint calculation process.

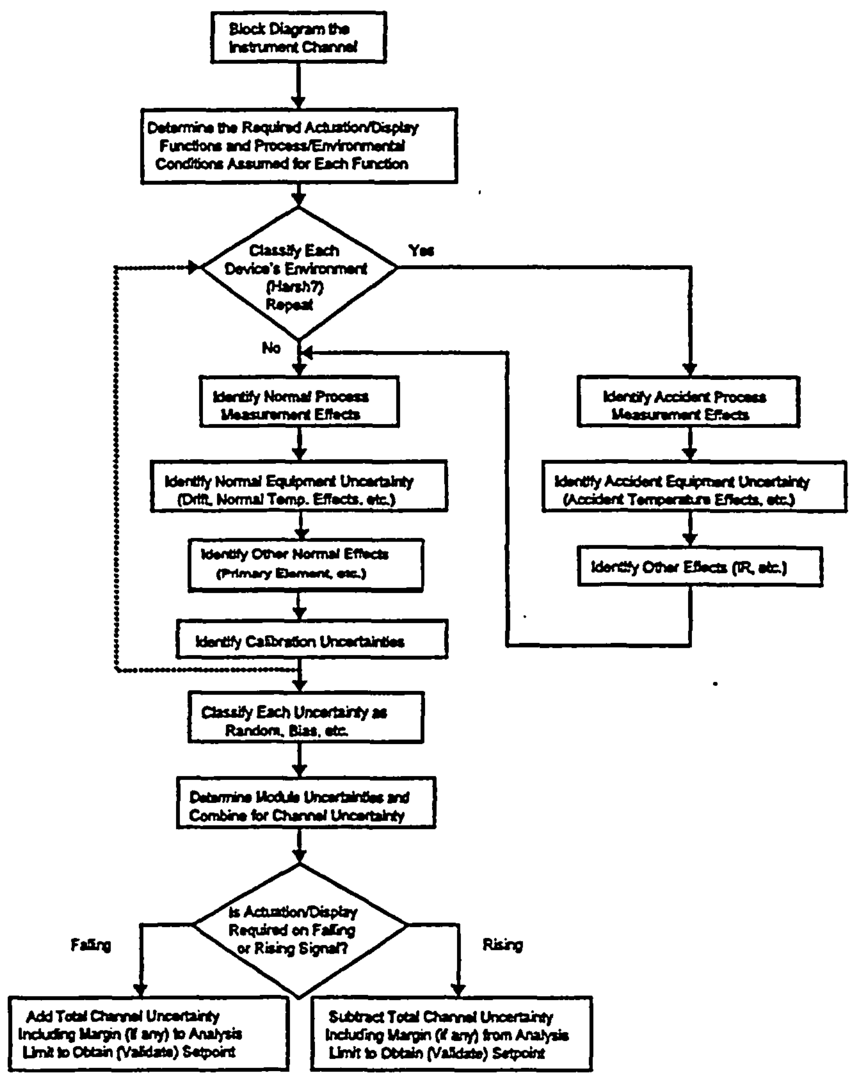


Figure 6-1
Setpoint Calculation Flowchart

Setpoint calculations shall be performed in accordance with DCM 2, *Preparation and Control of Manual Calculations and Analyses*. Review and verification of the calculation is performed in accordance with DCM 4, *Design Verification*.

Each calculation should be formatted similarly to provide consistency between calculations and simplify the review process for other personnel that may have to revise or refer to the calculation. The following sections describe the preferred format and required content of a calculation.

6.1 Section 1 - Purpose (Problem/Objective/Method)

This section shall consist of Section (1.1) which states the problem/reason that the calculation is being prepared or revised, Section (1.2) which states the calculators objective and Section (1.3) which states the method/methodology to be used to meet the objective and/or resolve the problem.

6.2 Section 2 - Assumptions

Explain the assumptions used in the calculation. Assumptions should be listed in a logical order so that the reviewer can follow the development of the uncertainty analysis to the instrument loop. See Attachment H to select any applicable evaluated assumptions. Any assumptions that require later verification shall be identified in the calculation by an asterisk and NOTE identifying the ACTS No. for tracking verification of the assumption.

6.3 Section 3 - References

References should be provided in sufficient detail to allow the reviewer to check all aspects of the calculation with the exception of some assumptions that might not have an explicit reference. References which are not easily retrievable or and are specific to the calculation (memos, vendor correspondence, etc.) should be considered for inclusion as an attachment. Extraneous references that do not substantially add value to the calculation should be excluded.

6.4 Section 4 - Attachments

Attach supporting documentation that might not be readily available or that might be needed as part of any review of the calculation (memos, vendor correspondence, etc.). Drawings, related calculations, IP3 procedures, and similar documents need not be attached.

6.5 Section 5 - Loop Function

The loop function is a short description of the purpose of the instrument loop and its role in the system operation. The loop function description serves two purposes. First, it familiarizes the reader with an overview of the system function in a manner that ties back to the calculation purpose. Second, it assures the reader that the calculation preparer understood the system and its requirements. To prepare the functional description the following information for each instrument channel of interest should be provided:

- Functional requirements
- Actuation functions
- Display functions
- Operating times
- Postulated environments to which the instrument is exposed, concurrent with the above actuations

6.6 Section 6 - Loop Diagram

Diagram the instrument channel(s) to be analyzed in a manner similar to that shown in Figure 6-2. The purpose of the diagram is to identify the various modules and interconnection devices that make up the instrument loop. Figure 6-2 shows a typical process measurement channel that could be used to provide a nuclear safety-related function and includes the interfaces, functions, sources of uncertainty, and the instrument module environments. Although Figure 6-2 shows a flow measurement loop, the layout is generally applicable to temperature, level, pressure and other parameter measurements.

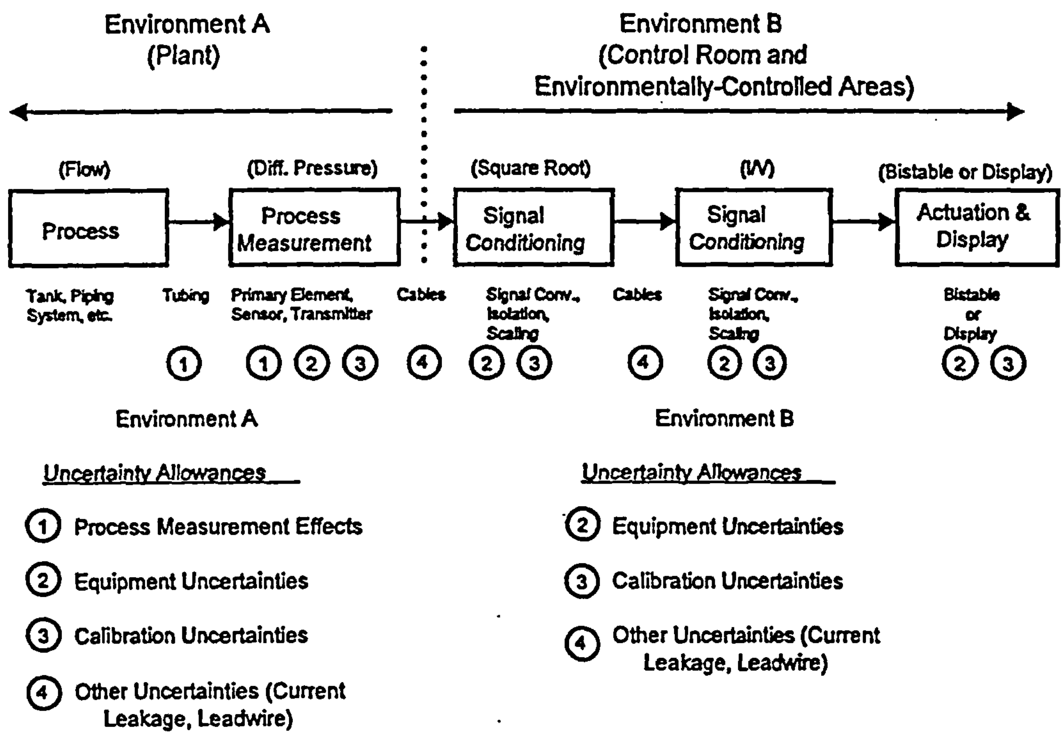


Figure 6-2
Typical Instrument Channel Layout

Anywhere from one to four transmitters or sensors may be used to satisfy the safety-related requirements for redundancy and reliability. If each independent instrument loop is functionally equivalent in terms of the types of modules shown in Figure 6-2, only one instrument channel diagram need be provided. In this case, include a cross-reference tabulation that provides the information needed to confirm that all loops are essentially identical in their design. Table 6-1 shows an example of a cross-reference table. Complete a similar table or tabulation with relevant information for all instruments.

Tag Number	Manufacturer	Model Number	Reference

Table 6-1
Instrument List for Uncertainty Analysis

Environmental boundaries are drawn for the channel as shown in Figure 6-2. For simplicity, two sets of environmental conditions are shown. The process measurement elements are usually located in plant areas where a harsh environment may exist during the time the instrument loop has to function. For most channels, signal conditioning and actuation are located in mild environments. Two sets of environmental conditions are defined, with conditions in Environment A (plant) harsher than conditions in Environment B (control room).

After the environmental conditions are determined, the potential uncertainties affecting each portion of the channel should be identified. For example, the process interface portion could be affected by process measurement effects and not by equipment calibration or other uncertainties. Also, cables in the mild conditions of Environment B would not be affected by insulation resistance (IR) effects, but IR effects may be a contributor to uncertainty for components located in Environment A. In summary, the following information is typically considered when an uncertainty analysis is prepared:

Instrument (module) data

Manufacturer
Model number
Location
Calibrated input range
Calibrated output range
Calibration procedure number
Module Algorithm

Vendor data (listed by manufacturer/model number):

Accuracy (repeatability, linearity, and hysteresis - may be specified separately or combined as a single accuracy statement)
Drift (algorithm) or drift value from statistical analysis
Temperature effect (algorithm)
Humidity effect (algorithm)
Radiation effect (algorithm)
Power supply effect (algorithm)
Static pressure effect (algorithm)
Seismic effect (algorithm)
Maximum span capability

Location data (listed by room or area):

Seismic response, frequency and acceleration
Environmental conditions (normal and accident)
Temperature
Humidity
Radiation

Calibration procedure data (listed by procedure):

Calibration procedure number
Calibration frequency
Setting tolerance
Test instruments/accuracy
Loop instrumentation required accuracy
Calibration static pressure

6.7 Section 7 - Equations

This section identifies the applicable equations to be used in the uncertainty analysis and establishes the general calculation requirements. The following equations are typically used in preparation of calculations in accordance with this standard. Refer to the Eqn. number and see Attachment B for additional information regarding the calculation methodology. Attachment B also provides guidance regarding how to handle each uncertainty element.

6.7.1 Channel Uncertainty (CU)

$CU^+ = +(PME^2 + PEA^2 + e_1^2 + \ldots + e_n^2)^{1/2} + B^+$ See Page 50, Eqn. B.10

$CU^- = -(PME^2 + PEA^2 + e_1^2 + \ldots + e_n^2)^{1/2} - B^-$ See Page 50, Eqn. B.10

6.7.2 Module Uncertainty (e_n Any Typical Module)

$e_n^+ = +(RA^2 + DR^2 + TE^2 + HE^2 + RE^2 + PS^2 + SP^2 + OP^2 + SE^2 + ALT^2 + MTE^2 + R^2)^{1/2} + B^+$ *
See Page 52, Eqn. B.11

$e_n^- = -(RA^2 + DR^2 + TE^2 + HE^2 + RE^2 + PS^2 + SP^2 + OP^2 + SE^2 + ALT^2 + MTE^2 + R^2)^{1/2} - B^-$ *
See Page 52, Eqn. B.11

6.7.3 As-found Tolerance (AFT_n Any Typical Module)

$AFT_n = \pm(RA_n^2 + DR_n^2 + ALT_n^2)^{1/2}$ *   See Page 49, Eqn. B.14

6.7.4 Trip Setpoint (TS)

$TS = AL \text{ or } NPL \pm(CU + Margin)$ See Page 56 & 57, Eqn. B.12 & B.13

6.7.5 Loop Allowable Value (AV)

$AV = TS \pm CU_{cal}$ See Page 21, Eqn. 6.1

where:

TS = The Trip Setpoint, and

CU_{cal} = The Channel Uncertainty as seen during loop calibration. Therefore, uncertainties due to a harsh environment, process measurement, or primary element are not considered. For CU_{cal} determination at IP3 usually only RA, DR, and ALT uncertainties are considered.

Therefore, CU_{cal} will be based on:

$CU_{cal} = \pm(e_{1cal}^2 + e_{2cal}^2 + \ldots + e_{ncal}^2)^{1/2}$, and $e_{ncal} = \pm(RA_n^2 + DR_n^2 + ALT_n^2)^{1/2}$ *

*** NOTE:**
Normally DR values will be the vendor's specified drift adjusted for IP3 Calibration Period including any Grace Period identified in the Technical Specification. For example; if the vendor's specified drift is X% of span/year and the IP3 Calibration Period is 24 months with a Technical Specification Grace Period of 6 months; the adjusted DR for the module would be determined by:

$$DR = \pm[2\ yr(X\%\ of\ span/yr)^2 + 1/2\ yr(X\%\ of\ span/yr)^2]^{1/2}$$

When the Drift Value has been determined Statistically based on As-Found/As-Left Calibration Data; as a minimum the RA Value shall be set Equal to 0.0 in the above equations.

6.8 Section 8 - Determine Contributing Uncertainties (PME, PEA & e_n)

Section 8 of the calculation should determine the various contributors to the measurement uncertainty, indication uncertainty, and actuation uncertainty as applicable. Section 8.1 shall address PME and determine any PME uncertainty value applicable. Section 8.2 shall address PEA and determine any PEA uncertainty value applicable. Additionally, Section 8 shall determine e_n and AFT for each module. Refer to 6.7.2 & 6.7.3 above and Attachment B (Section B.3) for the various contributors to uncertainty that should be considered as part of an evaluation.

6.9 Section 9 - Determine Channel Uncertainty (CU)

The individual module uncertainties and other uncertainty terms are combined to determine the overall channel uncertainty. See Section 6.7.1 above and Attachment B for specific guidance regarding the calculation of the channel uncertainty.

6.10 Section 10 - Analytical Limit (AL) or Nominal Process Limit (NPL)

The trip setpoint can not be established until the analytical limit is defined. The basis or source of the analytical limit must be clearly explained. Any inherent margins in the analytical limit should be quantified, if possible. Attachment B provides additional information regarding the relationship between the analytical limit and the trip setpoint.

For applications without an analytical limit, the nominal process limit that should not be exceeded should be explained, if applicable.

6.11 Section 11 - Determine Setpoint (TS)

Calculate the trip setpoints in accordance with the methodology provided in Section 6.7.4 and Attachment B. If the same setpoint is used for more than one actuation function, EOP action or decision point, and/or monitoring requirement, the function with the most limiting (largest error producing) environmental requirement should be used or individual calculations for each function should be performed, each with the appropriate set of conditions.

6.12 Section 12 - Allowable Value (AV) and Related Requirements

Determine the allowable value and the as-found tolerances. The following sections provide specific requirements.

6.12.1 Determination of Allowable Value

The allowable value is a limiting value that the trip setpoint may have when tested periodically, beyond which appropriate action shall be taken. If the as-found condition measured during calibration is within the allowable value limit, the instrument loop will satisfy the system and safety requirements. The allowable value methodology used at IP3 is referenced in the Technical Specifications by report number. The report, Reference 3.3.1, NYPA Report IP3-RPT-MULT-00763, Revision 1, *24 Month Operating Cycle Technical Specification Operability and Acceptance Criteria*, is included here as the basis for allowable value determinations.

In order to determine that the loop allowable value is not exceeded, the following variables will be considered as follows:

$$AV = TS \pm CU_{cal} \quad \text{Eqn. 6.1}$$

where:

TS = The Trip Setpoint, and

CU_{cal} = The Channel Uncertainty as seen during loop calibration. Therefore, uncertainties due to a harsh environment, process measurement, or primary element are not considered. For CU_{cal} determination at IP3 usually only RA, DR, and ALT uncertainties are considered.

Therefore, CU_{cal} will be based on:

$$CU_{cal} = \pm(e_{1cal}^2 + e_{2cal}^2 + \ldots + e_{ncal}^2)^{1/2}, \text{ and}$$

$$e_{ncal} = \pm(RA_n^2 + DR_n^2 + \ldots + ALT_n^2)^{1/2}$$

Non-adjustable devices such as potential transformers or flow nozzles are not considered modules in the above context and are not included in the Loop Operability and Acceptance Criteria Tolerance.

Calibration is not performed on a loop basis at IP3; individual instruments are calibrated. For this reason, the Loop Operability and Acceptance Criteria Tolerance must be distributed among the various modules in an instrument loop. For those modules calibrated on a refueling interval, the Module Operability and Acceptance Criteria Tolerance (t) is set equal to the as-found tolerance as defined in the 24 Month Cycle Extension Project Drift Monitoring Program. Given that the Loop Operability and Acceptance Criteria Tolerance and the refueling interval module as-found tolerances are essentially fixed, the remaining margin in the allowable value determination is assigned to the bistable.

By the above process, a significant portion of the Loop Operability and Acceptance Criteria Tolerance might be assigned to the bistable. But, slight shifts in bistable performance might indicate a degrading instrument. For this reason, the bistable should still have an as-found tolerance that is more indicative of its expected performance. The as-found tolerance is larger than the as-left tolerance to allow for a small amount of drift during normal operation. The as-found tolerances for all loop components should be reviewed with respect to the Loop Operability and Acceptance Criteria Tolerance to ensure that loop performance allowances remain conservative.

In conclusion, NYPA Report IP3-RPT-MULT-00763, Revision 1, *24 Month Operating Cycle Technical Specification Operability and Acceptance Criteria*, is the basis for the allowable value process at IP3 and should be reviewed as part of the setpoint calculation process.

6.12.2 Channel Check Criteria

Channel check criteria are established only for certain Technical Specification instruments. Reference 3.3.3 provides a list of the instruments that have been provided with engineering recommendations for channel check limits. Wherever possible, the channel check criteria used in this reference should be maintained to minimize the impact on Operations. Whenever a channel check limit is modified, Operations must be formally informed of the change.

Most instrument loops for indication will consist of the sensing transmitter, an isolator, and an indicator. What is read from the indicator represents the measurement estimate including uncertainty for that portion of the instrument loop. The indication portion of an instrument loop will often have a greater error during normal operation than the actuation portion of an instrument loop. A channel check through indicators can provide an early warning of a possible loop problem.

6.13 Section 13 - Scaling Calculations

Scaling information should be provided by the calculation to ensure that the setpoint requirements are properly translated to the bistable settings. Attachment N provides additional information regarding scaling calculations. Determine the scaling requirements for all evaluated modules.

6.14 Section 14 - Summary/Conclusions

Summarize the results. Provide adequate detail so that all conclusions can be understood in this section. The summary of results shall include all information to be provided to I&C and Operations Engineering, such as M&TE requirements (accuracy etc.), the as-found and as-left tolerances, scaling results, and any EOP value if applicably.

6.15 Notification

In all cases, the preparer is responsible for identifying those individuals, organizations and locations on Attachment 4.1 of DCM-2 (Reference 3.2.1), that may require the calculation results as input to their procedures (e.g., System Engineering, I&C Engineering, Operations Engineering, etc.). Document Control shall make the distribution of the calculation based on the preparers completed Attachment 4.1 of DCM-2 listing.

Additionally, if a setpoint change is required, the processing shall be in accordance with the MCM-8 (Reference 3.2.3) procedure process.

ATTACHMENT A
GLOSSARY

95%/95% - Standard statistics term meaning that the results have a 95 percent probability with a 95 percent confidence.

A

Allowable Value (AV) - A limiting value that the trip setpoint may have when tested periodically, beyond which appropriate action shall be taken.

Ambient Temperature - The temperature of the medium surrounding a device.

Amplifier - A device that enables an input signal to control power from a source independent of the signal and thus be capable of delivering an output that bears some relationship to, and is generally greater than, the input signal.

Analog - The continuous and observable representation of a variable reflecting any and all changes in value; continuously variable over a given range.

Analog-to-Digital Converter (A/D) - A device that converts analog signals into a digital form. This enables a digital computer to operate on such signals.

Analytical Limit (AL) - Limit of a measured or calculated variable established by the safety analysis to ensure that a safety limit is not exceeded.

Arbitrarily Distributed Uncertainty - An uncertainty treated as a bias of unknown direction. It is added as a bias in both the positive and negative directions.

As-Found - The condition in which a channel, or portion of a channel, is found after a period of operation and prior to any calibration.

As-Found Tolerance (AFT) - The tolerance allowed in accuracy between calibrations of a device or group of devices. The as-found tolerance establishes the limit of error the defined devices can have and still be considered functional.

As-Left - The condition in which a channel, or portion of a channel, is left after calibration or surveillance check.

As-Left Tolerance (ALT) - The tolerance that establishes the required accuracy band that a device or group of devices must be calibrated to within and remain to avoid recalibration when periodically tested.

Attenuation - A diminishing of the strength of a signal (particularly an oscillatory signal) by a transducer.

B

Bias (B) - A shift in the signal zero point by some amount (see Figure B-2). For control systems, bias is a signal or constant added to or subtracted from an input signal to provide elevation or suppression. For uncertainty evaluations, both module and process biases must be considered.

C

Calibrated Span - The maximum calibrated upper range value less the minimum calibrated lower range value.

Calibration Interval - The elapsed time between the initiation or successful completion of calibrations or calibration checks on the same instrument, channel, instrument loop, or other specified system or device.

Channel Uncertainty - The combined effect of all instrument/device uncertainties in a loop. Depending on the loop configuration, this uncertainty could apply to actuation or indication.

Confidence Interval - An interval that contains the population mean to a given probability.

Conformity - The maximum difference, over the range of an instrument, between the indicated value and the true value being measured. The closeness that the output of an instrument approximates (or conforms to) a specified desired curve (linear, polynomial, logarithmic, etc.).

Control Loop - A group of interconnected instruments that measures the process variable, compares that value to a predetermined desired value, and applies to the process variable any change necessary to make the process value match the desired value.

D

Deadband - The range through which an input signal may be varied, upon reversal of direction, without initiating observable change in the output signal.

Dead Time - The interval of time between initiation of an input change or stimulus and the start of the resulting observable response.

Dependent - In statistics, dependent events are those for which the probability of all occurring at once is different than the product of the probabilities of each occurring separately. In setpoint determination, dependent uncertainties are those uncertainties for which the sign or magnitude of one uncertainty affects the sign or magnitude of another uncertainty.

Desired Value - A measurement value with no error existing.

Differential Pressure (ΔP or D/P) - Measurement of one pressure with respect to another pressure.

Digital - Representation of system variables by a limited number of discrete values.

Digital-to-Analog Converter - An electronic device that converts data (digital signal) into an analog signal of corresponding value.

Drift (DR) - An undesired change in output over a period of time, which change is unrelated to the input, environment, or load.

E

Effect - An undesired change in output produced by some outside phenomenon or by internal changes in a device.

Elevated-Zero Range - A range in which the zero value of the measured variable or signal is greater than the lower range value. The zero may be between the lower and upper range values, at the upper range value, or above the upper range value.

Error - The undesired algebraic difference between a value that results from measurement and a corresponding true value. In a closed loop, the difference between the actual value of a particular signal and its desired value.

ESF - Engineered Safeguards Features

ESFAS - Engineered Safeguards Features Actuation System

F

Final Setpoint Device - A component, or assembly of components, that provides input to the process voting logic for actuated equipment. Examples of final setpoint devices are bistables, relays, pressure switches, and level switches.

Fixed Gain - A multiplication factor for a process control value. A user cannot change a fixed gain without reconfiguring the system or device that establishes this parameter.

Full Scale - The 100% value of the measured parameter on an instrument. Full scale and span are equivalent for a zero-based instrument.

Functionally Equivalent - Instruments with similar design and performance characteristics that can be combined to form a single population for analysis purposes.

G

Gain - The ratio of change in output divided by the change in input that caused it; the ratio of the output to the input. The gain of a loop is the product of the gains of all elements in the loop. Frequently used to mean the proportional gain of a PID controller, but can also be used with integral or derivative action, e.g., the integral gain of the controller is 2.5.

H

Harsh Environment - The environment in any plant area is considered to be harsh as a result of postulated accidents, i.e., Loss of Coolant Accident (LOCA), High Energy Line Break (HELB), Main Steam Line Break (MSLB), or other Design Basis Event (DBE), if the temperature, pressure, relative humidity, or radiation significantly increase above the normal conditions.

Head - Pressure resulting from gravitational forces on liquids.

Humidity Effect (HE) - The change in instrument output for a constant input when exposed to varying levels of ambient humidity.

Hysteresis - The difference between upscale and downscale results in instrument response when subjected to the same input approached from the opposite direction (see Figure B-5).

I

I/O - Input to output.

Independent - In statistics, independent events are those in which the probability of all occurring at once is the same as the product of the probabilities of each occurring separately. In setpoint determination, independent uncertainties are those for which the sign or magnitude of one uncertainty does not effect the sign or magnitude of any other uncertainty.

Input/Output - Signal reception and transmission, or signal interfacing. Input for a process control device involves accepting and processing signals from field devices. Output, for a process control device, involves converting commands into electrical signals to field devices.

Instrument Channel - An arrangement of components and modules as required to generate a single protective action or indication signal which is required by a generating station condition. A channel loses its identity where single protective action signals are combined.

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

Insulation Resistance Effect (IRE) - The change in signal caused by a low insulation resistance of an interconnecting device or cable (see Attachment C).

L

Limiting Safety System Setting (LSSS) - Settings for automatic protective devices related to those variables having significant safety functions.

Linear - A straight-line relationship between one variable and another. When used to describe the output of an instrument, it means that the output is proportional to the input.

Linearity - The closeness to which a curve approximates a straight line (see Figure B-6). Linearity is usually measured as a nonlinearity and expressed as linearity. It is the maximum deviation between an average curve and a straight line.

Linearize - To substitute, for a non-linear function, a linear function that gives approximately the same relationships over a particular, limited range of the variables.

Loop Diagram - A representation of the various parts of a control loop, showing interconnected elements.

M

Margin - An additional allowance added to the instrument channel uncertainty to allow for unknown uncertainty components. The addition of margin moves the setpoint further away from the analytical limit or nominal process limits.

Maximum Span - The instrument's maximum upper range limit less the maximum lower range limit.

Mean - The average value of a random sample or population. For *n* measurements of X_I, where *I* ranges from 1 to *n*, the mean is given by

$$\bar{X} = \frac{\sum X_I}{n}$$

Measured Signal - The electrical, mechanical, pneumatic, or other variable applied to the input of a device.

Measured Variable - A quantity, property, or condition that is measured, e.g., temperature, pressure, flow rate, or speed.

Measurement - The present value of a variable such as flow rate, pressure, level, or temperature.

Measurement and Test Equipment Effect (MTE) - The uncertainty attributed to measuring and test equipment that is used to calibrate the instrument loop components.

Mild Environment - An environment that at no time is more severe than the expected environment during normal plant operation, including anticipated operational occurrences.

Module - Any assembly of interconnecting components which 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 which 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.

Module Uncertainty (e_n) - The total uncertainty attributable to a single module. The uncertainty of an instrument loop through a display of actuation device will include the uncertainty of one or more modules.

N

Noise - An unwanted component of a signal or variable. It causes a fluctuation in a signal that tends to obscure its information content.

Nominal Value - The value assigned for the purpose of convenient designation but existing in name only; the stated or specified value as opposed to the actual value.

Nonlinear - A relationship between two or more variables that cannot be described as a straight line. When used to describe the output of an instrument, it means that the output is of a different magnitude than the input, e.g., square-root relationship.

Normal Distribution - The density function of the normal random variable X, with mean μ and variance σ^2 is

$$n(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\,\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Normal Process Limit (NPL) - The limit, high or low, beyond which the normal process parameter should not vary. Trip setpoints associated with non-safety-related functions might be based on the normal process limit.

O

Operating Conditions - Conditions to which a device is subjected, other than the variable measured by the device. Examples of operating conditions include ambient pressure, ambient temperature, electromagnetic fields, gravitational force, power supply characteristics, radiation, shock, and vibration.

Outlier - A data point significantly different in value from the rest of the sample.

Output Signal - The signal provided by an instrument; for example, the signal that the controller delivers to the valve operator is the controller output.

P

Percent of Span - A method for describing instrument spans or ranges as a simple percentage. The low end of span is the 0% point and the high end of span is the 100% point.

Power Supply Effect (PSE) - The uncertainty attributed to variations in normal expected power supply output voltage.

Precision - The repeatability of measurements of the same quantity under the same conditions.

Primary Element - The system element that quantitatively converts the measured variable energy into a form suitable for measurement.

Primary Element Effect (PEA) - The uncertainty attributed to a primary element device such as an orifice plate.

Process Error - The difference between the desired setpoint and the actual process variable.

Process Measurement Effect (PME) - The uncertainty associated with a process measurement that is not attributable to the measurement device, such as liquid density variations.

R

Radiation Effect (RE) - The uncertainty attributed to radiation exposure.

Random - 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 Figure B-1).

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

Reference Accuracy - A number or quantity that defines the limit that errors will not exceed when the device is used under reference operating conditions (see Figure B-3). In this context, error represents the change or deviation from the ideal value.

Repeatability - The ability of an instrument to produce exactly the same result every time it is subjected to the same conditions (see Figure B-4).

Reverse Action - An increasing input to an instrument producing a decreasing output.

Rise Time - The time it takes a system to reach a certain percentage of its final value when a step input is applied. Common reference points are 50%, 63%, and 90% rise times.

RPS - Reactor Protection System.

RTD - Resistance temperature detector.

S

Safety Limit - A limit on an important process variable that is necessary to reasonably protect the integrity of physical barriers that guard against the uncontrolled release of radioactivity.

Safety-Related Instrumentation - Instrumentation that is essential to the following:

- 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 can be operated without undue risk to the health and safety of the public.

Other instrumentation, such as certain Regulatory Guide 1.97 instrumentation, may be treated as safety related even though it may not meet the strict definition above.

Seismic Effect (SE) - The change in instrument output for a constant input when exposed to a seismic event of specified magnitude.

Sensor - The portion of a channel which responds to changes in a plant variable or condition and converts the measured process variable into an electric or pneumatic signal.

Setpoint - The desired value of the measured variable at which an actuation occurs.

Signal - Information in the form of a transmission medium (pneumatic pressure, electric current, or mechanical position) that is conveyed from one control loop component to another.

Signal Conditioning - One or more modules that perform further signal conversion, buffering, isolation or mathematical operations on the signal as needed.

Signal Converter - A transducer that converts one transmission signal to another.

Span - The algebraic difference between the upper and lower values of a range.

Span Shift - An undesired shift in the calibrated span of an instrument (see Figure B-8). Span shift is one type of instrument drift that can occur.

Spurious Trip - An undesired protective actuation when the actual process value has not exceeded the trip setpoint.

Square-Root Extractor - A device whose output is the square root of its input signal.

SRSS - Square root of the sum of the squares.

Standard Deviation (Population) - A measure of how widely values are dispersed from the population mean and is given by

$$\sigma = \sqrt{\frac{n\sum x^2 - (\sum x)^2}{n^2}}$$

Standard Deviation (Sample) - A measure of how widely values are dispersed from the sample mean and is given by

$$s = \sqrt{\frac{n\sum x^2 - (\sum x)^2}{n(n-1)}}$$

Static Pressure - The steady-state pressure applied to a device.

Static Pressure Effect (SP) - The change in instrument output for a constant input when measuring a differential pressure and simultaneously exposed to a static pressure.

Steady-State - A characteristic of a condition, such as value, rate, periodicity, or amplitude, exhibiting only a negligible change over an arbitrary long period of time.

Suppressed-Zero Range - A range in which the zero value of the measured variable is less than the lower range value.

Surveillance Interval - The elapsed time between the initiation or completion of successive surveillances or surveillance checks on the same instrument, channel, instrument loop, or other specified system or device.

T

Temperature Effect (TE) - The change in instrument output for a constant input when exposed to different ambient temperatures.

Test Interval - The elapsed time between the initiation or completion of successive tests on the same instrument, channel, instrument loop, or other specified system or device.

Time Constant - For the output of a first-order system forced by a step or impulse, the time constant T is the time required to complete 63.2% of the total rise or decay.

Time-Dependent Drift - The tendency for the magnitude of instrument drift to vary with time.

Time-Independent Drift - The tendency for the magnitude of instrument drift to show no specific trend with time.

Time Response - An output expressed as a function of time, resulting from the application of a specified input under specified operating conditions.

Tolerance - The allowable variation from a specified or true value.

Tolerance Interval - An interval that contains a defined proportion of the population to a given probability.

Total Harmonic Distortion (THD) - The distortion present in an AC voltage or current that causes it to deviate from an ideal sine wave.

Transfer Function - The ratio of the transform of an output of a system to the transform of the input to the system.

Transmitter - A device that measures a physical parameter such as pressure or temperature and transmits a conditioned signal to a receiving device.

Trip Setpoint (TS) - A predetermined value at which a bistable or switching device changes state to indicate that the quantity under surveillance has reached the selected value.

Turndown Ratio - The ratio of maximum span to calibrated span for an instrument.

U

Uncertainty - The amount to which an instrument channel's output is in doubt (or the allowance made therefore) due to possible errors either random or systematic which have not been corrected for. The uncertainty is generally identified within a probability and confidence level.

Upper Range Limit (URL) - The maximum upper calibrated span limit for the device.

Upper Range Value - The highest value of the measured variable that device is adjusted to measure.

Z

Zero - The point that represents no variable being transmitted (0% of the upper range value).

Zero Shift - An undesired shift in the calibrated zero point of an instrument (see Figure B-7). Zero shift is one type of instrument drift that can occur.

Zero Adjustment - Means provided in an instrument to produce a parallel shift of the input-output curve.

Zero Elevation - For an elevated-zero range, the amount the measured variable zero is above the lower range value.

Zero Suppression - For a suppressed-zero range, the amount the measured variable zero is below the lower range value.

ATTACHMENT B
UNCERTAINTY ANALYSIS FUNDAMENTALS

The ideal instrument would provide an output that accurately represents the input signal, without any error, time delay, or drift with time. Unfortunately, this ideal instrument does not exist. Even the best instruments tend to degrade with time when exposed to adverse environments. Typical stresses placed on field instruments include ambient temperature, humidity, vibration, temperature cycling, mechanical shock, and occasionally radiation. These stressors may affect an instrument's reliability and accuracy. Attachment B discusses the various elements of uncertainty that should be considered as part of an uncertainty analysis. The methodology to be applied to uncertainty analysis and the determination of trip setpoints is also described in Attachment B.

Not all categories of uncertainty described in this Attachment will apply to every configuration. But, the analyst should provide in the body of the calculation a discussion sufficient to explain the rationale for any uncertainty category that is not included.

B.1 Categories of Uncertainty

The basic model used in this design standard requires that the user categorize instrument uncertainties as random, bias, or arbitrarily distributed. This section describes the various categories of instrument uncertainty and provides insight into the process of categorizing instrumentation based on performance specifications, test reports, and plant calibration data.

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

It should not be assumed that, since this design standard addresses three categories of uncertainty, all three types must be used in each uncertainty calculation. Additionally, it should not be assumed that instrument characteristics will fit neatly into a single category. For example, the nature of some data may require that an instrument's static pressure effect be described as bimodal, which might best be represented as a random uncertainty with an associated bias.

B.1.1 Random Uncertainties

When repeated measurements are taken of some fixed parameter, the measurements will generally not agree exactly. Just as these measurements do not precisely agree with each other, they also deviate by some amount from the true value. Uncertainties that fluctuate about the true value without any particular preference for a particular direction are said to be *random.*

Random uncertainties are sometimes 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 in the mean), and the probable error.

In the context of instrument uncertainty, it is generally accepted that random uncertainties are those instrument uncertainties that a manufacturer specifies as having a ± magnitude and are defined in statistical terms. It is important to understand the manufacturer's data thoroughly and be prepared to justify the interpretation of the data. After uncertainties have been categorized as random, it is required that a determination be made whether there exists any dependency between the random uncertainties. Figure B-1 shows the expected nature of randomly distributed data. There is a greater likelihood that data will be located near the mean; the standard deviation defines the variation of data about the mean.

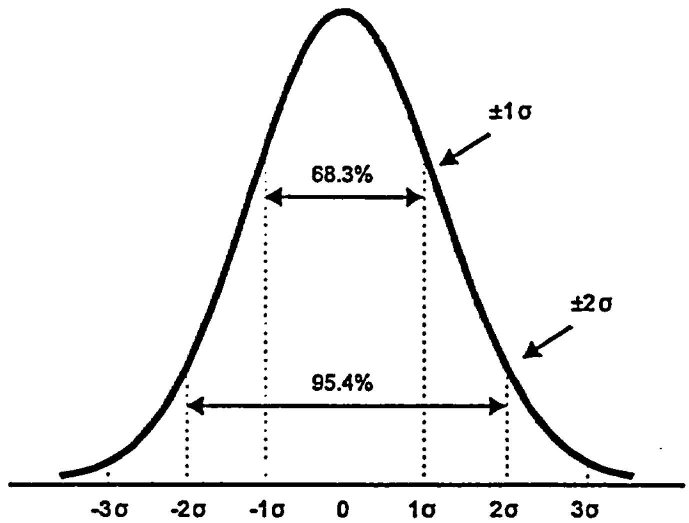


Figure B-1
Random Behavior

B.1.2 Bias Uncertainties

Suppose that a tank is actually 50% full, but a poorly designed level monitoring circuit shows the tank level as fluctuating randomly about 60%. As discussed in the previous section, the fluctuations about some central value represent random uncertainties. However, the fixed error of 10% in this case is called a *systematic* or *bias* uncertainty. In some cases, the bias error is a known and fixed value that can be calibrated out of the measurement circuit. In other cases, the bias error is known to affect the measurement accuracy in a single direction, but the magnitude of the error is not constant.

Bias is defined as a systematic or fixed instrument uncertainty which is predictable for a given set of conditions because of the existence of a known direction (positive or negative). A very accurate measurement can be made to be inaccurate by a bias effect. The measurement might otherwise have a small standard deviation (uncertainty), but read entirely different than the true value because the bias effectively shifts the measurement over from the true value by some fixed amount. Figure B-2 shows an example of bias; note that bias as shown in Figure B-2 shifts the measurement from the true process value by a fixed amount.

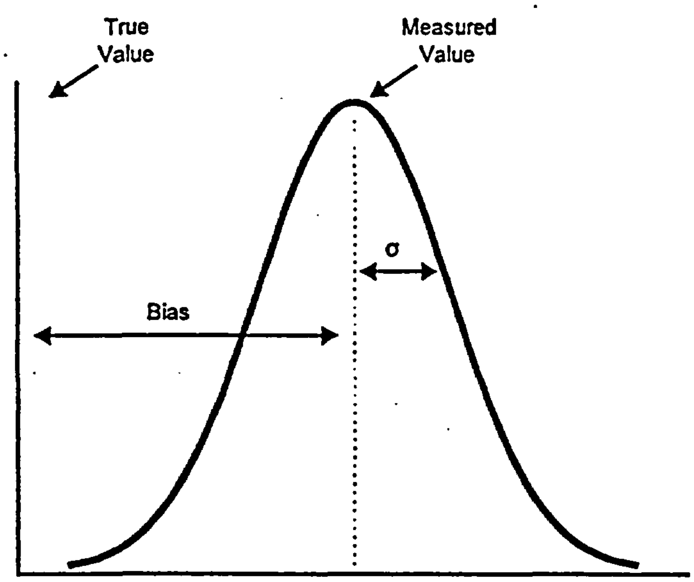


Figure B-2
Effect of Bias

Examples of bias include head correction, range offsets, reference leg heat-up or flashing and changes in flow element differential pressure because of process temperature changes. A bias error may have a random uncertainty associated with the magnitude.

Some bias effects, such as static head of the liquid in the sensing lines, can be corrected by the calibration process. These bias effects can be left out if verified to be accounted for by the calibration process. Note that other effects, such as density variations of the static head, might still contribute to the measurement uncertainty.

B.1.3 Arbitrarily Distributed Uncertainty

Some uncertainties do not have distributions that approximate the normal distribution. Such uncertainties may not be eligible for the square root of the sum of the squares combinations and are categorized as arbitrarily distributed uncertainties. Because they are equally likely to have a positive or a negative deviation, worst-case treatment should be used.

It is important that the user recognize that the direction (sign) associated with a bias is known, whereas the sign associated with an arbitrarily distributed uncertainty is not known but is assumed based on a worst-case scenario. For example, the environmental allowance (EA) term in the Westinghouse methodology is treated as an arbitrarily distributed uncertainty.

B.1.4 Independent Uncertainties

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

B.1.5 Dependent Uncertainties

Because of the complicated relationships that may exist between the instrument channels and various instrument uncertainties, it should be recognized that a dependency may exist between some uncertainties. The methodology presented here provides a conservative means for addressing these dependencies. If in the user's judgment, two or more uncertainties are believed to be dependent, then these uncertainties should be added algebraically to create a new, larger independent uncertainty. For example, this treatment has been applied to module drift and module accuracy in the Westinghouse methodology. For the purpose of this design standard, dependent uncertainties are those for which the user knows or suspects that a common root cause exists which influences two or more of the uncertainties with a known relationship.

B.2 Interpretation of Uncertainty Data

The proper interpretation of uncertainty information is necessary to ensure that high confidence levels are selected and that protective actions are initiated before safety limits are violated. Also, proper interpretation is necessary for the valid comparison of instrument field performance with setpoint calculation allowances. This comparison confirms the bounding assumptions of the appropriate safety analysis.

Accuracy (uncertainty) values should be based on a common confidence level (interval) of at least two standard deviations (95% corresponds to approximately 2 standard deviations). The use of three or more standard deviations may be unnecessarily conservative, resulting in reduced operating margin. Some uncertainty values may need to be adjusted to 2-standard deviation values.

For example, if a vendor reference accuracy for a 99% level (3 standard deviations) is given as ±6 psig, the 95% confidence level corresponds to ±4 psig (= 2/3 x 6). This approach assumes that vendor data supports this 3 standard deviation claim.

Performance specifications should be provided by instrument or reactor vendors. Data should include reference accuracy, drift, environmental effects and reference conditions. Since manufacturer performance specifications often describe a product line, any single instrument may perform significantly better than the group specification. If performance summary data is not available or if it does not satisfy the needs of the users, raw test data may need to be reevaluated or created by additional testing.

If an uncertainty is known to consist of both random and bias components, the components should be separated to allow subsequent combination of like components. Bias components should not be mixed with random components during the square root of the sum of the squares combination.

Historically, there have been many different methods of representing numerical uncertainty. Almost all suffer from the ambiguity associated with shorthand notation. For example, without further explanation, the symbol ± is often interpreted as the symmetric confidence interval associated with a random, normally distributed uncertainty. Further, the level of confidence may be assumed to be 68% (standard error, 1 standard deviation), 95% (2 standard deviations) or 99% (3 standard deviations). Still others may assume that the ± symbol defines the limits of error (reasonable bounds) of bias or non-normally distributed uncertainties. Vendors should be consulted to avoid any misinterpretation of their performance specifications or test results.

Reactor vendors typically utilize nominal values for uncertainties used in a setpoint analysis associated with initial plant operation. These generic values are considered conservative estimates, which may be refined if plant-specific data is available. Since plant-specific data may be less conservative than the bounding generic data, care should be taken to ensure that it is based on a statistically significant sample size.

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

The limited data base from an environmental qualification test also precludes adjusting the measured net effects for normal environmental uncertainties, reference accuracies, etc. Thus, the results of such tests describe several mutually exclusive categories of uncertainty. For example, the results of a severe environment test may contain uncertainty contributions from the instrument reference accuracy, measuring and test equipment 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.

In summary, avoid improper use of vendor performance data. Just as important, do not apply overly conservative values to uncertainty effects to the point that a setpoint potentially limits normal operation or expected operational transients. Because of the diversity of data summary techniques. notational ambiguities, inconsistent terminology and ill-defined concepts that have been apparent in the past, it is recommended that vendors be consulted whenever questions arise. If a vendor-published value of an uncertainty term (source) is confirmed to contain a significant bias uncertainty, then the ± value should be treated as an estimated limit of error. If the term is verified to represent only random uncertainties (no significant bias uncertainties), then the ± value should be treated as the 2-standard deviation interval for an approximately normally distributed random uncertainty.

B.3 Elements of Uncertainty

B.3.1 Process Measurement Effects

Process measurement effects (PME) are those effects that have a direct effect on the accuracy of a measurement. PME variables are independent of the process instrumentation used to measure the process parameter. PME can often be thought of as physical changes in the monitored parameter that can not be detected by conventional instrumentation.

The following are examples of PME variables:

- Temperature stratification and inadequate mixing of bulk temperature measurements
- Reference leg heatup and process fluid density changes from calibrated conditions
- Piping configuration effects on level and flow measurements
- Fluid density effects on flow and level measurements
- Line pressure loss and pressure head effects
- Temperature variation effect on hydrogen partial pressure
- Gas density changes on radiation monitoring

Some PME terms are easily calculated, some PME terms are quite complex and are obtained from Westinghouse documents, and other PME terms are allowances developed and justified by Westinghouse.

B.3.2 Primary Element Accuracy

Primary element accuracy (PEA) is generally described as the accuracy associated with the primary element, typically a flow measurement device such as an orifice, venturi, or other devices from which a process measurement signal is developed. The following devices are typically considered to have a primary element accuracy that requires evaluation in an uncertainty analysis:

- Flow venturi
- Flow nozzle
- Orifice plate
- RTD or thermocouple thermowell
- Sealed sensors such as a bellows unit to transmit a pressure signal

PEA can change over time because of erosion, corrosion, or degradation of the sensing device. Installation uncertainty effects can also contribute to PEA errors.

B.3.3 Reference Accuracy

Reference accuracy defines a limit that error will not exceed when a device is used under reference or specified operating conditions. An instrument's accuracy consists of three instrument characteristics: repeatability, hysteresis, and linearity. These characteristics occur simultaneously and their cumulative effects are denoted by a band that surrounds the true output (see Figure B-3). This band is normally specified by the manufacturer to ensure that their combined effects adequately bound the instrument's performance over its design life. Deadband is another attribute that is sometimes included within the reference accuracy (see Section B.3.9).

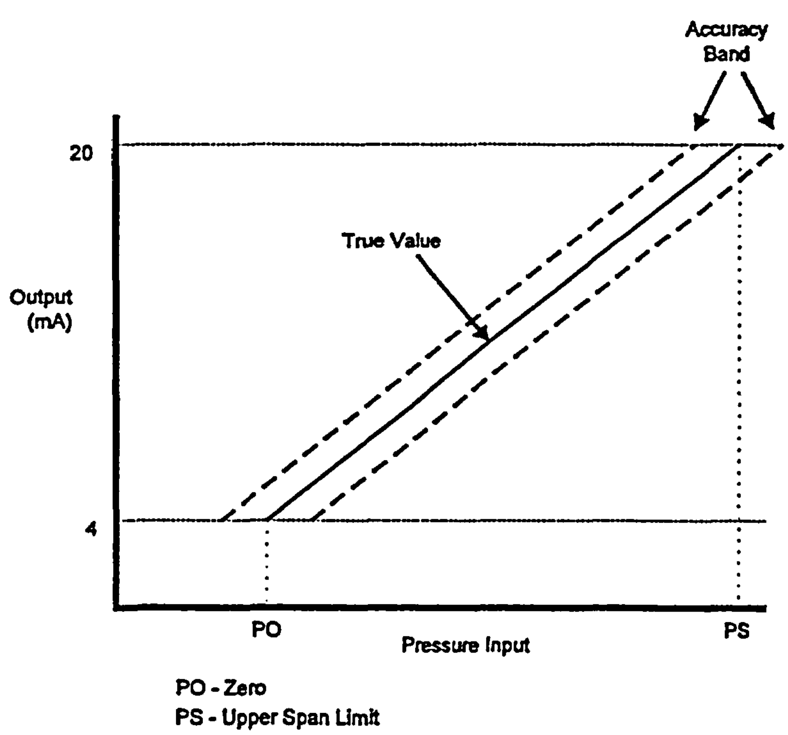


Figure B-3
Instrument Accuracy

Repeatability is an indication of an instrument's stability and describes its ability to duplicate a signal output for multiple repetitions of the same input. Repeatability is shown on Figure B-4 as the degree that signal output varies for the same process input. Instrument repeatability can degrade with age as an instrument is subjected to more cumulative stress, thereby yielding a scatter of output values outside of the repeatability band.

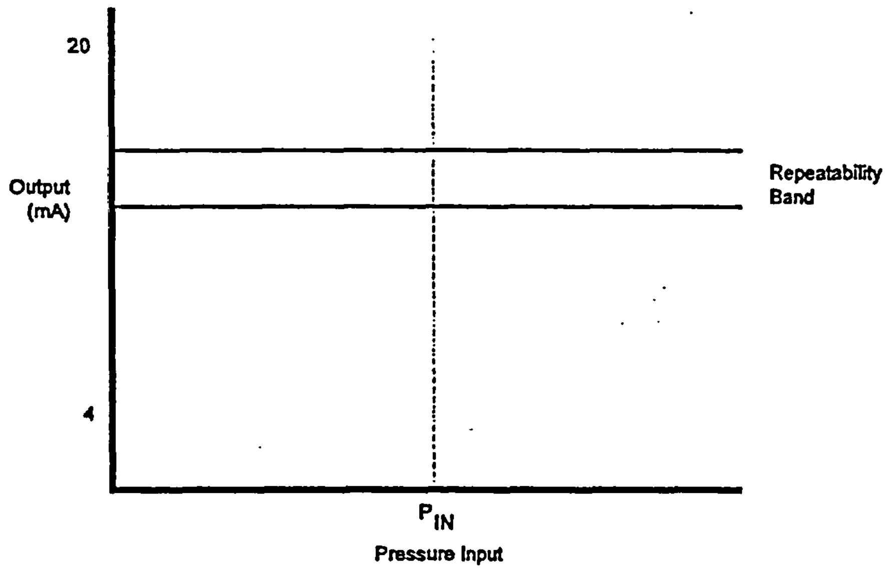


Figure B-4
Repeatability

Hysteresis describes an instrument's change in response as the process input signal increases or decreases (see Figure B-5). The larger the hysteresis, the lower is the corresponding accuracy of the output signal. Stressors can affect the hysteresis of an instrument.

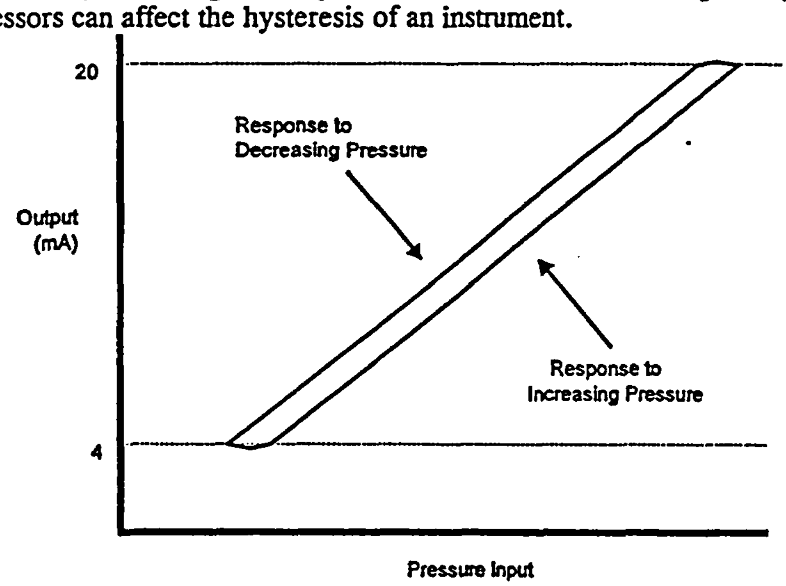


Figure B-5
Hysteresis

All instrument transmitters preferably exhibit linear characteristics, i.e., the output signal should be linearly and proportionately related to the input signal. Linearity describes the ability of the instrument to provide a linear output in response to a linear input (see Figure B-6). The linear response of an instrument can change with time and stress.

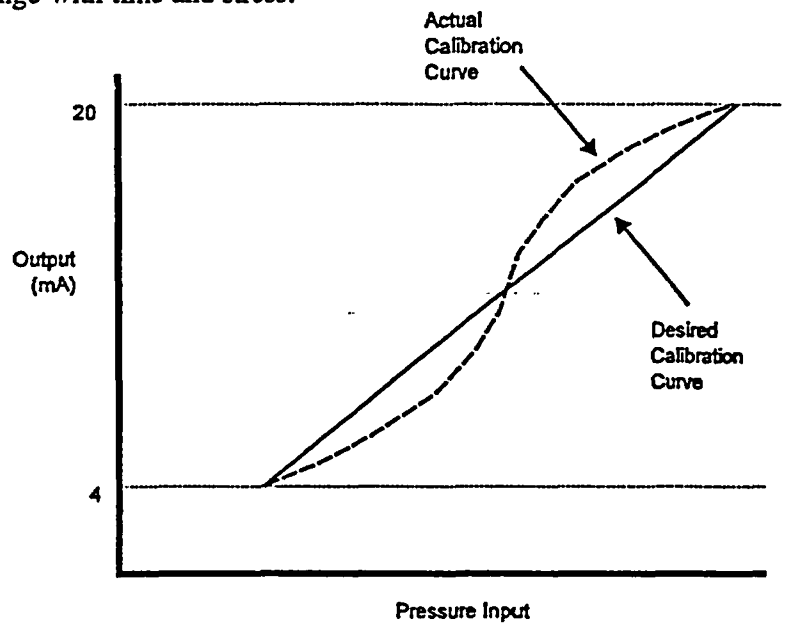


Figure B-6
Linearity

In cases in which the measurement process is not linear, the more appropriate term to use is conformity, meaning that the output follows some desired curve. Linearity and conformity are often used interchangeably.

As discussed, reference accuracy is generally described as the combined effect of hysteresis, linearity, and repeatability. These three separate effects are sometimes combined to form the bounding estimate of reference accuracy as follows:

$$RA = \pm(h^2 + l^2 + r^2)^{1/2} \quad \text{Eqn. B.1}$$

where,

RA	=	Reference accuracy
h	=	Hysteresis
l	=	Linearity
r	=	Repeatability

Accuracy can not be adjusted, improved, or otherwise affected by the calibration process. Rather, accuracy is a performance specification against which the device is tested during calibration to determine its condition. A 5-point calibration check (0%, 25%, 50%, 75%, and 100%) of an instrument's entire span verifies linearity. If a 9-point check is performed by checking up to 100% and back down to 0%, hysteresis is also verified. Finally, if the calibration check is performed a second time (or more), repeatability is verified. The calibration check process is rarely performed to a level of detail that also confirms repeatability. For this reason, the vendor's reference accuracy term should be checked to verify that it includes the combined effects of linearity, hysteresis, and repeatability. If the vendor's accuracy specification does not include all of these terms, the missing terms are included into the accuracy specification as follows:

$$RA = \pm(va^2 + h^2 + l^2 + r^2)^{1/2} \qquad \text{Eqn. B.2}$$

where,

RA	=	Revised estimate of reference accuracy
va	=	Vendor's stated accuracy with some terms not included
h	=	Hysteresis (if not already included)
l	=	Linearity (if not already included)
r	=	Repeatability (if not already included)

Reference accuracy is considered an independent and random uncertainty component unless the manufacturer specifically states that a bias or dependent effect also exists. Reference accuracy is normally expressed as a percent of instrument span, but this should be confirmed from the manufacturer's specifications.

Bistables, trip units, and pressure switches may not require a consideration of hysteresis and linearity because the calibration might be checked only at the setpoint. If the accuracy is checked at the setpoint for these devices, the accuracy elsewhere in the instrument's span is not directly verified.

The calibration process might not adequately confirm the reference accuracy if the measuring and test equipment (M&TE) uncertainty significantly exceeds the accuracy of the device being calibrated. For example, the calibration process can not verify a 0.1% accuracy specification with M&TE having an uncertainty of 0.5%. If the M&TE uncertainty exceeds the specified reference accuracy, then the reference accuracy should be considered no better than the M&TE allowance.

B.3.4 Drift

Drift is commonly described as an undesired change in output over a period of time; the change is unrelated to the input, environment, or load. A shift in the zero setpoint of an instrument is the most common type of drift. This shift can be described as a linear displacement of the instrument output over its operating range as shown in Figure B-7. Zero shifts can be caused by transmitter aging, an overpressure condition such as water hammer, or sudden changes in the sensed input that might stress or damage sensor components.

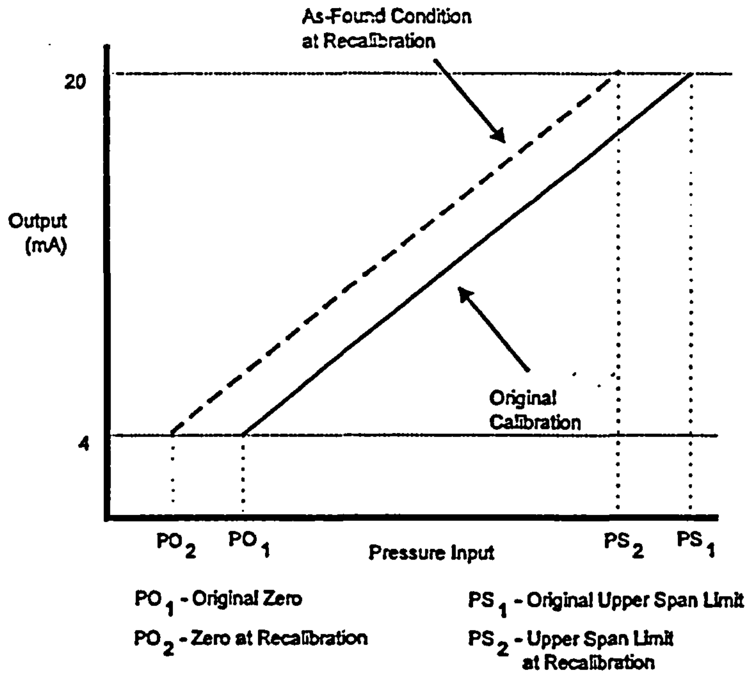


Figure B-7
Zero Shift Drift

Span shifts are less common than zero shifts and are detected by comparing the minimum and maximum current outputs to the corresponding maximum and minimum process inputs. Figure B-8 shows an example of forward span shift in which the instrument remains in calibration at the zero point, but has a deviation that increases with span. Reverse span shift is also possible in which the deviation increases with decreasing span.

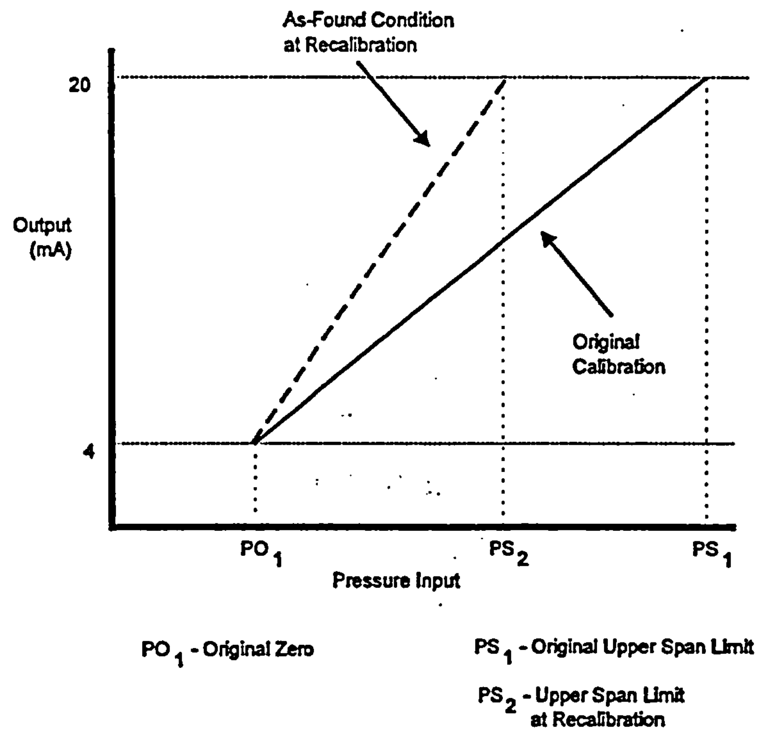


Figure B-8
Span Shift Drift

The amount of drift allowed for an instrument depends on the manufacturer's drift specifications and the period of time assumed between calibrations. For safety-related devices, the drift allowance should be based on the Technical Specification allowance for plant operation (previously 18 months and recently changed to 24 months) plus an additional allowance of 25%. Note that not all equipment is checked at this frequency; the Technical Specifications still states a shorter frequency for certain equipment, such as quarterly checks of bistables.

The manufacturer's specified drift is often based on a maximum interval of time between calibration checks. Several methods are available to adjust the drift allowance to match the calibration period of the instrument. If the instrument drift is assumed to be linear as a function of time, the drift allowance would be calculated as follows:

$$DR = (1.25 \times cp) \times vd \qquad \text{Eqn. B.3}$$

where,

DR	=	Drift allowance to be used in the uncertainty analysis
cp	=	Instrument calibration period (typically in months)
vd	=	Vendor's drift specification per unit of time (also in months)
1.25	=	Maximum allowance on time requirements in the Technical Specifications (30 ÷24 months)

For example, if the vendor provides a drift allowance of 0.5% per 6 months, the drift used in the uncertainty analysis for a 2-year fuel cycle could be as large as follows:

$$DR = \pm(1.25 \times 24 \text{ months}) \times (0.5\% \div 6 \text{ months}) = \pm 2.5\% \text{ of span}$$

The above approach assumes that the drift is a linear function of time that continues in one direction once it starts. In the absence of other data, this is a conservative assumption. However, if the vendor states that the drift during the calibration period is random and independent, then it is just a likely for drift to randomly change directions during the calibration period. In this case, the square root of the sum of the squares of the individual drift periods between calibrations could be used. In this case, the total drift allowance would be:

$$DR = \pm(0.5\%^2 + 0.5\%^2 + 0.5\%^2 + 0.5\%^2 + 0.5\%^2)^{1/2} = \pm 1.12\% \text{ of span}$$

Some vendors have stated that the majority of drift tends to occur in the first several months following a calibration and that the instrument output will not drift significantly after the "settle-in period". In this case, a lower drift value might be acceptable provided that the vendor can supply supporting data of this type of drift characteristic. Based on analyses of drift characteristics of typical components in service in IP3 and for reasons of conservatism, it is recommended that the following calculation be used for the 30-month drift value:

$$DR = \pm[DR_{yr}^2 + DR_{yr}^2 + (DR_{yr}^2 \div 2)]^{1/2}$$

In the above expression of drift, dr_{yr} represents the annual drift estimate and the resultant drift, DR, represents the 30-month drift estimate. If $dr_{yr} = 1\%$, the 30-month drift estimate is obtained by:

$$DR = \pm[1.0\%^2 + 1.0\%^2 + (1.0^2 \div 2)]^{1/2} = \pm 1.15\% \text{ of span}$$

Drift can also be inferred from instrument calibration data by an analysis of as-found and as-left (AFAL) data. Typically, the variation between the as-found reading obtained during the latest calibration and the as-left reading from the previous calibration is taken to be indicative of the drift during the calibration interval. By evaluating the drift over a number of calibrations for functionally-equivalent instruments, an estimate of the drift can be developed. Typically, the calibration data is used to calculate the mean of drift, the standard deviation of drift, and the tolerance interval that contains a defined portion of the drift data to a certain probability and confidence level (typically 95%/95%). This statistically-determined value of drift can be used to validate the vendor's performance specification and can also be used as the best estimate of drift in the uncertainty calculation. Assigning all of the statistically-determined drift from plant specific data is especially conservative because this drift allowance contains many other contributors to uncertainty, including:

- Instrument hysteresis and linearity error present during the first calibration
- Instrument hysteresis and linearity error present during the second calibration
- Instrument repeatability error present during the first calibration
- Instrument repeatability error present during the second calibration
- Measurement and test equipment error present during the first calibration
- Measurement and test equipment error present during the second calibration
- Personnel-induced or human-related variation or error during the first calibration
- Personnel-induced or human-related variation or error during the second calibration
- Instrument temperature effects due to a difference in ambient temperature between the two calibrations (this is particularly true for 18 month cycle plants in which the first calibration is performed in the winter and the second calibration is performed in the summer)
- Environmental effects on instrument performance, e.g., radiation, temperature, vibration, etc., between the two calibrations that cause a shift in instrument output

- Misapplication, improper installation, or other operating effects that affect instrument calibration during the period between calibrations
- True instrument "drift" representing a change, time-dependent or otherwise, in instrument output over the time period between calibrations

Regardless of the approach taken for determining the drift allowance, the uncertainty calculation should provide the basis for the value used. Continuous confirmation of the validity of the drift values used will be provided by application of IP3 Administrative Directive IC-AD-34, *Drift Monitoring Program* (Reference 3.2.5).

B.3.5 Temperature Effects

The ambient temperature is expected to vary somewhat during normal operation. This expected temperature variation can influence an instrument's output signal and the magnitude of the effect is referred to as the temperature effect. Larger temperature changes associated with accident conditions are considered part of the environmental allowance and the effect of larger temperature changes was determined as part of an environmental qualification test. The temperature effects described here only relate to the effect on instrument performance during normal operation.

The vendor normally provides an allowance for the predicted effect on instrument performance as a function of temperature. For example, a typical temperature effect might be ±0.75% per 100°F change from the calibrated temperature. This vendor statement of the temperature effect would be correlated to plant-specific performance as follows:

$$TE = \pm(|nt - ct| \times vte) \qquad \text{Eqn. B.4}$$

where,

TE	=	Temperature effect to assume for the uncertainty calculation
nt	=	Normal expected maximum or minimum temperature (both sides should be checked)
ct	=	Calibration temperature
vte	=	Vendor's temperature effects expression

For example, if the vendor's temperature effects expression is ±0.75% of span per 100°F, the calibration temperature is 70°F, and the maximum expected temperature is 110°F. This vendor statement of the temperature effect would be correlated to plant-specific performance as follows:

$$TE = \pm[|110°F - 70°F| \times (0.75\% \div 100°F)] = \pm 0.30\ \%\ \text{of span}$$

Notice that the above approach starts with the expected or estimated calibration temperature, and then determines the maximum expected variation from the calibration temperature under normal operating conditions. FSAR Section 5.1.1 describes the normal containment environment. Area surveys and temperature profiles in TSP-11 specify other plant location normal environments. The control room temperature is normally maintained between 55°F and 85°F, and is normally kept at 75°F. If an instrument is located inside an enclosure (cabinet) without forced ventilation, the assumed ambient temperature must consider the temperature inside the enclosure. NYPA Report, *Evaluation of Indian Point 3 Central Control Room Instrumentation and Cabinet Temperature Rise*, provides this information for selected applications.

The above discussion applies to temperature effects on instrumentation in response to expected ambient temperature variations during normal plant operation. Some manufacturers have also identified accident temperature effects that describe the expected temperature effect on instrumentation for even larger ambient temperature variations. An accident temperature effect describes an uncertainty limit for instrumentation operating outside the normal environmental limits.

Temperature effect is considered a random error term unless otherwise specified by the manufacturer.

B.3.6 Radiation Effects

During normal operation, most plant equipment is exposed to relatively low radiation levels. Although the lower dose rate radiation effects might have a nonreversible effect on an instrument, they can be eliminated by the calibration process. If the dose rate is low enough, the ambient environment might be considered mild during normal operation and radiation effects can be considered negligible. Any effects of relatively low radiation effects are considered indistinguishable from drift and are calibrated out during routine calibration checks.

If the normal operation dose rate is high enough that radiation effects should be considered, the environmental qualification test report will provide the best source of radiation effect information. During the worst-case accident environment, radiation effects can be part of the simultaneous effect of temperature, pressure, steam, and radiation that was determined during the environmental qualification process. Other plant locations might experience a more benign temperature and pressure environment, but still be exposed to significant accident radiation. For each case, the determination of the radiation effects should rely on the data in the environmental qualification report. Environmental qualification test report data should usually be treated as an arbitrarily distributed bias unless the manufacturer has provided data supporting its treatment as a random contributor to uncertainty.

B.3.7 Static Pressure Effects

Some devices exhibit a change in output because of changes in process or ambient pressure. A differential pressure transmitter might measure flow across an orifice with a differential pressure of a few hundred inches of water while the system pressure is over 1,000 psig. The system pressure is essentially a static pressure placed on the differential pressure measurement. The vendor usually specifies the static pressure effect; a typical example is shown below:

Static pressure effect = $\pm 0.5\%$ of span per 1,000 psig

The static pressure effect is a consequence of calibrating a differential pressure instrument at low static pressure conditions, but operating at high static pressure conditions.

If the static pressure effect is considered a bias by the manufacturer, the operating manual usually provides instructions for calibrating the instrument to read correctly at the normal expected operating pressure, assuming that the calibration is performed at low static pressure conditions. This normally involves changing the zero and span adjustments by a manufacturer-supplied correction factor at the low-pressure (calibration) conditions so that the instrument will provide the desired output signal at the high-pressure (operating) conditions. The device could also be calibrated at the expected operating pressure to reduce or eliminate this effect, but is not normally done because of the higher calibration cost and complexity.

Some static pressure effects act as a bias rather than randomly. For example, some instruments are known to read low at high static pressure conditions. If the bias static pressure effect is not corrected by the calibration process, the uncertainty calculation needs to include a bias term to account for this effect.

Ambient pressure variation can cause some gauge and absolute pressure instruments to shift up or down scale depending on whether the ambient pressure increases above or decreases below atmospheric pressure. Normally, this effect is only significant on 1) applications measuring very small pressures or 2) applications in which the ambient pressure variations are significant with respect to the pressure being measured. Gauge pressure instruments can be sensitive to this effect when the reference side of a sensing element is open to the atmosphere. If the direction of the ambient pressure change is known, the effect is a bias. If the ambient pressure can randomly change in either direction, the effect is considered random.

B.3.8 Overpressure Effect

In cases where an instrument can be over-ranged by the process pressure without the process pressure exceeding system design pressure, an overpressure effect must be considered. Overpressure effects are often considered in low-range monitoring instruments in which the reading is expected to go off-scale high as the system shifts from shutdown to operating conditions. Some pressure switches may also be routinely over-ranged during normal operation. The overpressure effect is normally considered random and is usually expressed as a percent uncertainty as a function of the amount of overpressure. The contribution of the overpressure effect on instrument uncertainty would only apply after the instrument has been over-ranged.

B.3.9 Deadband

Deadband represents the range within which the input signal can vary without experiencing a change in the output (see Figure B-9). The ideal instrument would have no deadband and would respond to input changes regardless of their magnitude. Instrument stressors can change the deadband width over time, effectively requiring a greater change in the input before a output response is achieved.

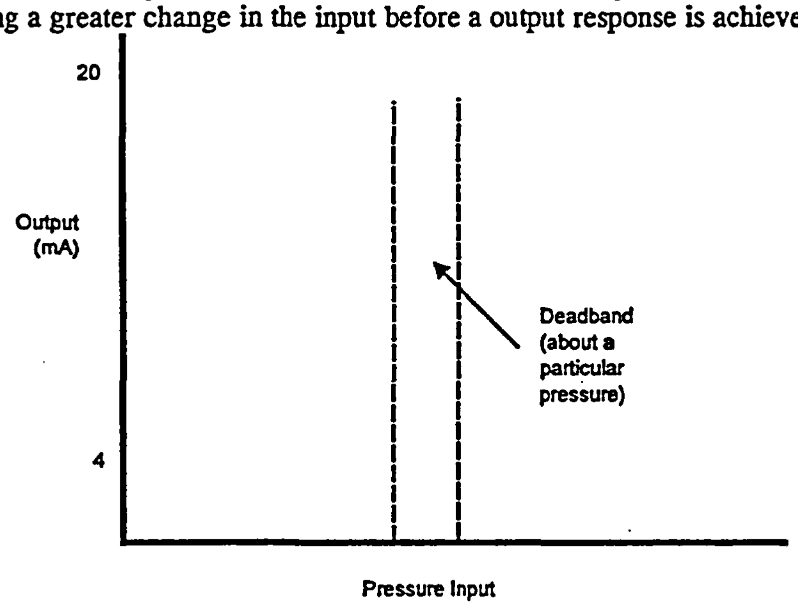


Figure B-9
Deadband

The vendor's instrument accuracy specification might include an allowance for deadband or it might be considered part of hysteresis (included in reference accuracy). Recorders generally have a separate allowance for deadband to account for the amount the input signal can change before the pen physically responds to the change.

Pressure switches are also susceptible to deadband. For this reason, a pressure switch setpoint near the upper or lower end of span should confirm that the setpoint allows for deadband. In extreme cases, the pressure switch might reach a mechanical stop with the deadband not allowing switch actuation.

B.3.10 Measuring and Test Equipment Uncertainty

Measuring and test equipment (M&TE) uncertainty is described in Attachment G.

B.3.11 Turndown Effect

If a transmitter has an adjustable span over some total range, the uncertainty expression may require adjustment by the turndown factor. For example, a transmitter may have a range of 3,000 psig with an uncertainty of 2% of the total range, sometimes referred to as the upper range limit (URL). If the span is adjusted such that only 1,000 psig of the entire 3,000 psig range is used, the transmitter has not somehow become more accurate. The 2% uncertainty of the 3,000 psig span is 60 psig, which equates to a 6% uncertainty for the 1,000 psig span. Transmitters with variable spans typically define performance specifications in terms of the total range and the calibrated span.

If the performance specifications are quoted as a percent of full span (FS), the uncertainty expression will not require an adjustment for the turndown factor.

B.3.12 Power Supply Effects

Power supply effects are the changes in an instrument's input-output relationship due to the power supply stability. For 2-wire current loop systems, AC supply variations must be considered for their effects on the loop's DC power supply. The consequential DC supply variations must then be considered for their effects on other components in the series loop, such as the transmitter.

Using the manufacturer's specifications, the power supply effect is typically calculated as follows:

$$PS = pss \times vpse \qquad \text{Eqn. B.5}$$

where,

PS	=	Power supply effect to assume for the uncertainty calculation
pss	=	Power supply stability
vpse	=	Vendor's power supply effect expression

Power supply stability refers to the variation in the power supply voltage under design conditions of supply voltage, ambient environment conditions, power supply accuracy, regulation, and drift. This effect can be neglected when it can be shown that the error introduced by power supply variation is ≤10% of the instrument's reference accuracy.

Harmonic distortion on the electrical system can also contribute to power supply uncertainty. Reference 3.3.5 provides additional information regarding the effect of harmonic distortion on power supply performance at IP3.

B.3.13 Indicator Reading Uncertainty

An analog indicator can only be read to a certain accuracy. The uncertainty of an indicator reading depends on the type of scale and the number of marked graduations. An analog indicator can generally be read to a resolution of ½ of the smallest division on the scale. Figure B-10 shows an example of a linear analog scale. As shown, the indicator would be read to ½ of the smallest scale. Anyone reading this scale is able to confirm that the indicator pointer is between 40 and 45. In this case, the estimated value would be 42.5. If an imaginary line is mentally drawn at the ½ of smallest scale division point, an operator can also tell whether the pointer is on the high side or the low side of this line. Therefore, the uncertainty associated with this reading would be ±¼ of the smallest scale division, or ±1.25 for the example shown in Figure B-10. Notice that this approach defines first the resolution to which the indicator could be read (½ of smallest scale division) with an uncertainty of ±¼ of smallest scale division about this reading resolution. In terms of an uncertainty analysis, it is not the reading resolution, but the uncertainty of the resolution that is of interest.

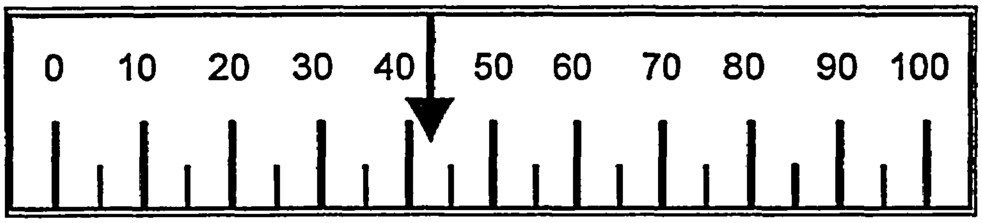


Figure B-10
Analog Scale

Type of Scale	Discussion
Analog Linear	An uncertainty of ±¼ of the smallest division should be assigned as the indication reading uncertainty.
Analog Logarithm or Exponential	Logarithm or exponential scales allow the presentation of a wide process range on a single scale. Radiation monitoring instruments commonly used an exponential scale. An uncertainty of ±¼ of the specific largest division of interest should be assigned as the indication reading uncertainty. This requires an understanding of where on the scale that the operators will be most concerned regarding the monitored process.
Analog Square Root	Square root scales show the correlation of differential pressure to flow rate. An uncertainty of ±¼ of the specific largest division of interest should be assigned as the indication reading uncertainty. This requires an understanding of where on the scale that the operators will be most concerned regarding the monitored process.
Digital	The reading uncertainty is the uncertainty associated with the least significant displayed digit which is usually negligible as an indication reading uncertainty. The digital display must be evaluated to confirm that the reading uncertainty is insignificant.
Analog Recorder	Analog recorders have the same reading uncertainties as do analog indicators. The only potential difference is that the indicator scale is fixed in place but the recorder chart paper can be readily replaced with a different scale paper. The chart paper used for the recorder should be checked to verify that the indication reading uncertainty can be estimated.

B.3.14 Seismic Effects

Two types of seismic effects should be considered: 1) normal operational vibration and minor seismic disturbances, and 2) design basis seismic events in which certain equipment performs a safety function.

The effects of normal vibration (or a minor seismic event that does not cause an unusual event) are assumed to be calibrated out on a periodic basis and are considered negligible. Abnormal vibrations (vibration levels that produce noticeable effects) and more significant seismic events (severe enough to cause an unusual event) are considered abnormal conditions that require maintenance or equipment modification.

Design basis seismic events can cause a shift in an instrument's output. For the equipment that must function following a design basis seismic or accident event, the environmental qualification test report should be reviewed to obtain the bounding uncertainty. The seismic effect may be specified as a separate effect or, in some cases, may be included in the overall environmental allowance.

For well-designed and properly mounted equipment, the seismic effect will often contribute no more than ±0.5% to the overall uncertainty. This effect can be considered random and can be included within the uncertainty expression as a random term. Including a small allowance for seismic effects is considered a conservative, but not required, approach to the uncertainty analysis.

B.3.15 Environmental Effects - Accident

The environmental allowance is intended to account for the effects of high temperature, pressure, humidity, and radiation that might be present during an accident, such as a LOCA or HELB event. Some manufacturers do not distinguish the uncertainties due to each of the accident effects. In such cases, the accident uncertainty may be a single ± value given for all accident effects.

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 available in the equipment qualification report. The manufacturer's specification sheet tends to be very conservative, as the worst-case performance result is normally presented.

Because of the limited sample size typically used in qualification testing, the conservative approach to assigning uncertainty limits is to use the bounding worst-case uncertainties. It is also recommended that discussions with the instrument manufacturer be conducted to gain insight into the behavior of the uncertainty (should it be considered random or bias?). This is important because if the uncertainty is random and of approximately the same magnitude as other random uncertainties, then SRSS methods might be used to combine the accident-induced uncertainty with other uncertainties. The environmental allowance should be of approximately the same size as the other random uncertainties if it is combined with other random terms in an SRSS expression. This consideration comes from the central limit theorem which allows the combination of uncertainties by SRSS as long as they are of approximately the same magnitude. If not, then the accident uncertainty should treated as an arbitrarily distributed uncertainty.

Using data from the qualification report in place of performance specifications, it is often possible to justify the use of lower uncertainty values that may occur at reduced temperatures or radiation dose levels. Typically, qualification tests are conducted at the upper extremes of simulated accident 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:

1. The highest uncertainties of all the units tested at the reduced temperatures or dose should be used. A margin should also be applied to the tested magnitude of the environmental parameter consistent with Institute of Electrical and Electronics Engineers 323-1975.

2. The units tested should have been tested under identical or equable conditions and test sequences.

3. If data for 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.

The requirement in Item (1) above is a conservative method to ensure that bounding uncertainties are used in the absence of a statistically valid sample size. Item (2) above is an obvious requirement for validity of this method. Item (3) ensures that sufficient thermal lag time through the instrument case is accounted for in drawing conclusions of performance at reduced temperatures. In other words, if a transmitter case has a one-minute thermal lag time, then ensure that the transmitter was held at the reduced temperature at least one minute prior to taking readings.

B.3.16 As-Left Tolerance Specification

The as-left tolerance establishes the required accuracy band that a device or group of devices must be calibrated to within and remain to avoid recalibration when periodically tested. If an instrument is found to be within the as-left tolerance, no further calibration is required for the instrument and calculations should assume that an instrument might be left anywhere within this tolerance.

The uncertainty calculation establishes the calibration as-left tolerance for a device. Historically, many IP3 instruments have had an as-left tolerance of $\pm 0.5\%$ of span. This tolerance was established because it is readily achievable by the calibration process and does not, in most cases, require special attention to measuring and test equipment accuracy. For all existing IP3 instruments, an as-left tolerance is already specified by the applicable calibration procedure. This as-left tolerance is recommended for use in the calculation unless other conditions suggest that a different tolerance is warranted. For example, a tighter tolerance is easily achievable for most electronic equipment and a tighter tolerance might provide needed margin for a setpoint calculation. Conversely, establishing a tighter tolerance than achievable by the device ensures that it will routinely be found out of calibration.

The as-left tolerance should be specified for all instruments covered by the associated calculation, even if the as-left tolerances are unchanged from the values already specified in the applicable calibration procedures. The as-left tolerance is treated as a random term in the uncertainty analysis.

B.3.17 As-Found Tolerance Specification

The as-found tolerance establishes the limit of error the defined devices can have and still be considered functional. The as-found tolerance will never be less than the as-left tolerance. The purpose of the as-found tolerance is to establish a level of drift within which the instrument is still clearly functional, but not so large that an allowable value determination is required. An instrument found outside the as-left tolerance but still within the as-found tolerance requires a recalibration but no further evaluation or response.

The as-found tolerance is generally defined to include the effects of reference accuracy, allowed drift, and as-left tolerance. The as-found tolerance is calculated as follows:

$$AFT = \pm \sqrt{RA^2 + DR^2 + ALT^2} \qquad \text{Eqn. B.14}$$

where,

AFT = As-found tolerance
RA = Device reference accuracy
DR = Device allowance for drift
ALT = As-left tolerance

The as-found tolerance should be specified for all instruments covered by the associated calculation. For certain instruments included in the Technical Specifications, the as-found tolerance as defined at IP3 impacts the allowable value calculation.

B.4 Uncertainty Analysis Methodology

An uncertainty calculation establishes a statistical probability and confidence level that bounds the uncertainty in the measurement and signal processing of a parameter such as system pressure or flow. Knowledge of the uncertainty in the process measurement is then used to establish an instrument setpoint or provide operators with the expected limits for process measurement indication uncertainty.

The basic approach used to determine the overall uncertainty for a given channel or module is to combine all terms that are considered random using the Square Root of the Sum of the Squares (SRSS) methodology, then adding to the result any terms that are considered nonrandom.

The basic formula for the uncertainty calculation takes the form of:

$$CU = \pm\sqrt{A^2 + B^2 + C^2} \pm \sum |F| + \sum L - \sum M \qquad \text{Eqn. B.6}$$

where,

A, B, C = Random and independent uncertainty terms. The terms are zero-centered, approximately normally distributed, and are indicated by a sign of $\pm$.

F = Arbitrarily distributed uncertainties (biases that do not have a specific known direction). The term is used to represent limits of error associated with uncertainties that are not normally distributed and do not have a known direction. The magnitude of this term is assumed to contribute to the total uncertainty in a worst-case direction and is indicated by a $\pm$ sign.

L and M = Biases (terms that are not random) with known direction. The terms can impart an uncertainty in a specific direction and, therefore, have a specific + or - contribution to the total uncertainty.

CU = Resultant uncertainty.

Note that the above bias terms do not all operate in the same direction. Although it could be argued that some bias terms operate in opposite directions and therefore should be somewhat self-canceling, the standard practice is to treat the positive and negative channel uncertainty separately, if bias terms are present. The reason for this approach is based on generally not knowing the actual magnitude of the bias terms at a particular instant; the bias terms are defined at bounding levels only. Accordingly, the maximum positive uncertainty is given by:

$$+CU = \sqrt{A^2 + B^2 + C^2} + \sum |F| + \sum L \qquad \text{Eqn. B.7}$$

The maximum negative uncertainty is given by:

$$-CU = -\sqrt{A^2 + B^2 + C^2} - \sum|F| - \sum M \qquad \text{Eqn. B.8}$$

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 algebraically summing the dependent random terms prior to calculating the SRSS. The uncertainty expression for such cases takes the following form:

$$CU = \pm\sqrt{A^2 + B^2 + C^2 + (D + E)^2} \pm \sum|F| + \sum L - \sum M \qquad \text{Eqn. B.9}$$

where,

D and E = Random dependent uncertainty terms independent of terms A, B, and C

B.5 Propagation of Uncertainty Through Modules

If signal conditioning modules such as scalars, summers, square root extractors, multipliers, or other similar devices are used in the instrument channel, the module's transfer function should be accounted for in the instrument uncertainty calculation. The uncertainty of a signal conditioning module's output can be determined when 1) the uncertainty of the input signal, 2) the uncertainty associated with the module, and 3) the module's transfer function are known. Equations have been developed to determine the output signal uncertainties for several types of signal conditioning modules. Refer to Attachment J for additional information.

B.6 Calculating Total Channel Uncertainty

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

Using the basic formulas described previously, the typical channel calculation takes the following form:

$$CU = \pm\sqrt{PME^2 + PEA^2 + Module\ 1^2 + \ldots + Module\ n^2} \pm \sum|F| + \sum L - \sum M \qquad \text{Eqn. B.10}$$

where,

CU = Total channel uncertainty. Depending on the loop, the uncertainty may be calculated for a setpoint(s), indication function, or control function. In some cases, all three functions may be calculated. Because each function will typically use different end-use devices, the channel uncertainty is calculated separately for each function.

PME = Random uncertainties that exist in the channel's basic process measurement. Refer to Attachment B for more information.

PEA = Random uncertainties that exist in a channel's primary element, if present, such as the accuracy of a flow orifice plate.

Module 1, *n* = Total random uncertainty of each module in the loop from Module 1 through Module *n*. For example, if Module 1 had three sources of uncertainty (a, b, and c), then the Module 1 term in the above equation would be of the form:

$$Module\ 1 = \pm\sqrt{a^2 + b^2 + c^2}$$

In actual loop tolerance calculations, the total module uncertainty will be designated "e",

where
$x = 1$ to n modules.

$\Sigma |F|$ = The total of all arbitrarily distributed uncertainties. The magnitude is taken of each individual term because a specific bias direction is not certain.

ΣL = The total of all positive biases associated with a channel. This includes any uncertainties from PME, PEA, or the modules that could not be combined as a random term.

ΣM = The total of all negative biases associated with a channel. This includes any uncertainties from PME, PEA, or the modules that could not be combined as a random term.

The biases for all modules would be combined outside the square root radical. Consider, for example an instrument loop with a +2% reference leg bias for PME, an arbitrarily distributed uncertainty of ±0.5% for Module 1, and a degraded insulation resistance effect of +1.0%. In this case, the bias terms are as follows:

$\Sigma L = B_{PME} + B_{IR} = 2.0\% + 1.0\% = 3.0\%$
$\Sigma M = 0\%$
$\Sigma |F| = \pm 0.5\%$

An instrument loop may contain several discrete instruments (modules) that process the measurement signal from sensor to display, or from sensor to bistable. An uncertainty calculation would determine the expected uncertainty for the selected instrument loop and each discrete component could have several uncertainty terms contributing to the overall expression for instrument uncertainty. For example, the sensor (typically considered Module 1) portion of the overall uncertainty calculation may contain any or all (or other) of the following uncertainty terms:

$$e_1 = \pm \sqrt{RA^2 + DR^2 + TE^2 + HE^2 + RE^2 + PS^2 + SP^2 + OP^2 + SE^2 + ALT^2 + MTE^2 + R^2}$$

$$\pm \sum |f| + \sum l - \sum m \qquad \text{Eqn. B.11}$$

where,

e_x = Total module uncertainty. When all module uncertainties are combined to calculate the channel uncertainty, CU, the random portion of the "e_x" terms is placed under the square root radical and the bias portions are combined algebraically.

RA = Sensor reference accuracy specified by the manufacturer.

DR = Drift of the sensor over a specific period. This has historically been the drift specified by the manufacturer.

TE = Temperature effect for the sensor; the effect of ambient temperature variations on the sensor accuracy.

HE = Humidity effect for the sensor; the effect of changes in ambient humidity on sensor accuracy, if any.

RE = Radiation effect for the sensor; the effect of radiation exposure on sensor accuracy.

PS = Power supply variation effects; the uncertainty due to instrument power supply variations.

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

OP = Overpressure effect; the effect of over ranging the pressure sensor of a transmitter.

SE = Seismic effect for the sensor; the effect of seismic or operational vibration on the sensor accuracy.

ALT = Calibration setting tolerances for the sensor; the uncertainty associated with calibration tolerances.

MTE = Maintenance and test equipment effect for the sensor; the uncertainties in the equipment utilized for calibration of the sensor.

R = Readability error associated with display functions.

f, l, m = Biases associated with the sensor, if any.

Note in the above example that the possible sources of uncertainty only include those associated with the sensor. Similar terms for signal isolators, indicators, bistables or other signal conditioning instruments would be combined to obtain an overall uncertainty expression for an entire instrument loop. The random uncertainty terms would be included with the sensor random terms within the square root radical. The bias terms are combined according to their direction outside the square root radical.

Table B-1 provides a checklist to consider when performing an uncertainty calculation.

Table B-1
Channel Uncertainty Calculation Checklist

	Task	Completed? Yes	Completed? No
1.	Diagram instrument channel.	☐	☐
2.	Identify functional requirements, including actuations, any EOP setpoint requirement.	☐	☐
3.	Identify operating times for functions.	☐	☐
4.	Identify environment associated with functions during defined operating times.	☐	☐
5.	Identify limiting environment and function.	☐	☐
6.	Identify process measurement effects (PME) associated with each function.	☐	☐
7.	Identify biases due to linear approximations of nonlinear functions (RTDs). Determine if the biases are of concern over the region of interest for the setpoint.	☐	☐
8.	Identify any modules with non-unity gains.	☐	☐
9.	Identify transfer function for each module with a non-unity gain.	☐	☐
10.	For each module, identify normal environment uncertainty effects, as applicable:		
	Primary element accuracy (PEA)	☐	☐
	Accuracy (A)	☐	☐
	Drift (D)	☐	☐
	Temperature effects (TE)	☐	☐
	Radiation effects (RE)	☐	☐
	Power supply effects (PS)	☐	☐
	Static pressure effects (SP)	☐	☐
	Overpressure effects (OP)	☐	☐
	Deadband (DB)	☐	☐
	Measuring and test equipment uncertainty (MTE)	☐	☐
	Turndown Effect (TD)	☐	☐
	Indicator reading uncertainty (R)	☐	☐
11.	For each module, identify harsh environment uncertainty effects, as applicable.		
	Accident temperature effects (ATE)	☐	☐
	Accident radiation effects (AR)	☐	☐
	Humidity effects (HE)	☐	☐
	Seismic effects (SE)	☐	☐
	EA (combination of the above)	☐	☐
12.	For electrical penetrations, splices, terminal blocks, or sealing devices in a harsh environment, determine current leakage effects.	☐	☐
13.	Classify each module and process effect as random or bias. Determine if any of the random terms are dependent. Combine dependent random terms algebraically before squaring in the SRSS.	☐	☐
14.	Combine random effects for each module by SRSS. Add bias effects algebraically outside the SRSS.	☐	☐
15.	If the instrument channel has a module with non-unity gain, the total uncertainties in the input signal to the module must be determined, the module transfer function effect on this uncertainty calculated, and the result combined with the non-unity gain module and downstream module uncertainties to determine total channel uncertainty.	☐	☐

B.7 Nominal Trip Setpoint Calculation

An uncertainty calculation defines the instrument loop uncertainty through a specific arrangement of instrument modules. This calculation is then used to determine an instrument setpoint based upon the safety parameter of interest. The relationship between the setpoint, the uncertainty analysis, and normal system operation is shown in Figure B-11.

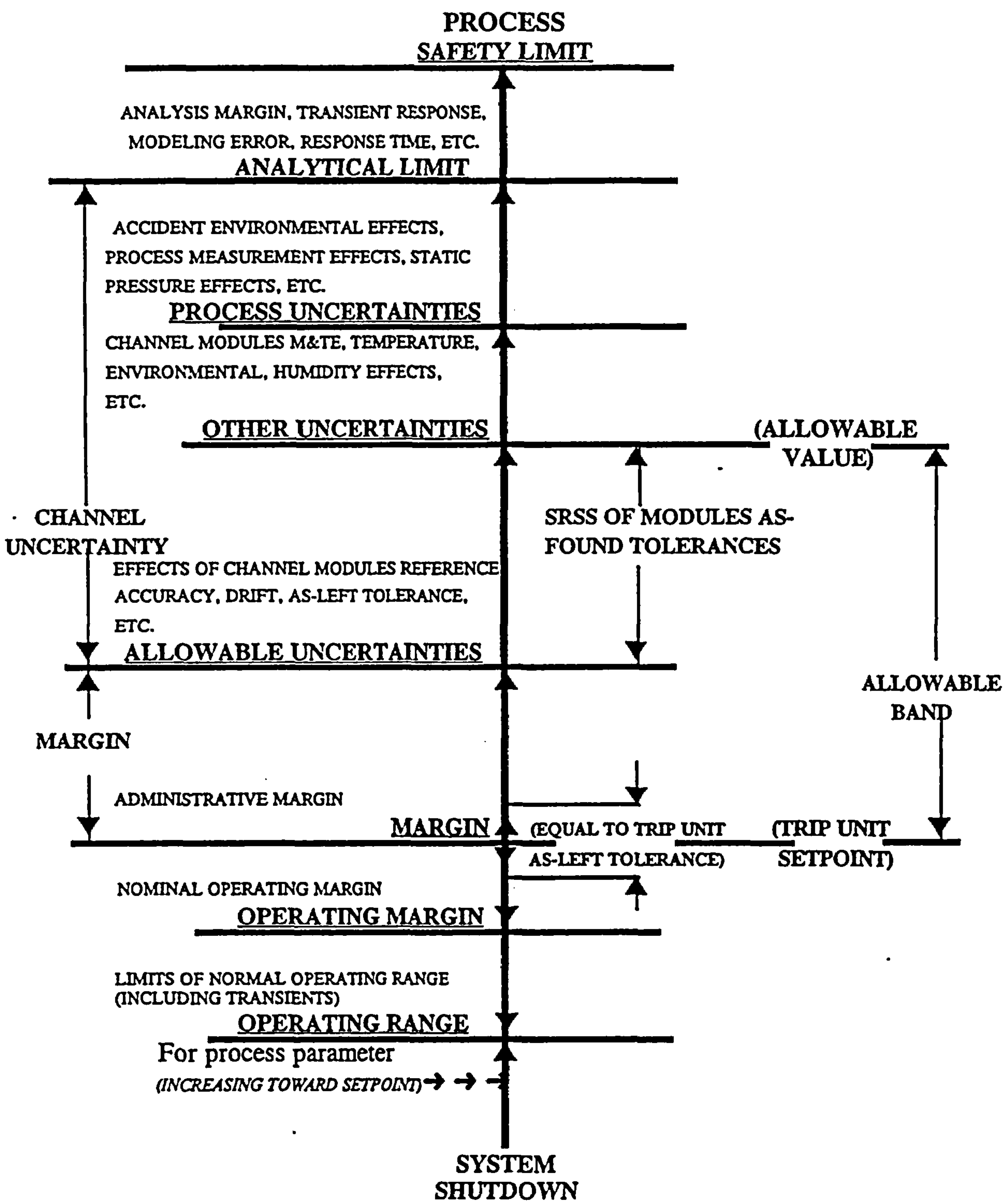


Figure B-11
Setpoint Relationships

The information provided in Figure B-11 prompts several observations:

- The relationships shown can vary between applications or plants, and is provided for illustrative purposes only.
- The setpoint has a nominal value. The upper and lower limits for the setpoint shown represent the allowed setting tolerance for the setpoint. Typically, an instrument found within the band defined by the setting tolerance does not require an instrument reset. For this reason, Figure B-11 refers to this band as the Leave-As-Is Zone.
- The setpoint relationship shown assumes that the process increases to reach the setpoint. If the process decreased towards the setpoint, the relationships shown in Figure B-11 would be reversed around the setpoint.
- The as-found tolerance is wider than the as-left tolerance and accounts for expected drift or certain other normal uncertainties during normal operation. Instruments found within the as-found tolerance, but outside the as-left tolerance require resetting with no further action. Instruments found outside the as-found tolerance require resetting and an evaluation to ensure that the allowable value was not exceeded.

Safety limits are established to protect the integrity of systems or equipment that guard against the uncontrolled release of radioactivity. Safety limits may also be established to protect against the failure, catastrophic or otherwise, of a system.

Analytical limits are established to ensure that the safety limit is not exceeded. The analytical limit includes the effects of system response times or actuation delays to ensure that the safety limit is not exceeded.

The allowable value is a value that the trip setpoint might have when tested periodically due to instrument drift or other uncertainties associated with the test. A setpoint found within the allowable value region, but outside the instrument setting tolerance, is usually considered acceptable with respect to the analytical limit. The instrument must be reset to return it within the allowed as-left tolerance. A setpoint found outside the allowable value region may require an evaluation for operability. Normally, an allowable value is assigned to Technical Specification parameters that also have an analytical limit.

The trip setpoint is the desired actuation point that ensures, when all known sources of measurement uncertainty are included, that an analytical limit is not exceeded. Depending on the setpoint, additional margin may exist between the trip setpoint and the analytical limit. The trip setpoint may be selected to ensure the analytical limit is not exceeded while also minimizing the possibility of inadvertent actuations during normal plant operation.

The relationship between the above parameters is expressed as follows:

$$TS = AL \pm (CU + Margin) \qquad \text{Eqn. B.12}$$

where,

TS	=	Trip setpoint
AL	=	Analytical limit
CU	=	Trip setpoint uncertainty (the channel uncertainty through the bistable)
Margin	=	An amount chosen, if desired, by the user for conservatism. Note that when the trip setpoint is very close to the systems's normal operating point, the margin may be very small or zero.

Some parameters do not have an analytical limit. However, there is often a process limit beyond which some action is desired. For example, a high level setpoint may start a pump to empty a tank and a low level setpoint may turn off the pump to prevent pump damage. In these cases, the trip setpoint is given by:

$$TS = NPL \pm (CU + Margin) \qquad \text{Eqn. B.13}$$

where,

TS	=	Trip setpoint
NPL	=	Nominal process limit
CU	=	Trip setpoint uncertainty (the channel uncertainty through the bistable)
Margin	=	An amount chosen, if desired, by the user for conservatism. Note that when the trip setpoint is very close to the systems's normal operating point, the margin may be very small or zero.

ATTACHMENT C
EFFECT OF INSULATION RESISTANCE ON UNCERTAINTY

C.1 Background

Under the conditions of high humidity and temperature associated with either a Loss of Coolant Accident (LOCA) or high energy line break (HELB), the insulation resistance (IR) may decrease in instrument loop components such as cables, splices, connectors, containment penetrations, and terminal blocks. A decrease in IR results in an increase in instrument loop leakage current and a corresponding increase in measurement uncertainty of the process parameters.

Degraded IR effects during a LOCA or HELB are a concern for instrumentation circuits due to the low signal current levels. A decrease in IR can result in substantial current leakage that should be accounted for in instrument setpoint and post accident monitoring uncertainty calculations. The NRC expressed concern with terminal block leakage currents in Information Notice 84-47. More recently, the NRC stated in Information Notice 92-12 that leakage currents should be considered for certain instrument setpoints and indication.

This Attachment provides an overview of IR effects on standard instrumentation circuits and provides examples of the effect of IR on instrument uncertainty. Specifically, this Attachment addresses the following:

- Qualitative effects of temperature and humidity on IR
- Analytical methodology for evaluating IR effects on instrument loop performance
- Technical information needed to perform an evaluation
- Application of results to uncertainty calculations
- Consideration of inherent margins in the analytical methodology

C.2 Environmental Effects on Insulation Resistance

IR is affected by changes in the environment. ASTM Standard D257-91, Standard Test Methods for D-C Resistance or Conductance of Insulating Materials, Appendix XI, provides a discussion of the factors that affect the resistance of a material. This ASTM standard discusses material properties in general; it does not limit itself to cables or any other type of particular construction. Factors that affect the resistance or the ability to measure resistance include:

- Temperature
- Humidity
- Time of electrification (electrical measurement of resistance)
- Magnitude of voltage
- Contour of specimen
- Measuring circuit deficiencies
- Residual charge

Temperature and humidity effects are of particular interest for circuits that may be exposed to an accident harsh environment. The resistance of an organic insulating material changes exponentially with temperature. Often, this variation can be presented in the form:

$$R = B \times e^{\left(\frac{m}{T}\right)} \qquad \text{Eqn. C.1}$$

where,

R = Resistance of an insulating material
B = Proportionality constant
m = Activation constant
T = Absolute temperature in degrees kelvin

One manufacturer predicts a similar exponential variation of IR with respect to temperature for their cable; the following equation is provided by the manufacturer for determining IR at a given temperature:

$$IR = (4 \times 10^{15}) \times \log\frac{D}{d} \times e^{(-0.079 \times T)} \qquad \text{Eqn. C.2}$$

where,

IR = Calculated cable insulation resistance, megohm for 1,000 ft
T = Temperature, degrees Kelvin
d = Diameter of conductor
D = Diameter of conductor and insulation

<u>Example C-1</u>

Using the above expression, a sample IR will be calculated at 300°F (422°K). Cable heatup due to current flow will be neglected for instrument cables since they carry no substantial current. Typical values for d and D are 0.051 in. and 0.111 in., respectively, for a 16 awg conductor.

$$IR = (4 \times 10^{15}) \times \log\frac{0.111}{0.051} \times e^{(-0.079 \times 422)} = 4.5 \ megohms \ per \ 1{,}000 \ ft$$

Using the above equation, a graph of the cable IR variation with temperature is provided in Figure C-1. This figure is illustrative only and does not necessarily apply to other configurations or materials.

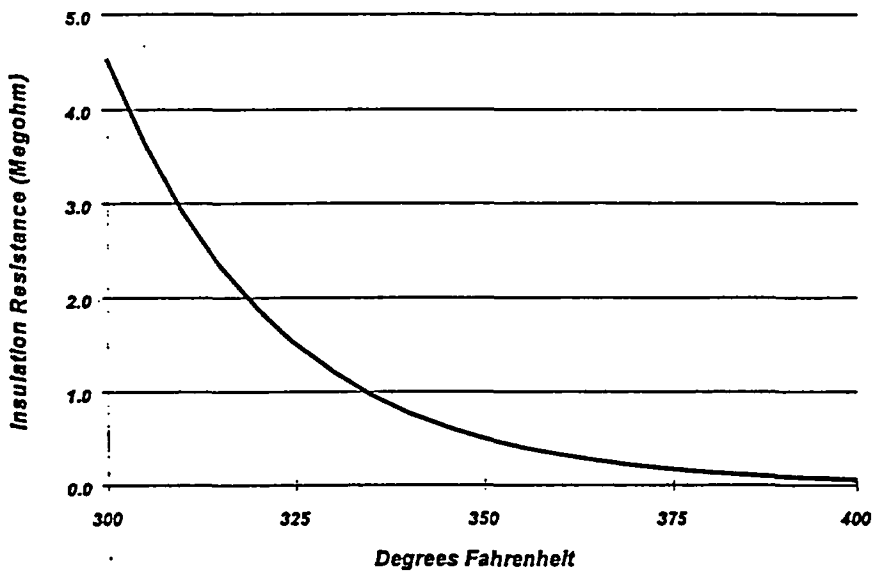


Figure C-1
Typical Cable Insulation Resistance Variation With Temperature

Insulation resistance of solid dielectric materials decreases with increasing temperature and with increasing humidity. Volume resistance of the insulating material is particularly sensitive to temperature changes. Surface resistance changes widely and very rapidly with humidity changes. In both cases, the change in IR occurs exponentially.

ASTM D257 discusses temperature and humidity as a combined effect on IR. In some materials, a change from 25°C to 100°C may change IR by a factor of 100,000 due to the combined effects of temperature and humidity. The effect of temperature alone is usually much smaller.

IR is a function of the volume resistance as well as the surface resistance of the material. In the case of an EQ test that includes steam and elevated temperatures, the minimum IR is expected near the peak of the temperature transient in a steam environment. Condensation of steam and chemical spray products will reduce the surface resistance substantially.

C.3 Analytical Methodology

C.3.1 Floating Instrument Loops (4 - 20 mA or 10 - 50 mA)

Instrument loops for pressure, flow or level measurement normally use a 4 to 20 mA (or 10 to 50 mA) signal. The instrument circuit typically consists, as a minimum, of a power supply, transmitter (sensor), and a precision load resistor from which a voltage signal is obtained for further signal processing. A typical current loop (without IR current leakage) is shown in Figure C-2.

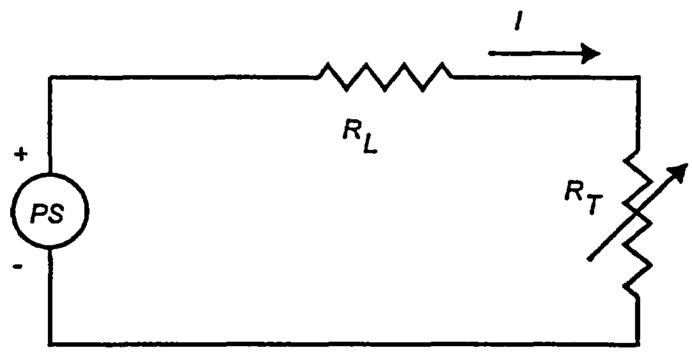


Figure C-2
Typical Instrument Circuit

In a current loop, the transmitter adjusts the current flow by varying its internal resistance, R_T, in response to the process. The transmitter functions as a controlled current source for a given process condition. The signal processor load resistor, R_L, is a fixed precision resistor. Under ideal conditions, the voltage drop across R_L is directly proportional to the loop current and normally provides the internal process rack signal.

If current leakage develops in an instrument loop due to a degraded insulation resistance, the path is represented as a shunt resistance, R_S, in parallel to the transmitter as shown in Figure C-3.

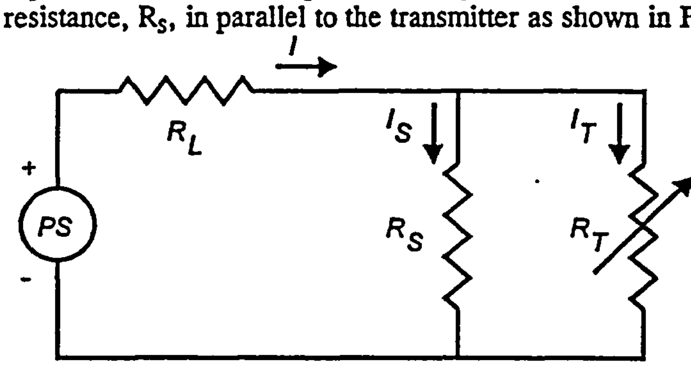


Figure C-3
Instrument Circuit With Current Leakage Path

Note that Figure C-3 applies only to floating instrument loops. In a floating instrument loop, the signal is not referenced to instrument ground. Thus, even if there is a low IR between cables or other instrument loop components to ground, the effect on instrument loop performance will be negligible as long as there is not a return path to ground for current flow. In this case, the only potential current leakage path is from conductor to conductor across the transmitter as shown in Figure C-3. See Section C.3.2 for the necessary analytical methodology if the signal negative is grounded.

Leakage current disrupts the one-to-one relationship between the transmitter current and load current, such that a measurement error is introduced at the load. For a standard 4 - 20 mA (or 10 to 50 mA) instrument loop, the error is always in the higher-than-actual direction, meaning that the load current will be higher than the transmitter output current. The magnitude of the error, E, caused by leakage is defined as the ratio of leakage current to the 16 mA span of a 4 - 20 mA loop, or,

$$E = \frac{I_s}{16}\ mA \qquad \text{Eqn. C.3}$$

This equation can be expressed in terms of voltage, current and resistance in the current loop consisting of a power supply, load resistance and low IR (shunt resistance) as follows:

$$V = (I_L \times R_L) + (I_S \times R_S) \qquad \text{Eqn. C.4}$$

where,

V = Power supply voltage
I_L = Current through the load resistor
I_S = Shunt current
R_L = Rack load resistance
R_S = Equivalent shunt (IR) resistance

Solving for I_S,

$$I_S = \frac{V - (I_L \times R_L)}{R_S} \qquad \text{Eqn. C.5}$$

Substituting Equation C.3 into Equation C.1 and converting all milliamps to amps yields the following result.

$$I_S = \frac{V - (I_L \times R_L)}{R_S \times (0.016)} \qquad \text{Eqn. C.6}$$

The error due to current leakage is inversely proportional to the IR, or R_S in the above equation. As R_S decreases, the loop error due to current leakage increases. Note that Equation C.4 has been simplified to provide an error in terms of percent span. For this case, the total instrument span is 16 mA for a 4 to 20 mA instrument loop.

R_S is an equivalent shunt resistance obtained from several parallel shunt paths. A typical circuit inside containment, showing all potential parallel current leakage paths, is shown in Figure C-4

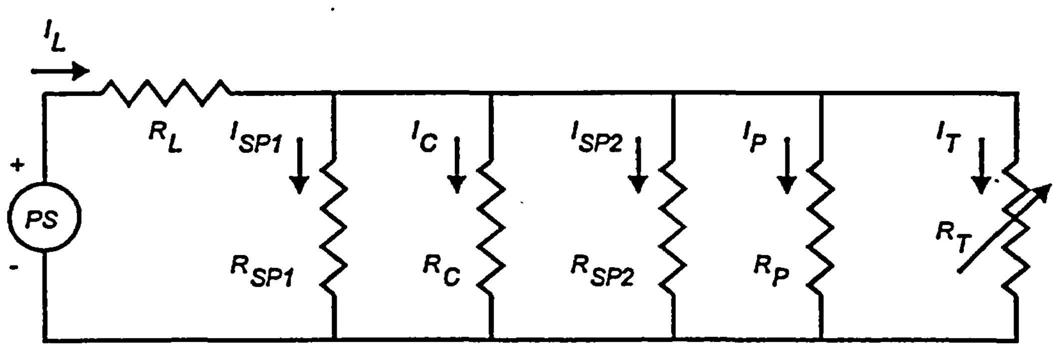


Figure C-4
Potential Current Leakage Paths

As depicted in Figure C-4, the current leakage paths include the following:

R_{SP1}	Raychem splice at sensor
R_C	Field cable
R_{SP2}	Raychem splice between field cable containment penetration
R_P	Containment penetration

Figure C-4 is intended to provide a feel for the various current leakage paths that might be present inside containment or a steam line break area; however, it is not necessarily complete. The containment penetrations might include the use of an extension (or jumper) cable to accomplish the transition from the field cable to the electrical penetration pigtail. Additional cables and splices may also be installed in the circuit, and each additional component should be included in the model. The splices can usually be combined into a single equivalent shunt resistance for purposes of analysis as shown in Figure C-5.

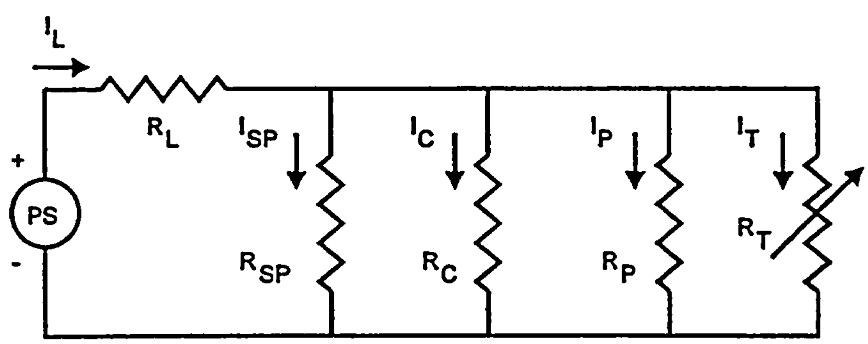


Figure C-5
Current Leakage Circuit Model

The total shunt resistance, R_S, shown on Figure C-3, is the parallel equivalent resistance of R_C, R_{SP}, and R_P shown above in Figure C-5. The equivalent resistance, R_S, for the parallel circuit can be calculated by Equation C.5.

$$\frac{1}{R_S} = \frac{1}{R_C} + \frac{1}{R_{SP}} + \frac{1}{R_P} \qquad \text{Eqn. C.7}$$

Remember that the above equation is conceptual; all sources of potential current leakage must be included by a careful analysis of the circuit. For a specific configuration, R_S calculated above is then applied to Equation C.4 to solve for the current leakage error.

<u>Example C-2</u>

Suppose we want to determine the IR that will affect the instrument loop uncertainty by 5%. The instrument loop conditions that yield the worst-case conditions for this example are as follows:

V = 50 VDC (highest typical loop power supply voltage)
I_L = 4 mA (0.004 A) (lowest possible loop current)
R_L = 250 ohm (lowest typical total load resistance).

Using Equation C.6,

$$5\% = \frac{50 - (0.004 \times 250)}{R_s \times (0.016)} \rightarrow R_s = 61{,}250 \ ohm$$

For a 10 to 50 mA loop, the result is as follows:

$$5\% = \frac{50 - (0.010 \times 100)}{R_s \times (0.040)} \rightarrow R_s = 24{,}500 \ ohm$$

The interpretation of the above result is that any combination of current leakage paths with an equivalent IR of 61,250 ohm can cause an error of 5% of span in a 4 to 20 mA loop. Note that the above example is based on a worst-case configuration. Any decrease in power supply voltage, or an increase in total load resistance or current, will result in a smaller percent error for a given shunt resistance. Note that leakage current is a bias, causing the load current to always be higher than the transmitter current.

C.3.2 Ground-Referenced Instrument Loops (4 - 20 mA or 10 - 50 mA)

The methodology provided in Section C.3.1 can be used if the signal negative is connected to ground; however, the circuit model is different in this case since there are additional current leakage paths than for a floating circuit. As discussed in Section C.3.1, a floating circuit is not ground-referenced; therefore, current leakage to ground is not likely since there is not a return path for current flow at the instrument power supply. In the case of an instrument loop with the signal current grounded at the instrument power supply, leakage paths to ground are possible since there is a return path to ground. This configuration is shown in Figure C-6.

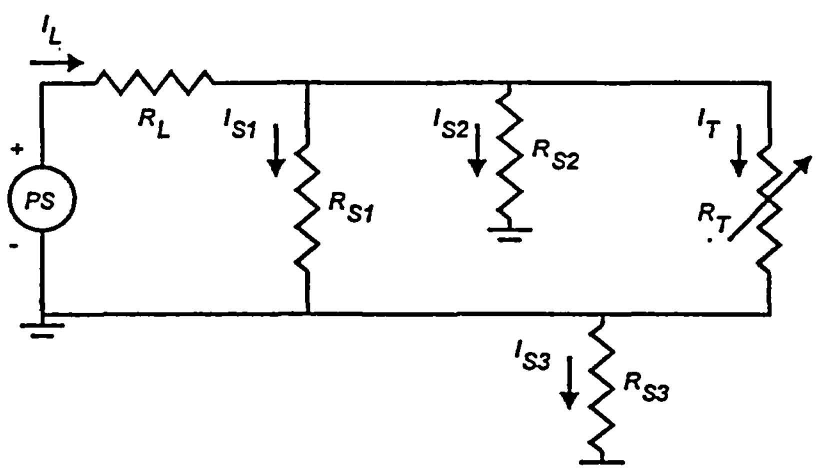


Figure C-6
Current Leakage Paths for a Ground-Referenced Instrument Loop

As shown in Figure C-6, the current leakage paths are as follows:

- R_{S1} Conductor-to-conductor for equivalent IR per Section C.3.1
- R_{S2} Positive conductor to ground IR equivalent resistance
- R_{S3} Negative conductor to ground IR equivalent resistance

All of the above terms are parallel equivalent resistances that are calculated from cables, connectors, splices, etc., in accordance with Equation C-5. Note that current leakage path R_{S3} can be neglected since it is effectively grounded at each end. The final configuration for analysis purposes is shown in Figure C-7.

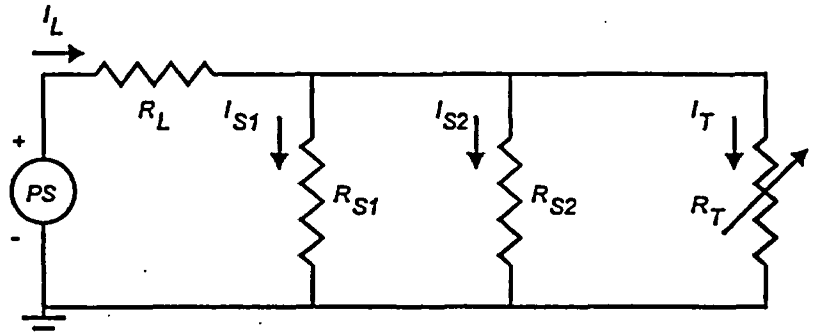


Figure C-7
Circuit Model for a Ground-Referenced Instrument Loop

The analysis of this circuit is identical to the methodology presented in Section C.3.1. Note that since there are additional current leakage paths, a ground-referenced instrument loop may be more susceptible to instrument uncertainty when its components are exposed to high temperature and humidity.

C.3.3 Resistance Temperature Detector Circuits (RTDs)

Resistance temperature detectors (RTDs) provide input to the Reactor Protection System and the Engineered Safety Features Actuation System. RTDs are also used for several post-accident monitoring functions. Because of these applications, the effect of degraded insulation resistance must be considered for RTD circuits. However, because of the difference in signal generation and processing, the analysis methodology is different than for 4 to 20 mA instrument loops.

An RTD circuit measures temperatures by the changing resistance of a platinum RTD, rather than a change in current. A typical 3-lead RTD circuit is shown in Figure C-8 (bridge and resistance to current [R/I] signal conditioner circuitry not shown for simplicity). Shunt resistances R_S and R_{SS} represent possible leakage current paths for this configuration.

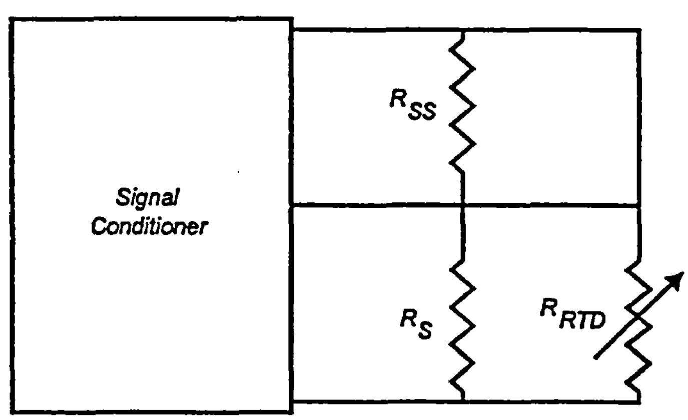


Figure C-8
RTD Circuit With Insulation Resistance Shown

The compensating lead wire resistance is approximately 0 ohms compared to the associated IR, R_{SS}. Therefore, R_{SS} is effectively shorted by the lead wire and will have no effect on the resistance signal received at the signal conditioner. This concept applies to 4-lead RTD circuits also. Shunt resistance (R_S) is in parallel with the RTD. The R/I signal conditioner will detect the equivalent resistance of the parallel resistances R_S and R_{RTD}. For this configuration, the equivalent resistance is R_E.

$$R_E = \frac{R_{RTD} \times R_S}{R_{RTD} + R_S} \qquad \text{Eqn. C.8}$$

The error, E, in °F introduced by the shunt resistance is defined as the difference between the temperature corresponding to the RTD resistance and the temperature corresponding to the equivalent resistance. In equation form,

$$E\ (°F) = Temp\ (R_E) - Temp\ (R_{RTD}) \qquad \text{Eqn. C.9}$$

Expressed in percent span,

$$E\ (\%) = \frac{Temp\ (R_E) - Temp\ (R_{RTD})}{Span} \times 100\% \qquad \text{Eqn. C.8}$$

Because the equivalent resistance seen by the signal conditioner will always be less than the RTD resistance, the resulting error will always be in the lower-than-actual temperature direction. In other words, the indicated temperature will always be lower than the actual temperature by the error amount.

<u>Example C-3</u>

As an example, calculate the IR in an RCS wide-range RTD instrument loop that will cause a 5 % error in temperature measurement. The instrument span is 700°F. Perform the evaluation at an RTD temperature of 700°F.

$$-5\% = \frac{Temp\ (R_E) - 700}{700} \times 100\%$$

or,

$$Temp\ (R_E) = 665°F$$

From standard 200Ω RTD tables, the corresponding resistance is approximately 466 ohm. This is the equivalent resistance R_E. The RTD resistance for 700°F is approximately 480 ohm. So, the IR shunt resistance can be calculated by equation C-6.

$$466 = \frac{480 \times R_S}{480 + R_S}$$

or,

$$R_S = 15{,}977\ \Omega$$

C.4 Information Required to Perform Analysis

The following information is normally obtained to complete an analysis of current leakage effects:

- Cable length and type in the area of interest
- Number of splices in the area of interest
- List of all potential current leakage sources. e.g., cables, containment penetrations, etc.
- EQ test report information providing measured insulation resistance for each component
- Instrument circuit power supply maximum rated output voltage
- Total instrument loop loading for the circuits of interest
- Instrument loop span (4 - 20 mA, 0-700°F, etc.)
- Power supply configuration, e.g., floating or grounded

<u>Example C-4</u>

Assuming the following design inputs, calculate the maximum uncertainty associated with IR current leakage effects. *Note: This is an example only and does not apply to a particular configuration.*

Containment electrical penetration IR: 4.4 x 10^6 Ω (obtained from EQ file)

Cable IR: 120 x 10^6 Ω/ft (obtained from EQ file)
Cable length inside containment is 250 ft (from design documents)
Note that cable IR is modeled as parallel resistances, or in this case, as 250 parallel resistances, each with a resistance of 120 x 10^6 Ω.
Or, cable IR = 120 x 10^6 / 250 = 0.48 x 10^6 Ω

Cable splices: 2.9 x 10^6 Ω (obtained from EQ file)

Perform calculation at maximum power supply voltage (assume 48 VDC) and minimum loading (4 mA on a floating loop).

First, calculate equivalent shunt resistance due to all IR paths:

$$\frac{1}{R_S} = \frac{1}{4.4 \times 10^6} + \frac{1}{0.48 \times 10^6} + \frac{1}{2.9 \times 10^6}$$

or,

$$R_S = 0.38 \times 10^6 \ \Omega$$

The error in percent span is calculated by:

$$\frac{48 - (0.004 \times 250)}{0.38 \times 10^6 \times (0.016)} = 0.77\% \ of \ span$$

This is the worst case configuration consisting of the minimum IR values from EQ test reports at the minimum loop loading. The uncertainty could be improved by including the actual instrument loop load. Also, the uncertainty could be calculated at the setpoint which often will have a higher loop current than the assumed 4 mA above.

C.5 Application of Results to Uncertainty Calculations

Uncertainty calculations are used to determine instrument setpoints or to establish bounds on measurement uncertainty for indication functions, such as post-accident monitoring. The basic expression for uncertainty calculations is as follows:

$$CU = \pm\sqrt{A^2 + B^2 + C^2} \pm \sum|F| + \sum L - \sum M$$

where,

A, B, C = Random and independent uncertainty terms. The terms are zero-centered, approximately normally distributed, and are indicated by a sign of ±.

F = Arbitrarily distributed uncertainties (biases that do not have a specific known direction). The term is used to represent limits of error associated with uncertainties that are not normally distributed and do not have a known direction. The magnitude of this term is assumed to contribute to the total uncertainty in a worst-case direction and is indicated by a ± sign.

L and M = Biases (terms that are not random) with known direction. The terms can impart an uncertainty in a specific direction and, therefore, have a specific + (L) or - (M) contribution to the total uncertainty.

CU = Resultant uncertainty.

Current leakage due to IR is a bias in the above instrument uncertainty equation. The direction of the bias depends on the type of circuit as follows:

- Instruments loops, e.g., 4 to 20 mA or 10 to 50 mA circuits, will indicate higher than actual. The bias term is positive.
- RTD circuits will indicate lower than actual. The bias term is negative.

C.6 Additional Considerations

Depending on the instrument loop components, the circuit configuration, and the existing margins in a calculation, the first pass on a calculation may indicate less-than-desired setpoint margins. In this case, the input parameters to the calculation can be reviewed for any inherent margin that can be justifiably removed from the analysis. The following should be considered:

- Worst case IR values from the EQ test report are typically used. If the worst case IR values are based on IR to ground measurements and the instrument loop of concern is floating, then only conductor-to-conductor leakage need be considered. This effectively doubles the IR to use for the calculation since the current leakage depends on the series IR of both conductor's insulation.
- If the EQ test attempted to envelope all plants and all postulated accidents with a high peak temperature, e.g., 450°F, but the plant requirement is to a lesser value, such as 300°F, then margin is contained in the test report. The IR of an insulating material decreases exponentially with temperature. The EQ test report should be reviewed to determine the measured IR at lower temperatures.

- The calculation may have been performed for the worst-case circuit configuration for the sake of simplicity. In this case, the calculation probably assumed the following circuit conditions:

  - Maximum power supply voltage
  - Minimum instrument loop loading
  - Minimum instrument loop current, e.g., 4 mA or 10 mA

  If the actual circuit configuration and desired current corresponding to the actual setpoint differs from the above assumptions, the calculation can be performed for the actual loop configuration and required setpoint to eliminate unnecessary conservatism.

- Consider the time during which the process parameter is required. If the instrument loop performs a trip function prior to the peak accident transient conditions or if the instrument loop provides a post-accident monitoring function after the peak accident transient conditions have passed, a lower value of IR may be defendable based upon a review of the appropriate EQ test reports.

C.7 Concluding Remarks

The effect of IR on instrument uncertainty is easily included into a setpoint or indication uncertainty calculation. This Attachment provides an analytical basis for current leakage calculations and discusses options to consider when the calculated results exceed the available margin.

Current leakage due to IR is not expected during normal operation. The methodology presented in this paper can also be used to determine IR effects during normal environmental conditions. Cable insulation resistance typically exceeds 1 megohm during normal operation. A comparison to Examples C-2 through C-4 readily shows that this high of insulation resistance provides a negligible contribution to the overall uncertainty.

ATTACHMENT D
FLOW MEASUREMENT UNCERTAINTY EFFECTS

D.1 Uncertainty of Differential Pressure Measurement

Differential pressure transmitters are generally used for flow measurement. The differential pressure measurement is normally obtained across a flow restriction such as a flow orifice, nozzle, or venturi. Each type of flow measurement device is briefly described below:

- A flow orifice is a thin metal plate clamped between gaskets in a flanged piping joint. A circular hole in the center, smaller than the internal pipe diameter, causes a differential pressure across the orifice plate that is measured by the differential pressure transmitter. A flow orifice is inexpensive and easy to install, but it has the highest pressure drop of all flow restrictor types.
- The flow nozzle is a metal cone clamped between gaskets in a flanged piping joint so that the cone tapers in the direction of fluid flow. The nozzle does not cause as large a permanent reduction in pressure as does the orifice because the entrance cone guides the flow into the constricted throat section, reducing the amount of turbulence and fluid energy loss.
- A flow venturi is a shaped tube inserted in the piping as a short section of pipe. The venturi has entrance and exit cones that serve as convergent and divergent nozzles, respectively, guiding the flow out of, as well as into, the constricted throat area. The venturi design is the most efficient and accurate of the flow restrictors. However, it is also the most expensive and difficult to maintain.

Regardless of how the pressure drop is created, flow transmitters measure the differential pressure across the flow restrictor. The high pressure connection is always made upstream of the flow restrictors. The low pressure connection is made downstream of orifices and nozzles (the exact location can vary), and in the constricted throat section of a venturi.

Flow is proportional to the square root of the differential pressure. This means that flow and differential pressure have a nonlinear relationship. The uncertainty also varies as a function of the square root relationship. The following example considers flow accuracy as a function of flow rate.

<u>Example D-1</u>

This example is illustrative only and does not directly correlate to any particular system flow rates or designs. However, the relative change in accuracy as a function of flow is considered representative of expected performance. A flow transmitter is used to monitor system flow. The instrument loop diagram is shown in Figure D-1.

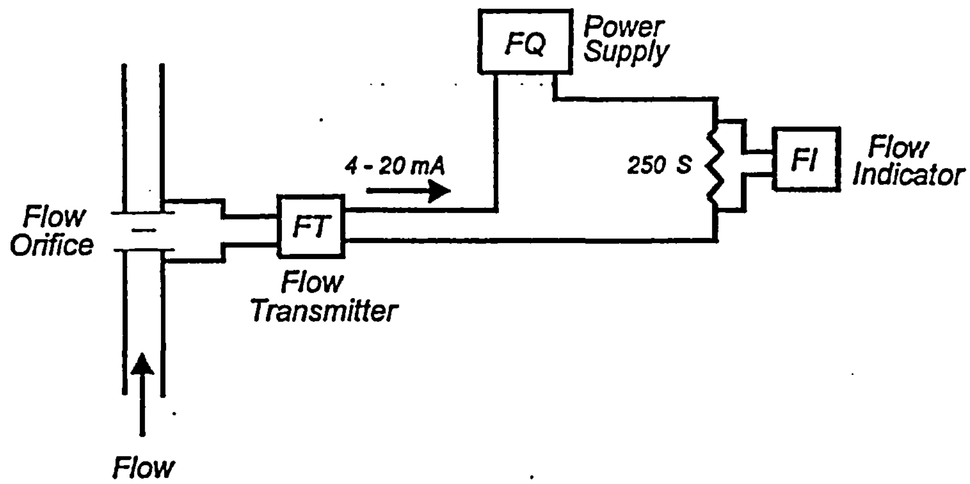


Figure D-1
Flow Monitoring Instrument Loop Diagram

The flow transmitter measures the differential pressure across the flow orifice. The relationship between flow in gpm and the differential pressure in inches is given by:

$$Flow = k\sqrt{\rho\ \Delta P} \qquad \text{Eqn. D.1}$$

The constant, k, is the flow constant for a specified configuration and the term, ρ, is the density of water at the design operating temperature (refer to ASME MFC-3M-1989 for a detailed explanation of the flow equation). If we assume that the fluid temperature is essentially constant, the density can be incorporated into the flow constant and the above expression simplifies to:

$$Flow = k\sqrt{\Delta P} \qquad \text{Eqn. D.2}$$

For this example and assuming constant fluid temperature, the maximum flow will be given as 1,500 gpm when differential pressure is 100 inches. Therefore, the flow constant is:

$$k = \frac{Flow}{\sqrt{\Delta P}} = \frac{1{,}500}{\sqrt{100}} = 150$$

Assume that the following measurement uncertainties were provided by the various manufacturers:

Flow Orifice
- Accuracy (PEA) - ±1.5%

Flow Transmitter
- Accuracy (TA) - ±0.5%
- Drift (TD) - ±1.0%
- Temperature Effects (TE) - ±0.5%

Indicator
- Accuracy (IA) - ±0.5%
- Drift (ID) - ±1.5%

Input Resistor
- Accuracy (RA) - ±0.1%

Assume that all of the above uncertainty terms are random and independent for this example. The transmitter is providing an output signal proportional to the differential pressure across the flow orifice.

For this reason, we should first determine the uncertainty in our differential pressure measurement. The flow uncertainty can be estimated by taking the square root of the sum of the squares of the individual component uncertainties:

$$Z = \sqrt{PEA^2 + TA^2 + TD^2 + TTE^2 + IA^2 + ID^2 + RA^2}$$

$$Z = \sqrt{1.5^2 + 0.5^2 + 1.0^2 + 0.5^2 + 0.5^2 + 1.5^2 + 0.1^2}$$

$$= \pm 2.5\%, \; = \pm 2.5 \textit{ inches } \Delta P$$

Now, remember that our understanding of flow is based on the square root relationship between flow and differential pressure. Because, the relationship is not linear, we must consider the flow uncertainty at specific points. We already determined that flow is related to differential pressure by the following expression:

$$Flow = 150 \times \sqrt{\Delta P}$$

Table D-1 provides the flow-to-ΔP relationship at different flow points:

Percent of Full Scale Flow	Flow (gpm)	Differential Pressure (inches)
100%	1,500	100.00
75%	1,125	56.25
50%	750	25.00
25%	375	6.25
10%	150	1.00

Table D-1
Flow Versus Differential Pressure for Example D-1

Now, let's estimate our uncertainty in flow for each of the above flow rates based on the ±2.5 inches of measurement uncertainty in differential pressure.

$$100\%: \quad Flow = 150 \times \sqrt{100 \pm 2.5} = 1{,}500 \begin{smallmatrix} +19 \\ -19 \end{smallmatrix} \; gpm$$

$$75\%: \quad Flow = 150 \times \sqrt{56.25 \pm 2.5} = 1{,}125 \begin{smallmatrix} +25 \\ -25 \end{smallmatrix} \; gpm$$

$$50\%: \quad Flow = 150 \times \sqrt{25 \pm 2.5} = 750 \begin{smallmatrix} +37 \\ -38 \end{smallmatrix} \; gpm$$

$$25\%: \quad Flow = 150 \times \sqrt{6.25 \pm 2.5} = 375 \begin{smallmatrix} +69 \\ -85 \end{smallmatrix} \; gpm$$

$$10\%: \quad Flow = 150 \times \sqrt{1.00 \pm 2.5} = 150 \begin{smallmatrix} +130 \\ -150 \end{smallmatrix} \; gpm$$

If the flow versus the uncertainty of that flow measurement is graphed, the relative uncertainty at low flow conditions is readily apparent (see Figure D-2). This example shows the problem of obtaining accurate flow measurements by differential pressure at low flow conditions. The use of more accurate instrumentation would change the magnitude of the uncertainty, but would not affect the relative difference in uncertainty at low flow versus high flow conditions.

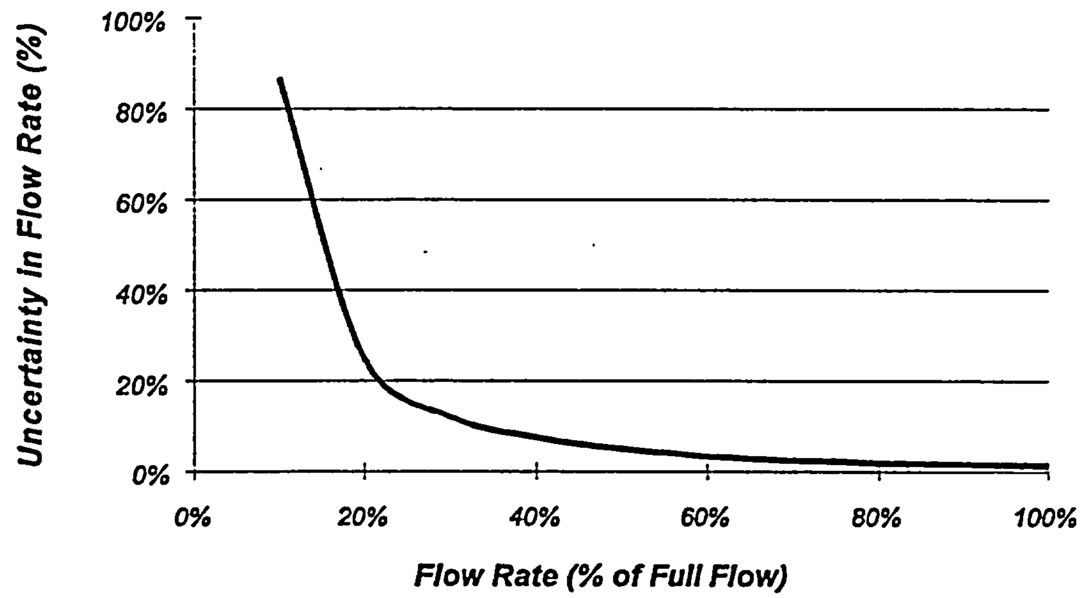


Figure D-2
Flow Uncertainty as a Function of Flow Rate

D.2 Effects of Piping Configuration on Flow Accuracy

Bends, fittings and valves in piping systems cause flow turbulence. This can cause process measurement uncertainties to be induced in flow elements. ASME has published guidance for various types of installation examples to show the minimum acceptable upstream/ downstream lengths of straight pipe before and after flow elements. Following this ASME guidance helps reduce the effect of this turbulence. The piping arrangement showing locations of valves, bends, fittings, etc., can usually be obtained from piping isometric drawings. ASME MFC-3M-1989, *Measurement of Fluid Flow in Pipes Using Orifice, Nozzle, and Venturi*, states that, if the minimum upstream and downstream straight-pipe lengths are met, the resultant flow measurement uncertainty for the piping configuration (not including channel equipment uncertainty) should be assumed to be 0.5%. If the minimum criteria cannot be met, additional uncertainty (at least 0.5%) should be assumed for conservatism based on an evaluation of the piping configuration and field measurement data, if available.

D.3 Varying Fluid Density Effects on Flow Orifice Accuracy

In many applications, process liquid and gas flow are measured using orifice plates and differential pressure transmitters. The measurement of concern is either the volumetric flow rate or the mass flow rate. Many reference books and standards have been written using a wide variety of terminology to describe the mathematics of flow measurement, but in basic form, the governing equations are:

$$Q = k \times A \times \sqrt{\frac{\Delta P}{\rho}} \qquad \text{Eqn. D.3}$$

and

$$W = k \times A \times \sqrt{\Delta P \times \rho} \qquad \text{Eqn. D.4}$$

where,

Q	=	Volumetric flow rate
W	=	Mass flow rate
A	=	Cross-sectional area of the pipe
ΔP	=	Differential pressure measured across the orifice
ρ	=	Fluid density
K	=	Constant related to the beta ratio, units of measurement, and various correction factors

As shown above, the density of the fluid has a direct influence on the measured flow rate. Normally, a particular flow-metering installation is calibrated or sized for an assumed normal operating density condition. As long as the actual flowing conditions match the assumed density, additional related process errors should not be present; however, some systems, such as safety injection, perform dual roles in plant operation. During normal operation, these systems may be aligned to inject makeup to the Reactor Coolant System from relatively low temperature sources of water. During the recirculation phase of a LOCA, the pump suction is shifted to the Containment sump, which contains a much higher temperature water.

If the flow-measuring system has been calibrated for the normal low-temperature condition, significant process uncertainties can be induced under accident conditions when the higher-temperature (lower-density) water is flowing. Of course, the flow measurement could be automatically compensated for density variations, but this is not the usual practice except on systems such as steam flow measurement.

To examine the effects of changing fluid density conditions, a liquid flow process shall be discussed. For most practical purposes, K and A can be considered constant. Actually, temperature affects K and A due to thermal expansion of the orifice, but this is assumed to be constant for this discussion to quantify the effects of density alone. If the volumetric flow rate, Q, is held constant, it is seen that a decrease in density will cause a decrease in differential pressure (ΔP), causing a measurement uncertainty. This occurs because the differential pressure transmitter has been calibrated for a particular differential pressure corresponding to a specific flow rate. A lower ΔP due to a lower fluid density causes the transmitter to indicate a lower flow rate.

Assuming the actual flow remains constant between a base condition (the density at which the instrument is calibrated, ρ_1) and an actual condition (ρ_2), an equality may be written between the base flow rate (Q_1) and actual flow rate (Q_2), as shown below:

$$Q_1 = Q_2$$

or

$$k \times A \times \sqrt{\frac{\Delta P_2}{\rho_2}} = k \times A \times \sqrt{\frac{\Delta P_1}{\rho_1}}$$

or

$$\frac{\Delta P_2}{\rho_2} = \frac{\Delta P_1}{\rho_1}$$

$$\frac{\Delta P_2}{\Delta P_1} = \frac{\rho_2}{\rho_1}$$

Density is the inverse of specific volume, SV. Accordingly, the above expression can be restated in terms of specific volume.

$$\frac{\Delta P_2}{\Delta P_1} = \frac{SV_1}{SV_2}$$

ATTACHMENT E
LEVEL MEASUREMENT TEMPERATURE EFFECTS

E.1 Level Measurement Overview

Differential pressure transmitters are typically used for level measurement involving an instrument loop. One side of a d/p cell is connected to a water column of fixed height (often called a reference leg) and the other side is connected to the fluid whose level is to be measured (see Figure E-1).

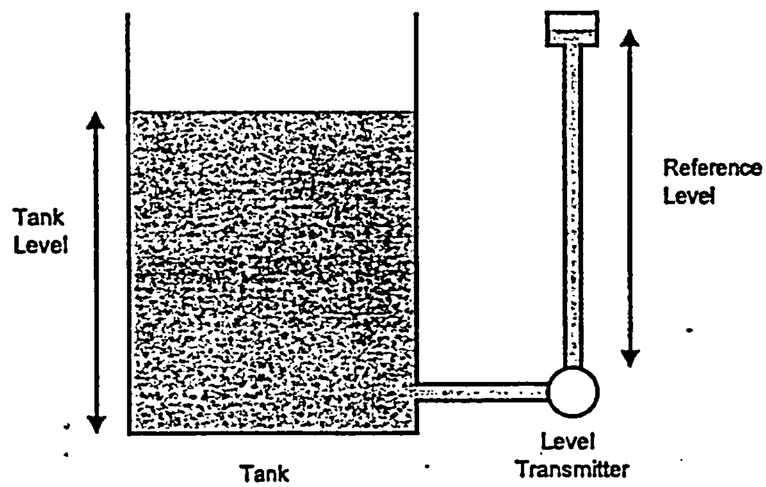


Figure E-1
Simplified Level Measurement in a Vented Tank

The measured level in Figure E-1 is determined by the pressure caused by the column of water in the reference leg minus the pressure caused by the water level in the tank:

$$\Delta P = (L_{ref} \times \gamma_{ref}) - (L_{tank} \times \gamma_{tank}) \qquad \text{Eqn. E.1}$$

where,

L_{ref} - Height of liquid in reference leg
γ_{ref} - Specific weight of liquid in reference leg
L_{tank} - Height of liquid in tank
γ_{tank} - Specific weight of liquid in tank

Notice in this case that tank level and differential pressure are inversely related. Maximum differential pressure occurs at minimum tank level.

As implied by the above expression, the specific weight of the liquid in the reference leg may not equal the specific weight of liquid in the tank. The two liquids might be at different temperatures (or might even be different liquids in the case of sealed reference legs). One example is a steam generator in which the reference leg will be at a different temperature than the steam generator water temperature unless design provisions are made to keep the temperatures the same. This configuration is shown in Figure E-2.

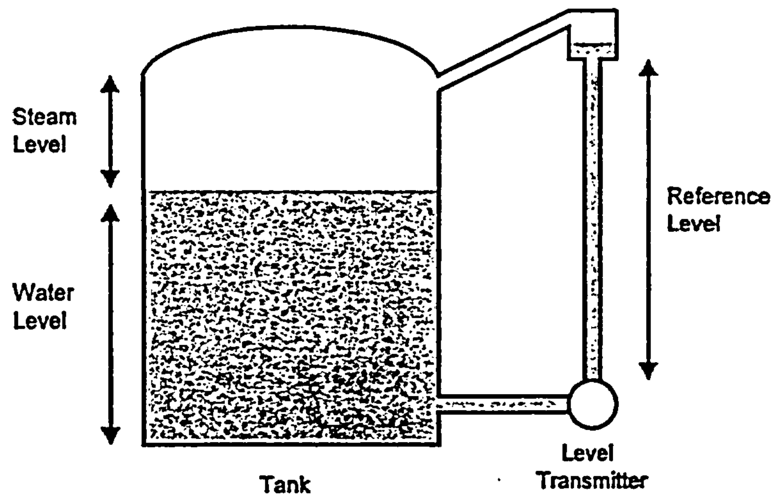


Figure E-2
Level Measurement in a Steam Generator

The measured level in Figure E-2 is determined by the pressure caused by the column of water in the reference leg minus 1) the pressure caused by the water level and 2) the pressure caused by the steam above the water in the steam generator:

$$\Delta P = (L_{ref} \times \gamma_{ref}) - (L_{SG} \times \gamma_{SG}) - (L_{steam} \times \gamma_{steam}) \qquad \text{Eqn. E.2}$$

where,

- L_{ref} - Height of liquid in reference leg
- γ_{ref} - Specific weight of liquid in reference leg
- L_{SG} - Height of liquid in steam generator
- γ_{SG} - Specific weight of liquid in steam generator
- L_{steam} - Height of steam above the liquid in steam generator up to the reference leg
- γ_{steam} - Specific weight of steam

The specific weight of saturated steam is about one-sixth of water at about 650°F. As shown in the above expression, this steam weight has an effect on the differential pressure. Any steam higher than the entrance to the reference leg has an equal effect on both sides of the differential pressure transmitter and can be ignored. The next section describes how to account for varying density effects on a differential pressure measurement.

E.2 Uncertainty Associated With Density Changes

Density changes in the reference leg fluid or the measured fluid can add to the uncertainty of a level measurement by a differential pressure transmitter. Differential pressure transmitters respond to the hydrostatic (head) pressure caused by a height of a liquid fluid column; for a given height, the response varies as the liquid density varies. The density changes as a function of temperature which then potentially changes the differential pressure measured by the transmitter. The transmitter cannot distinguish between the difference caused by a level change and the difference caused by a fluid density change.

Two types of level measurement system uncertainties are presented here. Section E.2.1 provides the methodology if no temperature compensation is provided for the vessel level measurement. Section

E.2.2 provides the methodology for those cases in which the vessel temperature is measured to provide automatic compensation of the vessel liquid density, but the reference leg is still not compensated.

E.2.1 Uncompensated Level Measurement Systems

The methodology developed and described in this section assumes that vessels are closed and contain a saturated mixture of stem and water. For this discussion, the reference leg is water-filled and also saturated. Note that the reference leg liquid may well be compressed (subcooled). Figure E-3 shows a closed vessel containing a saturated steam/water mixture. The symbols used to explain the effect of density variations are provided immediately below Figure E-3.

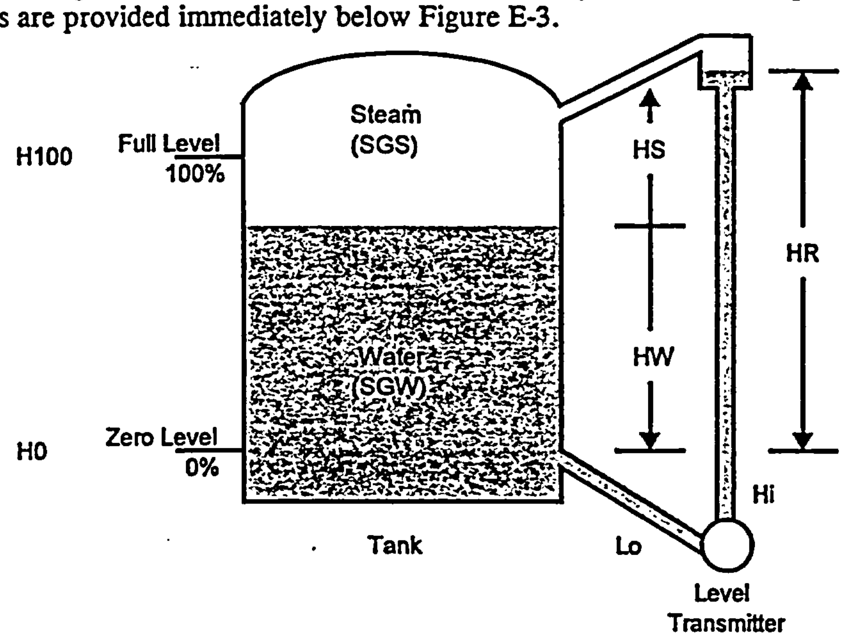


Figure E-3
Saturated Liquid/Vapor Level Measurement

Table E-1 provides the list of symbols used in a level measurement analysis and their explanation.

HW: Height of water	SVW: Specific volume of water at saturation temperature
HS: Height of steam	SVS: Specific volume of steam at saturation temperature
HR: Height of reference leg	SVR: Specific volume of reference leg fluid
H0: Height of 0% indicated level	SGW: Specific gravity of water at saturation temperature
H100: Height of 100% indicated level	SGS: Specific gravity of steam at saturation temperature
ΔP: Differential pressure (inches H_2O)	SGR: Specific gravity of reference leg fluid

Table E-1
Symbols Used in a Level Measurement Density Effect Analysis

All heights in Table E-1 are referenced to the centerline of the lower level sensing line. HS and HR are measured to the highest possible water column that can be obtained by condensing steam. Specific gravity is calculated by the specific volume of water at 68°F divided by the specific volume of the fluid at the stated condition.

Referring to Figure E-3, the differential pressure applied to the transmitter is the difference between the high pressure and the low pressure inputs:

$$\Delta P = Pressure\ (Hi) - Pressure\ (Lo) \qquad \text{Eqn. E.3}$$

The individual terms above are calculated by:

$$Pressure\ (Hi) = (HR \times SGR) + Static\ Pressure \qquad \text{Eqn. E.4}$$

$$Pressure\ (Lo) = (HW \times SGW) + (HS \times SGS) + Static\ Pressure \qquad \text{Eqn. E.5}$$

Substituting the above equations into the general expression for differential pressure yields:

$$\Delta P = (HR \times SGR) - (HW \times SGW) - (HS \times SGS) \qquad \text{Eqn. E.6}$$

Referring to Figure E-3, it can be seen that the height of the steam (HS) is equal to the height of the reference leg (HR) minus the height of the water (HW). Substituting (HR - HW) for HS yields:

$$\Delta P = (HR \times SGR) - (HW \times SGW) - (HR - HW) \times SGS \qquad \text{Eqn. E.7}$$

or

$$\Delta P = [HR \times (SGR - SGS)] + [HW \times (SGS - SGW)] \qquad \text{Eqn. E.8}$$

Using Equation E.1 and substituting for HW the height of water at 0% level (H0) and at 100% level (H100), the differential pressures at 0% (ΔP0) and at 100% (ΔP100) can be determined. Note that HR, H0, and H100 are normally stated in inches above the lower sensing line tap centerline. It is normally assumed that the fluid in both sensing lines below the lower sensing line tap are at the same density if the contain the same fluid and are at equal temperature. The specific gravity or specific weight terms (SGW, SGR, and SGS) are unitless quantities, which means that ΔP, ΔP0, and ΔP100 are normally stated in "inches of water".

The transmitter is calibrated for proper performance at a given operating condition. Before the transmitter calibration requirements can be expressed, it is necessary to define the reference operating conditions in the vessel and reference leg from which SGW, SGR, and SGS may be determined by the use of thermodynamic steam tables. After the specific gravity terms are known, they can be used in Equation E.1 along with HR, H0, and H100 and the equation solved for the minimum and maximum level conditions, ΔP0 and ΔP100.

Provided that the actual vessel and reference leg conditions remain unchanged, the indicated level is a linear function of the measured differential pressure; no density error effects are present. Under this base condition, the following proportionality can be written:

$$\frac{HW - H0}{H100 - H0} = \frac{\Delta P - \Delta P0}{\Delta P100 - \Delta P0} \qquad \text{Eqn. E.9}$$

Solving for HW yields:

$$HW = [(H100 - H0) \times \frac{\Delta P - \Delta P0}{\Delta P100 - \Delta P0}] + H0 \qquad \text{Eqn. E.10}$$

Now, assess the effects of varying the vessel and reference leg conditions from the assumed values. Let an erroneous differential pressure, ΔPU, and erroneous water level, HU, be developed because of an operating condition different from that assumed for the transmitter calibration. The uncertainty in the water level is given by:

$$HW \pm HU = [(H100 - H0) \times \frac{\Delta P \pm \Delta PU - \Delta P0}{\Delta P100 - \Delta P0}] + H0 \qquad \text{Eqn. E.11}$$

Or, the uncertainty HU is given by:

$$HU = (H100 - H0) \times \frac{\Delta PU}{\Delta P100 - \Delta P0} \qquad \text{Eqn. E.12}$$

And, ΔP100 - ΔP0 can be expressed by:

$$\Delta P100 - \Delta P0 = [HR \times (SGR - SGS) + (H100 \times (SGS - SGW)] - [HR \times (SGR - SGS) + H0 \times (SGS - SGW)] \qquad \text{Eqn. E.13}$$

or

$$\Delta P100 - \Delta P0 = (H100 - H0) \times (SGS - SGW) \qquad \text{Eqn. E.14}$$

Thus, the uncertainty HU is given by:

$$HU = \frac{\Delta PU}{SGS - SGW} \qquad \text{Eqn. E.15}$$

The term ΔPU is just the difference between the differential pressure measured at the actual conditions, ΔPA, minus the differential pressure measured at the base condition, ΔPB:

$$\Delta PU = \Delta PA - \Delta PB \qquad \text{Eqn. E.16}$$

Assuming that HR and HW are constant (only the density is changing, not the actual levels), ΔPA and ΔPB can be expressed as:

$$\Delta PA = HR \times (SGRA - SGSA) + HW \times (SGSA - SGWA) \qquad \text{Eqn. E.17}$$

$$\Delta PB = HR \times (SGRB - SGSB) + HW \times (SGSB - SGWB) \qquad \text{Eqn. E.18}$$

Substituting into the expression for ΔPU yields:

$$\Delta PU = HR \times (SGRA - SGSA - SGRB + SGSB) + HW \times (SGSA - SGWA - SGSB + SGWB)$$

Eqn. E.19

Returning to the expression for the uncertainty in measured level, HU, the substitution of the above expression for ΔPU yields:

$$HU = \frac{HR \times (SGRA - SGSA - SGRB + SGSB) + HW \times (SGSA - SGWA - SGSB + SGWB)}{SGSB - SGWB}$$

Eqn. E.20

The above expression for level measurement uncertainty describes the uncertainty caused by liquid density changes in the vessel, reference leg, or both.

E.2.2 Temperature-Compensated Level Measurement System

The previous section describes the analysis methodology for the case in which no temperature compensation is provided to the level measurement system. This section clarifies the methodology for a system in which the vessel temperature is monitored and the level measurement system includes automatic temperature compensation account for the vessel's liquid density changes.

If the temperature inside the vessel is monitored, then the specific gravity of the steam and the water inside the vessel can be corrected as a function of temperature. In the analysis methodology for the water level measurement uncertainty, HU, the following terms become effectively equal because of the automatic correction for temperature:

$$SGSA = SGSB \quad \text{and} \quad SGWA = SGWB$$

In this case, the vessel density effects are eliminated, but note that the reference leg density changes are not monitored and still require consideration. The uncertainty of the differential pressure measurement reduces to:

$$\Delta PU = HR \times (SGRA - SGRB) \qquad \text{Eqn. E.21}$$

The above equation shows that the differential pressure uncertainty becomes increasingly negative as the actual temperature increases above the reference temperature. As the temperature in the reference leg increases above the reference temperature, the fluid density decreases, causing a negative ΔPU. Returning to Figure E-3, note that a lower differential pressure means that a higher level will be indicated, or a negative ΔPU will cause a positive level uncertainty HU. The magnitude of the error can be estimated by:

$$HU = \frac{HR \times (SGRA - SGRB)}{SGSB - SGWB} \qquad \text{Eqn. E.22}$$

If the transmitter connections were reversed (high pressure connection reversed with low pressure connection to reverse the ΔP), the above discussion would still apply, but the uncertainty would change direction:

$$\Delta PU = HR \times (SGRB - SGRA) \qquad \text{Eqn. E.23}$$

The above equations calculate uncertainties in actual engineering units. If desired, the quantities HU and ΔPU can be converted to percent span units by dividing each term by (H100 - H0) or (ΔP100 - ΔP0), respectively, and multiplying the results by 100%. As discussed above, the sign (or direction of the uncertainty) for ΔPU depends on which way the high- and low-pressure sides of the transmitter are connected to the vessel.

E.2.3 Example Calculation for Uncompensated System

For this example, assume that a level measurement is not compensated for density changes and has the following configuration:

1. HR = 150 in.
2. H0 = 50 in.
3. H100 = 150 in.
4. HW = 100 in.
5. Reference conditions:
   Vessel temperature = 532°F (saturated water)
   Reference leg temperature = 68°F (assume saturated, but could be compressed)

6. Actual conditions:
   Vessel temperature = 500°F (saturated water)
   Reference leg temperature = 300°F (assume saturated, but could be compressed)

Determine the level measurement uncertainty for this operating condition.

First, calculate the specific gravity terms for each condition by using steam table specific volumes of water (SVW) and specific volumes of steam (SVS). The following values are calculated:

$$SGWA = \frac{SVW\ (68°F)}{SVW\ (500°F)} = \frac{0.016046\ ft^3/lbm}{0.02043\ ft^3/lbm} = 0.78541$$

$$SGSA = \frac{SVW\ (68°F)}{SVS\ (500°F)} = \frac{0.016046\ ft^3/lbm}{0.67492\ ft^3/lbm} = 0.02377$$

$$SGRA = \frac{SVW\ (68°F)}{SVW\ (300°F)} = \frac{0.016046\ ft^3/lbm}{0.01745\ ft^3/lbm} = 0.91954$$

$$SGWB = \frac{SVW\ (68°F)}{SVW\ (532°F)} = \frac{0.016046\ ft^3/lbm}{0.02123\ ft^3/lbm} = 0.75582$$

$$SGSA = \frac{SVW\ (68°F)}{SVS\ (532°F)} = \frac{0.016046\ ft^3/lbm}{0.50070\ ft^3/lbm} = 0.03205$$

$$SGRB = \frac{SVW\ (68°F)}{SVW\ (68°F)} = \frac{0.016046\ ft^3/lbm}{0.016046\ ft^3/lbm} = 1.0$$

Next, substitute HW = 100 in. and HR = 150 in., as well as the above quantities, into the expression for HU:

$$HU = \frac{HR \times (SGRA - SGSA - SGRB + SGSB) + HW \times (SGSA - SGWA - SGSB + SGWB)}{SGSB - SGWB}$$

$$= \frac{150 \times (.91954 - .02377 - 1.0 + .03205) + 100 \times (.02377 - .78541 - .03205 + .75582)}{.03205 - .75582}$$

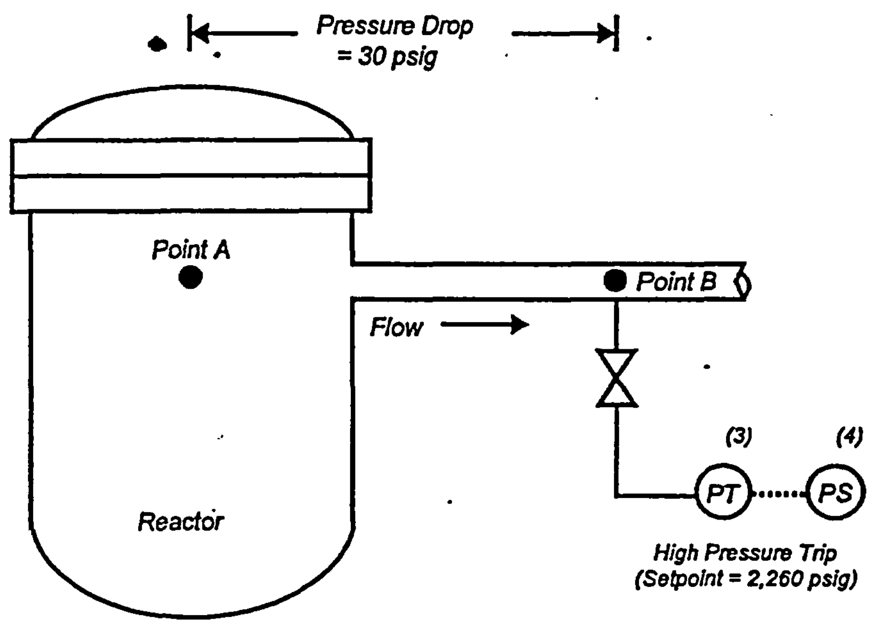
$$= +20.2\ inches$$

In percent of span, the uncertainty is given by:

$$HU\ \% = \frac{HU}{H100 - H0} \times 100\% = \frac{20.2}{150 - 50} \times 100\% = +20.2\%\ span$$

ATTACHMENT F
STATIC HEAD AND LINE LOSS PRESSURE EFFECTS

The flow of liquids and gases through piping causes a pressure drop from Point A to some Point B due to fluid friction (see Figure F-1). Many factors are involved, including piping length, piping diameter, pipe fittings, fluid viscosity, fluid velocity, etc. If a setpoint is based on pressure at a point in the system that is different from the point of measurement, the pressure drop between these two points must be taken into account.



Notes:

(1) Reactor trip must occur before pressure at Point A exceeds 2,300 psig (Analytical Limit).

(2) Loop equipment error = 10 psig

(3) PT - Pressure transmitter

(4) PS - Pressure switch (or bistable)

Figure F-1
Line Pressure Loss Example

<u>Example F-1</u>

Refer to Figure F-1 for this example. If protective action must be taken during an accident when the pressure at Point A exceeds the analysis limit (AL) = 2,300 psig, the pressure switch setpoint needs to be adjusted to account for the line loss (30 psig) and channel equipment errors (10 psig) as shown below (it is assumed that the sensing line head effect for the accident condition is negligible in this case).

Setpoint = AL - Line Loss - Total Channel Equipment Uncertainty

= 2,300 - 30 - 10

= 2,260 psig

Note that if the line loss had been neglected and the setpoint adjusted to the analysis limit minus equipment error (2,290 psig), the resultant setpoint would be nonconservative. In other words, when the trip occurred, the pressure at Point A could be equal to 2,290 + 30 = 2,320 psig, which nonconservatively exceeds the analysis limit.

Example F-2

If the pipe had dropped down vertically to Point B, the result would be a head effect plus line loss example. Assume the head pressure exerted by the column of water in the vertical section of piping is 5 psig and that the line loss of Point A to Point B is still equal to 30 psig. Also, assume that the pressure at Point A is not to drop below 1,500 psig without trip action. For this example, the setpoint is calculated as follows:

Setpoint = AL + Head + Total Channel Equipment Uncertainty

= 1,500 + 5 + 10 = 1,565 psi

In this case, the 30 psig line loss was neglected for conservatism.

Note that the head effect/line loss errors are bias terms, unless they can be calibrated out in the transmitter, in which case this effect can be removed from the channel uncertainty calculation. If it is included in the channel uncertainty calculation, the effect must be added or subtracted from the analytical limit, depending on the particular circumstances, to ensure that protective action occurs before exceeding the analytical limit.

ATTACHMENT G
MEASURING AND TEST EQUIPMENT UNCERTAINTY

M&TE uncertainty is the inaccuracy introduced by the calibration process due to the limitations of the test instruments. M&TE uncertainty includes three principal components: (1) reference accuracy of the test equipment, (2) effect of temperature on the test equipment, and (3) accuracy of the test equipment calibration process. The first two components are included directly in the M&TE uncertainty and the third is assumed to be included in the conservatism of the reference accuracy of the test equipment.

All (100%) of test equipment is certified to pass the calibration requirements, not just 95%, the common confidence level used for uncertainty calculations. Discussion with vendors shows that the actual accuracy of the test equipment is better than the vendor published values. Both of these provide conservatism in the accuracy of the test equipment and, therefore conservatism in the M&TE determination. As discussed in G.1 below the standards used to calibrate the test equipment are generally rated 4:1 better than the equipment being calibrated. For these reasons it is generally accepted that the published reference accuracy of the test equipment includes the uncertainty of the calibration standard since reference accuracy divided by 4 is negligible in the relation to other uncertainties. For the purposes of setpoint and uncertainty calculations, the total M&TE uncertainty for any module should be based on test equipment which has been calibrated using 4:1 reference standards.

The module calibration also includes a As-Left tolerance (ALT) which can be related to the test equipment uncertainty. An instrument does not provide an exact measurement of the true process value; there is always some level of uncertainty or error in our measurement. The As-Left tolerance (ALT) is (1) a reflection of the best accuracy that we can realistically obtain or (2) the minimum accuracy that we feel is needed to assure that the process is properly controlled. The As-Left tolerance (ALT) is sometimes called the *leave-as-is* zone because the instrument can be considered in calibration and left unadjusted if its output is within the As-Left tolerance (ALT).

For example, a pressure transmitter may have a reference accuracy (RA) of ±0.1%, but its As-Left tolerance (ALT) may be allowed to be ±0.5%. Thus, the instrument technician is allowed to leave the instrument as-is if it is found anywhere within ±0.5% of the calibration check point. Without any other considerations, we would have to conclude that the calibrated condition of the instrument is only accurate to ±0.5% rather than the device's RA of ±0.1%. If greater accuracy is needed, the calibration procedure should be revised for a the tighter As-Left tolerance.

Attachment G provides the details for IP3 calculation preparers to consider when evaluating the M&TE uncertainty for a module.

G.1 General Requirements

The control of measuring and test equipment (M&TE) is governed by IP3 Instrument and Control Department Directive IC-AD-2, *Calibration & Control of Measuring and Test Equipment*. This directive states that its purpose "is to establish the requirements of a calibration and control program for Measuring and Test Equipment (M&TE) under the custody and/or control of the I&C Department which is used to calibrate or determine the operability of Category I systems.

The following discusses specific requirements of this directive:

1. Reference standards used for calibrating M&TE shall have an uncertainty (error) requirement of not more than ¼ of the tolerance of the equipment being calibrated. A greater uncertainty may be acceptable as limited by "State of the Art".

2. Precision pressure test gauges used specifically as M&TE will bear an I&C identification number and shall be calibrated to an accuracy of 0.25% full scale (FS).

3. No measurement and test equipment shall be used if the record date for recelebrating the test equipment has been exceeded.

The directive does not address the accuracy of M&TE equipment with respect to the installed plant equipment being checked for calibration. Given the present program as defined in IC-AD-2, the M&TE uncertainty will be considered in terms of the as-left setting tolerance of the installed instrumentation. For example, the total M&TE uncertainty (MTE) associated with calibration of plant equipment with an accuracy requirement of ±0.5% could be as follows:

$$MTE_t = \pm\sqrt{MTE^2 + SS^2 + PS^2} \qquad \text{Eqn. G.1}$$

where,

MTE_t	= Total M&TE uncertainty
MTE	= Statistical combination of M&TE used to calibrate plant equipment
SS	= Statistical combination of secondary standards used to calibrate MTE
PS	= Statistical combination of primary standards used to calibrate SS

Using the above equation, two cases can be calculated:

<u>Ideal</u>

$$MTE_t = \pm\sqrt{0.5^2 + \left(\frac{0.5}{4}\right)^2 + \left(\frac{0.5}{4}\right)^2} = \pm\ 0.53\%$$

<u>Allowable</u>

$$MTE_t = \pm\sqrt{0.5^2 + 0.5^2 + 0.5^2} = \pm\ 0.87\%$$

For the purposes of setpoint and uncertainty calculations, the total M&TE uncertainty should be based on 4:1 references standards. If the test equipment accuracy is not based on 4:1 reference standards, the required total M&TE uncertainty should be met by using better test equipment for calibration. The differences between Example G-2 and Example G-3 show one method by which the total M&TE uncertainty may be kept within acceptable limits. [(0.05% x 5 volts) + (2 x 0.001 volt)] ÷ 4 volts x 100 =±0.1125% of CS. Example G-4 indicates another approach.

In the case of the ±0.5% required accuracy above, the total M&TE uncertainty requirement of ≤ ±0.53% could still be met with 1:1 reference standards provided the uncertainty of the M&TE used for calibration is ≤ ±0.3% as follows:

$$MTE_t = \pm\sqrt{0.3^2 + 0.3^2 + 0.3^2} = \pm\ 0.52\%$$

In general, it is desirable to minimize the contribution of M&TE to the uncertainty of the loop. Every effort should be made to use the most accurate M&TE available during calibration.

G.2 Uncertainty Calculations Based on Plant Calibration Practices

The M&TE uncertainty included in an uncertainty calculation is based on historical practices. The implicit design assumption is that M&TE used in the future will be equal to or better than the M&TE used in the past (due to improvements in State of the Art test equipment). In order to ensure this assumption is not invalidated by future calibrations, review the M&TE specified in the applicable I&C procedures. Verify the uncertainty of the M&TE specified (including calibration standards) is bounded by the drift uncertainty used in the calculation as shown in the following sections for each type of instrument or configuration.

G.2.1 Sensors

For all transmitters (sensors) with an as-left setting tolerance (ALT) of ±0.5% or greater, the M&TE uncertainty (MTE) used for calibration should be no greater than ±0.5%. The total M&TE uncertainty (MTE_t) including reference standards, should be no greater than ±0.53%.

The calculation of M&TE uncertainty used to calibrate plant equipment should include both the input and output M&TE. M&TE errors are present with the input signal provided to the input of the sensor as well as with the instrumentation used to measure the output of the sensor (see Figure G-1). The input M&TE is independent from the output M&TE.

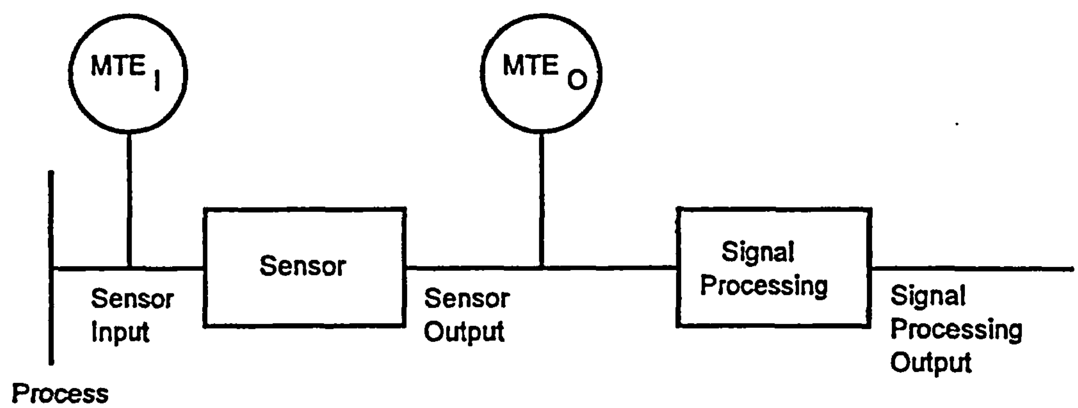


Figure G-1
Measuring and Test Equipment Uncertainty

In the case of a transmitter (sensor), a ±0.5% M&TE accuracy should be met by the statistical combination of the following:

$$MTE = \pm \sqrt{MTE_I^2 + MTE_O^2} \qquad \text{Eqn. G.2}$$

where,

MTE	= M&TE used to calibrate plant equipment
MTE_I	= Statistical combination of input M&TE
MTE_O	= Statistical combination of output M&TE

Example G-1

For a 0-100 psig transmitter with a required accuracy of ±0.5% and M&TE of a Heise (0-200 psig ±0.1% FS), Fluke 8060A (4½ digit, 20 V scale, ±0.05% reading + 2 digits), 250 Ω precision test resistor (±0.1%), determine if the M&TE requirements are met.

Convert all uncertainties to percent of calibrated span (CS).

Heise (H): (±0.1% x 200 psig)/100 psig = ±0.2% of CS

DVM: Assuming the calibration is 4-20 mA across a 250 Ω resistor voltage, the DVM will read 1-5 volts. This gives ±[(0.05% x 5 volts) + (2 x 0.001 volt)] ÷ 4 volts x 100 = ±0.1125% of CS.

Resistor (R): ±0.1% of CS

In addition, if an analog gauge is used and calibration inputs are not based on fixed scale divisions, an additional readability uncertainty (RE) should be included. Assuming no readability uncertainty for this example, the M&TE uncertainty (MTE) can be calculated as follows:

$$MTE = \pm\sqrt{H^2 + DVM^2 + R^2 + RE^2} = \pm\sqrt{0.2^2 + 0.1125^2 + 0.1^2 + 0^2} = \pm\ 0.25\%$$

The above result provides an M&TE ratio of 2:1. Given reference standards with an uncertainty of ±0.25% (1:1) or better, the total M&TE uncertainty is acceptable.

Example G-2

Consider a 1,700-2,500 psig pressurizer pressure transmitter (800 psig span) with a required accuracy of ±0.5% and M&TE of a Heise (0-3,000 psig ±0.1% FS), Fluke 8060A (4½ digit, 20 V scale, ±0.05% reading + 2 digits), 250 Ω precision test resistor (±0.1%), determine if the M&TE requirements are met.

Convert all uncertainties to percent of calibrated span (CS).

Heise (H): (±0.1% x 3,000 psig)/800 psig = ±0.375% of CS

DVM: Assuming the calibration is 4-20 mA across a 250 Ω resistor voltage, the DVM will read 1-5 volts. This gives [(0.05% x 5 volts) + (2 x 0.001 volt)] ÷ 4 volts x 100 = ±0.1125% of CS.

Resistor (R): ±0.1% of CS

In addition, if an analog gauge is used and calibration inputs are not based on fixed scale divisions, an additional readability uncertainty (RE) should be included. Assuming no readability uncertainty for this example, the M&TE uncertainty (MTE) can be calculated as follows:

$$MTE = \pm\sqrt{H^2 + DVM^2 + R^2 + RE^2} = \pm\sqrt{0.375^2 + 0.1125^2 + 0.1^2 + 0^2} = \pm\ 0.4\%$$

The above result provides an M&TE ratio of near 1:1. This example shows that even high quality M&TE can sometimes result in a relatively high M&TE uncertainty. In this case, the pressurizer pressure span was only 800 psig, but the elevated zero required the use of a 3,000 psig pressure gauge.

Example G-3

Let's reconsider Example G-2 with the use of a different pressure gauge. The IC-AD-2 requirement is only that the pressure gauge accuracy be ±0.25% of FS. The 1,700-2,500 psig pressurizer pressure transmitter (800 psig span) has a required accuracy of ±0.5%.

With M&TE of the Heise (0-3,000 psig ±0.25% FS), Fluke 8060A (4½ digit, 20 V scale, ±0.05% reading + 2 digits), and the 250 Ω precision test resistor (±0.1%), determine if the M&TE requirements are met.

Convert all uncertainties to percent of calibrated span (CS).

Heise (H): (±0.25% x 3,000 psig)/800 psig = ±0.9375% of CS

DVM: Assuming the calibration is 4-20 mA across a 250 Ω resistor voltage, the DVM will read 1-5 volts. This gives [(0.05% x 5 volts) + (2 x 0.001 volt)] ÷ 4 volts x 100 = ±0.1125% of CS.

Resistor (R): ±0.1% of CS

Once again, assuming no readability uncertainty for this example, the M&TE uncertainty (MTE) can be calculated as follows:

$$MTE = \pm\sqrt{H^2 + DVM^2 + R^2 + RE^2} = \pm\sqrt{0.9375^2 + 0.1125^2 + 0.1^2 + 0^2} = \pm\ 0.95\%$$

In this case, the desired M&TE can not be met with a ±0.25% pressure gauge. Specific M&TE requirements should be established with I&C as part of the setpoint calculation process.

G.2.2 Individual Components

For all individual components with a setting tolerance of ±0.25% or greater, the M&TE uncertainty used for calibration should be no greater than ±0.25%. The total M&TE uncertainty should be no greater than ±0.265%. For individual components with a setting tolerance of less than ±0.25%, the M&TE uncertainty used for calibration should be no greater than the setting tolerance.

<u>Example G-4</u>

For an electronic module such as an I/I signal converter with a required accuracy of ±0.25%, the M&TE that may be used could include 2 DVMs (Fluke 8060A as described previously) and 2 precision resistors. Determine if the M&TE requirements are met as follows:

$$MTE = \pm\sqrt{DVM_I^2 + DVM_O^2 + R_I^2 + R_O^2}$$

$$= \pm\sqrt{0.1125^2 + 0.1125^2 + 0.1^2 + .1^2} = \pm\ 0.21\%$$

Given reference standards with an uncertainty of ±0.1% (2.5:1) or better, the total M&TE uncertainty is acceptable. Note that the use of 2 Fluke 8060As on the 20 mA scale (±0.3% of reading + 2 digits) would not provide the required accuracy.

For a required accuracy of ±0.1%, the use of this M&TE would not be acceptable. In this case, the use of 2 Fluke 8842As (5½ digit, 20 V scale, +0.0035% of reading + 2 counts) and 2 +0.01% precision resistors would be acceptable.

The point of these examples is that existing M&TE can often be applied in a manner that best achieves the desired uncertainty limit. Similarly, the M&TE can be misapplied such that the overall uncertainty is made worse.

G.2.3 Instrument Loops

For an entire instrument loop, excluding sensor, with four or more individual components, the M&TE uncertainty used for calibration should be no greater than +0.5%. The total M&TE uncertainty should be no greater than +0.53%.

G.2.4 Special Cases

If required and specified, the actual uncertainty for the M&TE and reference standards may be used in the setpoint or uncertainty calculation.

In all cases, the total M&TE uncertainty assumed should become an explicit M&TE assumption in the uncertainty calculation. The applicable calculation assumptions should be formally transmitted to the I&C Supervisor. The method of transmittal shall be through the MCM-8 procedure process, if the results of the calculation require a setpoint change. If the results of the calculation show that no setpoint change is required, the method of transmittal shall be a IP3 Memorandum. If the existing I&C procedures do not specify the proper M&TE or if no M&TE is specified, formal transmittal and incorporation of M&TE requirements will ensure that setpoint and uncertainty calculation assumptions are not invalidated by future calibrations.

ATTACHMENT H
NEGLIGIBLE UNCERTAINTIES

The uncertainties listed in Table H-1 can be assumed to be negligible under normal operating conditions. The basis and assumption limits for Table H-1 are discussed below. Personnel performing an uncertainty calculation must evaluate the calculation with respect to this Attachment to verify that special circumstances or unusual configurations do not invalidate any of these assumptions.

H.1 Normal Radiation Effects

Outside the Containment and inside the Containment (Outside the Biological Shield Wall), there is not a substantial increase in radiation during normal operating (non-accident) conditions. In these areas, radiation changes during normal operation do not exist or are minimal. It is assumed that any accumulative effects of normal radiation are calibrated out on a periodic basis. For these reasons, the uncertainty introduced by any radiation effect during normal operation is assumed to be negligible.

H.2 Humidity Effects

Most manufacturers' literature and technical manuals do not address the effect of humidity (10% RH to 95% RH) on their equipment. The uncertainty introduced by humidity changes during normal operation is assumed to be negligible unless the manufacturer specifically discusses humidity effects in the technical manual. The effects of humidity changes is assumed to be calibrated out on a periodic basis. A condensing environment is considered an abnormal event that would require equipment maintenance. A humidity below 10% is considered to occur very infrequently.

H.3 Seismic/Vibration Effects

The effects of normal vibration (or a minor seismic event that does not cause an unusual event) on a component are assumed to be calibrated out on a periodic basis. As such, the uncertainty associated with this effect is assumed to be negligible. Abnormal vibrations, e.g., levels that produce noticeable effects on equipment, are considered abnormal events that require maintenance or equipment modification.

H.4 Normal Insulation Resistance Effects

The uncertainties associated with insulation resistance are assumed to be negligible during normal plant operating (non-accident) conditions. Typical insulation resistances are greater than 1,000 megohm. As an example, assume that the total IR is only 10 megohm and assume minimum instrument loop loading. Using the methodology provided in Attachment C, the expected uncertainty attributable to IR is given by:

$$\frac{48 - (0.004 \times 250)}{10 \times 10^{6} \times (0.016)} = 0.03\%$$

As can be seen, the IR can be considered negligible as long as the environment remains mild.

H.5 Lead Wire Effects

Since the resistance of a wire is equal to the resistivity times the length divided by the cross-sectional area, it is assumed that the very small differences in wire lengths between components do not contribute to any significant resistance differences between wires. The uncertainty associated with these insignificant resistance variations is assumed to be negligible.

If a system design includes lead wire effects that must be considered as a component of uncertainty, the requirement must be included in the design basis. The general design standard is to eliminate lead wire effects as a concern both in equipment design and installation. Failure to do so is a design fault that should be corrected. Unless specifically identified to the contrary, lead wire effects are to be assumed to be negligible. An exception to this is thermocouples and RTDS. These cases require individual evaluation of lead wire effects.

H.6 Calibration Temperature Effects

Generally, the temperature at which an instrument is calibrated is within the normal operating range of the instrument. Also, the ambient temperature effects are small. Therefore, the uncertainty associated with the temperature variations during calibration is assumed to be negligible. Note that this applies only to temperature changes for calibration. Temperature effects over the expected range of equipment operation still must be considered.

H.7 Atmospheric Pressure Effects

Assuming that the atmospheric pressure might change as much as one inch of mercury, this equates to approximately 0.5 psi. Because this change is small, this effect will be assumed negligible for pressures of 5 psi and larger, unless the pressure transmitter is measuring a relatively small pressure.

H.8 Dust Effects

Any uncertainties associated with dust are assumed to be compensated for during normal periodic calibration and are assumed to be negligible.

H.9 RTD Self Heating Errors

To determine a typical RTD self heating error, the following computation is provided:

RTD: Rosemount Model 104 RTD
Self Heating Effect: 0.1°C or less
Resistance @ 400°C: 249.61 Ω
Resistance @ 380°C: 242.58 Ω
Resistance/°C around 400°C = (249.61 - 242.58)/20 = 0.35 Ω/°C
Self Heating Error = 0.1°C x 0.35 Ω/°C = 0.035 Ω

At 400°C = 0.035/249.61 = 0.014%

The above results show that the RTD self heating error can be assumed to be negligible.

H.10 Digital Signal Processing

An accuracy of 0.1 % of full scale or less is often specified. Additionally, linearity and repeatability are often specified as 1 least significant bit (LSB). When this 0.1% uncertainty is compared to the percent uncertainty for the rest of the instrument loop, it is clear that this uncertainty can be neglected. In these cases, these uncertainties are considered to be negligible as long as manufacturers specifications on calibration are followed.

Uncertainty	Outside Containment or HELB Area	Inside Containment or HELB Area
Radiation Effect	X	No
Humidity Effects	X	X
Seismic/Vibration Effects	X	X
Normal Insulation Resistance Effect	X	X
Lead Wire Effects (Note 1)	X	X
Calibration Temperature Effects	X	X
Atmospheric Pressure Effects	X	X
Dust Effects	X	X
RTD Self-Heating Errors	X	X
Digital Signal Processing Errors	X	N/A

Table H-1
Negligible Uncertainties During Normal Operation

Note 1: RTDs and thermocouples must be evaluated.

ATTACHMENT I
DIGITAL SIGNAL PROCESSING UNCERTAINTIES

This Attachment presents a discussion on digital signal processing and the uncertainties involved with respect to determining instrument channel setpoints for a digital system. This Attachment assumes that a digital signal processing system exists that receives an analog signal and provides either a digital or analog output. In many respects, the digital processor is treated as a black box; therefore, the discussion that follows is applicable to many different types of digital processors.

The digital processor is programmed to perform a controlled algorithm. Basic functions performed are addition, subtraction, multiplication and division, as well as data storage. The digital processor is the most likely component to introduce rounding and truncation errors.

In general, an analog signal is received by the digital processor, filtered, digitized, manipulated, converted back into analog form, filtered again and sent out. The analog input signal is first processed by a filter to reduce aliasing noise introduced by the signal frequencies that are high relative to the sampling rate. The filtered signal is sampled at a fixed rate and the amplitude of the signal held long enough to permit conversion to a digital word. The digital words are manipulated by the processor based on the controlled algorithm. The manipulated digital words are converted back to analog form, and the analog output signal is smoothed by a reconstruction filter to remove high-frequency components.

Several factors affect the quality of the representation of analog signals by digitized signals. The sampling rate affects aliasing noise, the sampling pulse width affects analog reconstruction noise, the sampling stability affects jitter noise and the digitizing accuracy affects the quantization noise.

I.1 Sampling Rate Uncertainty

If the sampling rate is higher than twice the analog signal bandwidth, then the sampled signal is a good representation of the analog input signal and contains all the significant information. If the analog signal contains frequencies that are too high with respect to the sampling rate, aliasing uncertainty will be introduced. Anti-aliasing band limiting filters can be used to minimize the aliasing uncertainty or else it should be accounted for in setpoint calculations.

I.2 Signal Reconstruction Uncertainty

Some information is lost when the digitized signal is sampled and held for conversion back to analog form after digital manipulation. This uncertainty is typically linear and about ±½ Least Significant Bit (LSB).

I.3 Jitter Uncertainty

The samples of the input signal are taken at periodic intervals. If the sampling periods are not stable, an uncertainty corresponding to the rate of change of the sampled signal will be introduced. The jitter uncertainty is insignificant if the clock is crystal controlled, which it is in the majority of cases.

I.4 Digitizing Uncertainty

When the input signal is sampled, a digital word is generated that represents the amplitude of the signal at that time. The signal voltage must be divided into a finite number of levels that can be defined by a digital word *n* bits long. This word will describe *2n* different voltage steps. The signal levels between these steps will go undetected. The digitizing uncertainty (also known as the quantizing uncertainty) can be expressed in terms of the total mean square error voltage between the exact and the quantized samples of the signal. An inherent digitizing uncertainty of ±½ the least significant bit (LSB) typically exists. The higher the number of bits in the conversion process, the smaller the digitizing uncertainty.

I.5 Miscellaneous Uncertainties

Analog-to-digital converters also introduce offset uncertainty, i.e., the first transition may not occur at exactly ±½ LSB. Gain uncertainty is introduced when the difference between the values at which the first transition and the last transition occurs is not equal. Linearity uncertainty is introduced when the difference between the transition values are not all equal.

As a rule of thumb, use ±½ LSB for relative uncertainty for the analog-to-digital conversion. For digital-to-analog conversion, the maximum linearity uncertainty occurs at full scale when all bits are in saturation. The linearity determines the relative accuracy of the converters. Deviations from linearity, once the converters are calibrated, is absolute uncertainty. As a rule of thumb, use ±½ LSB for absolute uncertainty and ± LSB for linearity uncertainty.

I.6 Truncation and Rounding Uncertainties

The effect of truncation or rounding depends on whether fixed-point or floating-point arithmetic is used and how negative numbers are represented. For the sign-and-magnitude one's compliment and two's compliment methods, the numbers are represented identically. The largest truncation error occurs when all bits discarded are one's.

For negative numbers, the effect of truncation depends on whether sign-and-magnitude, two's compliment or one's compliment representation is used. Rounding is used on the magnitude of the numbers, and uncertainty is independent of the method of negative numbers representation.

For positive numbers and two's compliment negative numbers, the truncation uncertainty is estimated by:

$$-2^{-b} < E_T \leq 0 \qquad \text{Eqn. I.1}$$

For sign-and-magnitude and one's compliment negative numbers, the truncation uncertainty is estimated by:

$$0 \leq E_T < 2^{-b} \qquad \text{Eqn. I.2}$$

where b is the number of bits to the right of the binary point after truncation or rounding.

Estimation for rounding uncertainty is:

$$(-½) \times 2^{-b} < E_R \leq (½) \times 2^{-b} \qquad \text{Eqn. I.3}$$

where b is the number of bits to the right of the binary point after truncation or rounding. Truncation and rounding affects the mantissa in floating point arithmetic. The relative uncertainty is more important than the absolute uncertainty, i.e., floating point errors are multiplicative.

For floating point arithmetic, the relative uncertainty for rounding is estimated by:

$$-2.2^{-b} < E \le 0 \qquad \text{Eqn. I.4}$$

For one's compliment and sign-and-magnitude, truncation uncertainty is estimated by:

$$-2.2^{-b} < E \le 0 \qquad x > 0 \qquad \text{Eqn. I.5}$$

$$0 \le E < -2.2^{-b} \qquad x < 0 \qquad \text{Eqn. I.6}$$

where x is the value before truncation.

ATTACHMENT J
PROPAGATION OF UNCERTAINTY THROUGH SIGNAL CONDITIONING MODULES

This attachment discusses techniques for determining the uncertainty of a module's output when the uncertainty of the input signal and the uncertainty associated with the module are known. Using these techniques, equations are developed to determine the output uncertainties for several common types of functional modules.

For brevity, error propagation equations (See Table J-1) will not be derived for all types of signal-processing modules. Equations for only the most important signal-processing functions will be developed; however, the methods discussed can be applied to functions not specifically addressed here. The equations derived are applicable to all signal conditioners of that type regardless of the manufacturer.

The techniques presented here are not used to calculate the inaccuracies of individual modules; they are used to calculate uncertainty of the output of a module when the module inaccuracy, input signal uncertainty and module transfer function are known.

This section discusses only two classifications of errors or uncertainties: those which are random and independent and can be combined statistically, and those which are biases which must be combined algebraically. The methods discussed can be used for both random and biased uncertainty components.

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, all modules in the process electronics for a particular instrument channel are tested together, they may be considered one device. The uncertainty associated with the output of that device should be equal to or less than the uncertainty calculated by combining all individual modules.

J.1 Error Propagation Equations Using Partial Derivatives and Perturbation Techniques

There are several valid approaches for the derivation of equations which express the effect of passing an input signal with an error component through a module that performs a mathematical operation on the signal. The approaches discussed here, which are recommended for use in developing error-propagation equations, are based on the use of partial derivatives or perturbation techniques, i.e., changing the value of a signal by a small amount and evaluating the effect of the change on the output. Either technique is acceptable and the results, in most cases, are similar.

For simplicity, this discussion assumes that input errors consist of either all random or all biased uncertainty components. The more general case of uncertainties with both random and biased components is addressed later in this attachment.

J.2 Propagation of Input Errors Through a Summing Function

The summing function is represented by the equation:

$$C = (k_1 \times A) + (k_2 \times B) \qquad \text{Eqn. J.1}$$

where,

C = Output signal

A, B = Input signals

k_1 and k_2 = Constants representing gain or attenuation of the input signals

The summing function is shown on Figure J-1.

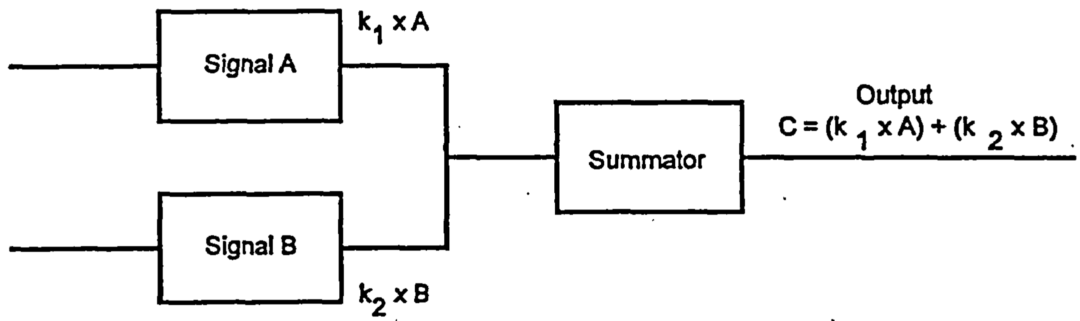


Figure J-1
Summing Function

The input signals are summed as shown above to provide an output signal. If the input signals A and B have errors, a and b, the output signal including propagated error is given by:

$$C + c = k_1 \times (A + a) + k_2 \times (B + b) \qquad \text{Eqn. J.2}$$

where c is the error of the output signal C. Subtracting Equation J.1 from Equation J.2 provides the following estimate of the output signal uncertainty:

$$c = (k_1 \times a) + (k_2 \times b) \qquad \text{Eqn. J.3}$$

Equation J.3 is appropriate if the errors, a and b, are bias errors. If the input errors are random, they can be combined as the square root of the sum of the squares to predict the output error:

$$c = \sqrt{(k_1 \times a)^2 + (k_2 \times b)^2} \qquad \text{Eqn. J.4}$$

The above expressions for uncertainty can also be derived using partial derivatives. Start by taking the partial derivative of Equation J.1 with respect to each input:

$$\frac{d}{dA} C = \frac{d}{dA}(k_1 \times A) + \frac{d}{dA}(k_2 \times B) \qquad \text{Eqn. J.5}$$

$$\frac{d}{dB} C = \frac{d}{dB}(k_1 \times A) + \frac{d}{dB}(k_2 \times B) \qquad \text{Eqn. J.6}$$

The input signals are independent. The input errors, a and b, represent the change in A and B, or $dA=a$ and $dB=b$. If c represents the change in C, then $dC=c$, yielding:

$$c = (k_1 \times a) + (k_2 \times b) \qquad \text{Eqn. J.7}$$

If the input signals are random, they can be combined as the square root of the sum of the squares to predict the output error:

$$dC = \sqrt{\left(\frac{dC}{dA} \times a\right)^2 + \left(\frac{dC}{dB} \times b\right)^2} \qquad \text{Eqn. J.8}$$

or

$$c = \sqrt{(k_1 \times a)^2 + (k_2 \times b)^2} \qquad \text{Eqn. J.9}$$

J.3 Propagation of Input Errors Through a Multiplication Function

The summing function is represented by the equation:

$$C = (k_1 \times A) \times (k_2 \times B) \qquad \text{Eqn. J.10}$$

where,

C	=	Output signal
A, B	=	Input signals
k_1 and k_2	=	Constants representing gain or attenuation of the input signals

The multiplication function is shown on Figure J-2.

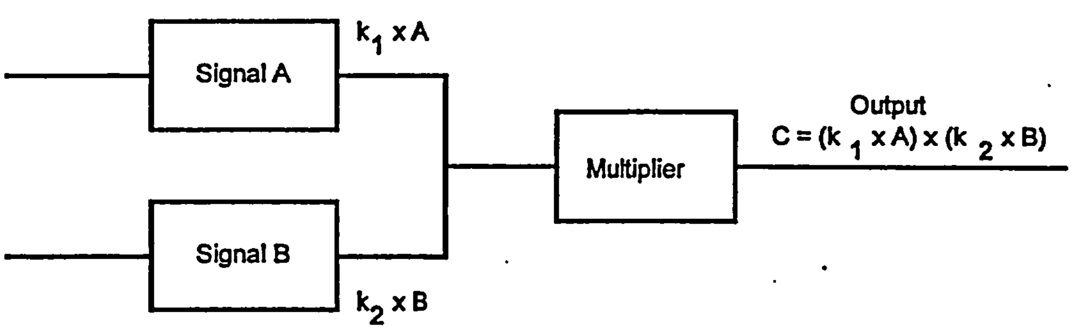


Figure J-2
Multiplication Function

The input signals are multiplied as shown above to provide an output signal. If the input signals A and B have errors, a and b, the output signal including propagated error is given by:

$$C + c = k_1 \times (A + a) \times k_2 \times (B + b) \qquad \text{Eqn. J.11}$$

where c is the error of the output signal C. Equation J.11 can be expanded as shown:

$$C + c = (k_1 \times A \times k_2 \times B) + (k_1 \times A \times k_2 \times b) + (k_1 \times a \times k_2 \times B) + (k_1 \times a \times k_2 \times b)$$

Eqn. J.12

Subtracting Equation J.12 from Equation J.10 provides the following estimate of the output signal uncertainty:

$$c = (k_1 \times A \times k_2 \times b) + (k_1 \times a \times k_2 \times B) + (k_1 \times a \times k_2 \times b) \qquad \text{Eqn. J.13}$$

or

$$c = k_1 \times k_2 \times [(A \times b) + (a \times B) + (a \times b)] \qquad \text{Eqn. J.14}$$

If a and b are small with respect to A and B, the term $a \times b$ is usually neglected to obtain the final result:

$$c = k_1 \times k_2 \times [(A \times b) + (a \times B)] \qquad \text{Eqn. J.15}$$

If the input signals are random, they can be combined as the square root of the sum of the squares to predict the output error:

$$c = k_1 \times k_2 \times \sqrt{(A \times b)^2 + (a \times B)^2} \qquad \text{Eqn. J.16}$$

J.4 Error Propagation Through Other Functions

Table J-1 shows equations for other functions derived by the same techniques presented in the previous sections. The *algebraic* expressions represent the more conservative approach assuming bias errors and the *SRSS* expressions apply to random errors. Refer to ISA-RP67.04, Part II, for more information.

Function	Treatment of Errors
Fixed Gain Amp $C = (k \times A)$	
$c = (k \times a)$	Algebraic
$c = (k \times a)$	SRSS
Summation $C = (k_1 \times A) + (k_2 \times B)$	
$c = (k_1 \times a) + (k_2 \times b)$	Algebraic
$c = \sqrt{(k_1 \times a)^2 + (k_2 \times b)^2}$	SRSS

Table J-1
Equations for Propagation of Uncertainties Through Modules Continues

Function	Treatment of Errors

Multiplication $C = (k_1 \times A) \times (k_2 \times B)$

$c = k_1 \times k_2 \times [(A \times b) + (a \times B) + (a \times b)]$ $c \approx k_1 \times k_2 \times [(A \times b) + (a \times B)]$	Algebraic
$c = k_1 \times k_2 \times \sqrt{(A \times b)^2 + (a \times B)^2 + (a \times b)^2}$ $c \approx k_1 \times k_2 \times \sqrt{(A \times b)^2 + (a \times B)^2}$	SRSS

Division $C = \dfrac{(k_1 \times A)}{(k_2 \times B)}$

$c \approx \dfrac{k_1}{k_2} \times \dfrac{(B \times a) - (A \times b)}{B^2}$	Algebraic
$c \approx \dfrac{k_1}{k_2} \times \dfrac{\sqrt{(B \times a)^2 + (A \times b)^2}}{B^2}$	SRSS

Logarithmic Amplification $C = k_1 + (k_2 \times Log\ A)$

$c = \dfrac{k_2 \times Log\ e}{A} \times a$	Algebraic
$c = \dfrac{k_2 \times Log\ e}{A} \times a$	SRSS

Table J-1
Equations for Propagation of Uncertainties Through Modules Continues

Function	Treatment of Errors

Squaring $C = A^2$

$c = (2 \times A \times a) + a^2$	Algebraic
$c = 2 \times A \times a$	SRSS

Square Root Extraction $C = \sqrt{A}$

$c = \sqrt{A + a} - \sqrt{A}$	Algebraic
$c = \dfrac{a}{2 \times \sqrt{A}}$	SRSS

Table J-1
Equations for Propagation of Uncertainties Through Modules

ATTACHMENT K
GRADED APPROACH TO UNCERTAINTY ANALYSIS

K.1 Introduction

The methodology presented in this engineering standard is intended to establish a minimum 95% probability with a high confidence that a setpoint will actuate when required. The methodology is based, in part, on ISA-S67.04, *Setpoints for Nuclear Safety-Related Instrumentation*, and ISA-RP67.04, *Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation.*

When a calculation is prepared in accordance with this engineering standard, it will accomplish a rigorous review of the instrument loop layout and design. Each element of uncertainty will be evaluated in detail and the estimated loop uncertainty will be justified at length. The setpoint will be carefully established with respect to the process analytical limit and the channel uncertainty. In short, a calculation prepared in accordance with this engineering standard will be comprehensive and can easily take an engineer one or more weeks to complete. This level of effort is justified for those calculations involving reactor and public safety. But, it is not intended that this level of effort be applied to all calculations, regardless of subject. For example, a toilet float switch should not be evaluated to the same level of detail as a pressurizer low pressure setpoint. The level of detail should be commensurate with the importance of the application. This attachment provides guidance regarding how to satisfy the needs for proper setpoint control while allowing for simpler approaches for less critical applications. Guidance is also provided for the reduction of setpoint margin in those cases where the setpoint is very close to the operating range of the monitored process.

ISA-67.04 recognizes that the importance of setpoints may differ, depending on the application. It provides the following guidance regarding a graded approach to setpoint analysis:

> "The importance of the various types of safety-related setpoints differ, and as such it may be appropriate to apply different setpoint determination requirements. For automatic setpoints that have a significant importance to safety, for example, those required by the plant safety analyses and directly related to Reactor Protection System, Emergency Core-Cooling Systems, Containment Isolation, and Containment Heat Removal, a stringent setpoint methodology should consider all of the items noted in [Section] 4.1-4.4.2. However, for setpoints that may not have the same level of stringent requirements, for example, those that are not credited in the safety analyses or that do not have limiting values, the setpoint determination methodology could be less rigorous. In general, all uncertainty terms for a particular setpoint methodology may not be required for all setpoint calculations. The methodologies utilized shall be documented and appropriate justification shall be provided."

In October 1996, the NRC issued proposed Revision 3 to Regulatory Guide 1.105 - Draft Regulatory Guide DG-1045, *Setpoints for Safety-Related Instrumentation.* This draft document is significant here in that it provides the NRC staff perspective on a graded approach. The Discussion section of this document provides the following NRC perspective:

> "Section 4 of ISA-S67.04-1994 states that the safety significance of various types of setpoints for safety-related instrumentation may differ, and thus one may apply a less rigorous setpoint determination method for certain functional units a limiting conditions of operation (LCOs). A setpoint methodology can include a graded approach. However, the grading technique chosen by the licensee should be consistent with the standard and should consider applicable uncertainties regardless of the setpoint application. Additionally, the application of the

standard, using a "graded" approach is also appropriate for non-safety system instrumentation for maintaining design limits described in the Technical Specifications. Examples may include instrumentation relied on in emergency operating procedures (EOPs) and for meeting applicable LCOs, and for meeting the variables in Regulatory Guide 1.97, "Instrumentation for Light-Water-Cooled Nuclear Power Plants to Assess Plant and Environs Conditions During and Following an Accident."

As can be seen with the above, industry and NRC consensus does recognize that a graded methodology is a reasonable approach to setpoint analysis.

K.2 IP3 Classification of Setpoint Types and Graded Approach Recommendations

MCM-8, *IP3 Setpoint Control*, distinguishes between applications by providing the following classifications of setpoint types:

Type 1: Technical Specification values for Reactor Protection System (RPS) Trips and Engineered Safety Features (ESF) initiations and isolations.

Type 2: Technical Specification and FSAR values not covered in Type 1 that are required for the operability of equipment required by Technical Specifications, NYPA's commitment to Regulatory Guide 1.97, and NYPA's commitment to Appendix R.

Type 3: Setpoints and settings for instruments and devices not determined to be Type 1 or 2 used to maintain system and process conditions within their prescribed functional envelope (e.g. heater drain tank level controls and alarms, filter regulator setting for feedwater control valve positioner, etc.).

Type 4: Setpoints and settings for instruments and devices whose primary function is the protection of other components (e.g. relief valve setpoints, low oil pressure alarms, etc.).

The above classifications are independent of quality assurance category. For example, Type 1 setpoints are safety related because they involve the RPS and ESF systems. But, Type 4 setpoints can include safety and non-safety related setpoints. The above classifications are defined by function rather than required level of quality assurance.

The following guidelines should be followed with regard to the level of detail required by a calculation:

- Type 1 and 2 setpoints must be prepared in accordance with this engineering standard and must account for all known sources of uncertainty. The expected result of these calculations is that they establish a well-documented basis for the 95% probability that the setpoint will actuate as desired. Instrument drift calculations based on plant-specific calibration data shall establish a minimum 95%/95% tolerance interval from the data (except where less stringent tolerances are specifically allowed by the NRC).

- Type 3 setpoints need not meet all requirements of this engineering standard, including the required level of detail or depth of analysis, unless they involve safety-related setpoints. Type 3 setpoints are normally associated with system control functions. Documented engineering judgement can be applied to those uncertainties that are not readily known or available. Instrument drift calculations based on plant-specific calibration data should establish a minimum 95%/75% tolerance interval from the data.

- Type 4 setpoints for safety-related applications must be prepared in accordance with this engineering standard and must account for all known sources of uncertainty. The expected result of these calculations is that they establish a well-documented basis for the 95% probability that the setpoint will actuate as desired. Instrument drift calculations based on plant-specific calibration data should establish a minimum 95%/95% tolerance interval from the data.

- Type 4 setpoints for non-safety-related setpoints need not meet all requirements of this engineering standard, including the required level of detail or depth of analysis. Documented engineering judgement can be applied to those uncertainties that are not readily known or available. Instrument drift calculations based on plant-specific calibration data should establish a minimum 95%/75% tolerance interval from the data. If justified for the specific application being evaluated, a 75%/75% tolerance interval may be used.

The minimum 95%/75% tolerance interval allowed for less important setpoints above is intended to provide additional operational margin where necessary. A higher degree of confidence can be used if operating margin is not needed.

Instruments that only have a single setpoint that is approached from a single direction can be corrected in accordance with the method presented in Section K.3.

Whenever there is doubt regarding the importance of a setpoint, be more, rather than less, conservative regarding the level of detail and the adequacy of engineering judgement. As specified by MCM-8, setpoint calculations for Type 1 and 2 instruments must be reviewed by Design Engineering. Setpoint calculations for Type 3 and 4 instruments do not necessarily require review by Design Engineering.

K.3 Correction for Single-Sided Setpoints

The methodology presented in this engineering standard is intended to establish a minimum 95% probability with a high confidence that a setpoint will actuate when required. Without consideration of bias effects, the probability is two-sided and symmetric about the mean as shown in Figure K-1.

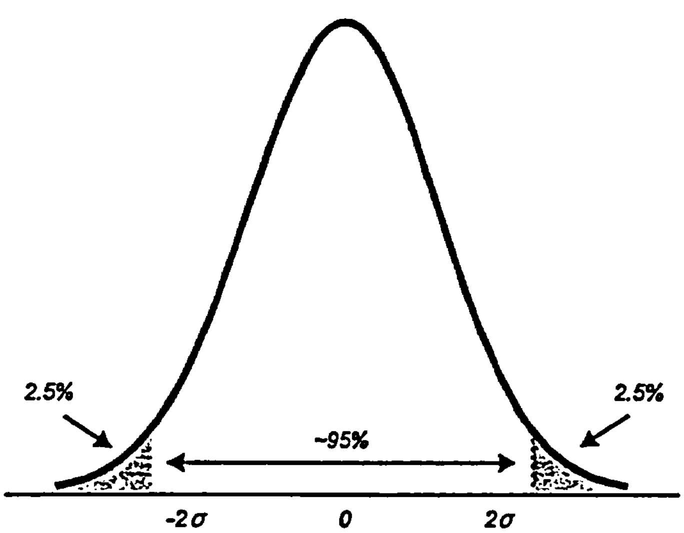


Figure K-1
Typical Two-Sided Setpoint at 95% Level

Figure K-1 shows the configuration in which there may be high and low setpoints associated with a single process. In some cases, there will only be a single setpoint associated with a particular sensor. For example, a pressure switch may actuate a high level alarm when a tank level is too high. In this case, a 95% probability is desired for the high level setpoint only as shown in Figure K-2.

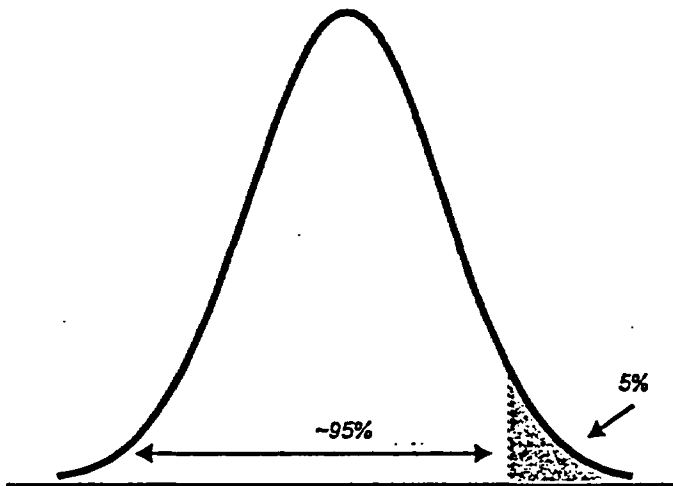


Figure K-2
Typical One-Sided Setpoint at 95% Level

A two-sided normally distributed probability at the 95% level will have 95% of the uncertainties falling within $\pm 1.96\sigma$ (see Example L-1), with 2.5% below -1.96σ and 2.5% above 1.96σ. However, for one-sided normally distributed uncertainties, 95% of the population will fall below $+1.645\sigma$ (see Table L-2). If the concern is that a single value of the process parameter is not exceeded and the single value is approached only from one direction, the appropriate limit to use for the 95% probability is $+1.645\sigma$ (or -1.645σ, depending on the direction from which the setpoint is approached).

Provided that the individual component uncertainties were developed at the 95% level, or greater, the final calculated uncertainty result can be corrected for a single side of interest by the following expression:

$$\frac{1.645}{1.96} = 0.839 \qquad \text{Eqn. K.1}$$

Example K-1

Suppose the calculated channel uncertainty is $\pm 2\%$ of span and this represents a 95% probability for the expected uncertainty. Suppose the uncertainty applies to only a high level trip setpoint. In this case, we are only concerned with what happens on the high end of span (near the setpoint). The setpoint can be established for a single side of interest by multiplying the Equation K.1 correction by the calculated channel uncertainty, or

$$0.839 \times 2\% = 1.68\%$$

Thus, rather than require that the setpoint require a 2% allowance for uncertainty, only a 1.68% allowance needs to be considered. This can provide additional margin for normal system operation.

ATTACHMENT L
UNCERTAINTY ANALYSIS METHODOLOGY BASIS

L.1 Introduction

Measurement uncertainty is unavoidable. Since the early twentieth century and the statement of the Heisenberg Uncertainty Principle, we have come to realize that we cannot simultaneously exactly know an objects speed and its location. Precise knowledge of one parameter invariably results in some degree of uncertainty in other parameters.

Naturally, this line of thought leads to the question, how much uncertainty is good enough? Or, how precisely must we measure a parameter to accomplish our goals? If your goal is to avoid a speeding ticket, you should be able to accomplish this goal and still drive near the speed limit if your measurement uncertainty of the speed is ±2 mph. However, you may occasionally get a speeding ticket if your measurement uncertainty is ±20 mph.

A new design engineer quickly learns the meaning of tolerances. A measurement should have a desired value as well as an allowed range of acceptable values. For example, a manufacturing company producing yardsticks may allow each ruler to be 36±0.1 inches. Some tolerance is necessary to account for 1) the ability of their machinery to reproduce the desired length from yardstick to yardstick and 2) the uncertainty in their ability to precisely measure length. If the company requires all yardsticks to be accurate to within +0.0001 inches, it is likely that the company will lose money on quality control rejected product. And, if the allowed tolerance is ±1.0 inches, the yardsticks are probably too inaccurate to meet the needs of the customer. For each product, the allowed tolerance must be defined in advance.

The same principles apply to the measurement and monitoring of process parameters. The installed instrumentation may only be capable of a certain accuracy. The selection of instrumentation should balance the need for accurate measurements with the higher cost often required to obtain increased accuracy. The process requirements should be matched with the measurement uncertainty of the process.

Uncertainty analysis inevitably involves the application of engineering judgement. The goal is to establish a reasonable and defendable estimate of the measurement uncertainty. However, this estimate should not be so pessimistic that it is unusable or so optimistic that it is negligent. For example, an engineer should be skeptical of a claim that installed process instrumentation provides an indication uncertainty of less than ±0.01% (the equipment used to calibrate it is probably not that accurate!). On the other hand, an uncertainty statement of ±50% is effectively useless. In each instance, the engineer should understand the accuracy needs of the application and any estimate of uncertainty should take the application into account.

L.2 Expressing Uncertainty

Uncertainty is normally expressed as the nominal, or best estimate, measurement with a range within which the actual process value may lie. Measurement uncertainty will usually be shown in the following format:

$$\textit{Expected value of } x = x_{measured} \pm \delta x \qquad \text{Eqn. L.1}$$

For example, a level indicator may show that a tank level is at the 50% level mark. The uncertainty associated with this measurement may be ±2 %. In this case, the actual tank level is expected to be:

$$Tank\ Level = 50\% \pm 2\%$$

As will be seen, there is a certain confidence associated with a statement of uncertainty. For any tank, we are completely certain that the tank level is somewhere between completely empty and completely full. Unfortunately, this absolute statement of uncertainty is also quite useless; we knew this much even before we installed a level sensor. As the range of uncertainty is quantified by analysis of the measurement design, application, and installation, a statistical statement of our confidence associated with the expected uncertainty is appropriate. For example, we may state that we are 95% confident that the actual level is within ±2% of the indicated value. Or, we may state that we are 99% confident that the actual level is within ±3% of the indicated value. Notice that the ± spread about the nominal value tends to increase as our confidence level increases.

Process instrumentation uncertainty is often expressed as a percent of the instrument span or measured value. Consider a tank level measurement in which the uncertainty in the tank level measurement is ±6 inches. Without knowing the actual height of the tank, this stated uncertainty is meaningless. If the tank is only 24 inches tall, then our knowledge of tank level in proportion to the tank size is very crude. Conversely, this uncertainty represents a very precise measurement if the tank is 200 ft tall. By expressing the uncertainty in relation to the measured value or instrument span, some intuitive feel regarding the precision of the measurement is possible.

A fractional uncertainty is an uncertainty expressed in relation to the measured value. Consider a measured tank level of 50 inches with an uncertainty of ±2 inches. The uncertainty is stated as:

$$Tank\ Level = 50 \pm 2\ inches$$

The fractional uncertainty allows us to express the uncertainty as a percent of the measured value:

$$Tank\ Level\ Uncertainty = \frac{\delta x}{x_{measured}} = \frac{2}{50} = 0.04 \quad (4\%) \qquad \text{Eqn. L.2}$$

Instrumentation uncertainty is often expressed as a percent of span because manufacturers generally specify an instrument's measurement uncertainty as a single value applicable throughout the instrument span. In this case, the measured value could be stated as a percent of the instrument span with the uncertainty similarly stated as a percent of span value. For example, a measured level of 50 inches on a tank level sensor with a span of 200 inches corresponds to a measurement of 25% of tank level. An uncertainty of 2% of span corresponds to an uncertainty of 4 inches. The expected tank level could be expressed as 50 ±4 inches or 25 % ±2% span.

L.3 Statistical Intervals

An uncertainty analysis produces an estimate of the indication or setpoint uncertainty. Once an uncertainty for a process measurement has been established, a natural question to ask is: how confident are we of our predicted uncertainty? A statistically-obtained uncertainty estimate normally includes a probability statement and an assessment of our level of confidence in the result. The following sections provide a technical overview of the statistics that are an important part of uncertainty analysis. The reader is assumed to have a basic understanding and application of the mean and standard deviation.

L.3.1 The Normal Distribution

The normal distribution has a special significance in statistical analysis; it is widely used and many analysis techniques rely on an assumption that the data is normally distributed. It is often said that analysts *believe* in the existence of the normal distribution. Engineers believe that mathematicians have a theorem that says random variables may be normally distributed, and mathematicians believe that engineers have routinely observed the normal distribution in practice. To a large degree, both beliefs are true.

If data is normally distributed, the distribution of probability is described by the following expression:

$$f(x; \mu, \sigma) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \quad \text{Eqn. L.3}$$

where,

x = An individual data point, and $-\infty \le x \le \infty$

μ = Mean (or average) value of the population (or $\bar{x}$ for a sample)

σ = Standard deviation of the population (or s for a sample)

Notice that the distribution of probability in a normal distribution is defined entirely by knowledge of the mean and standard deviation. This feature is one of the more important reasons for its wide use. The mean is simply the average value of a set of data. The standard deviation, σ, is a measure of the degree of dispersion of the data about the mean. The width of the normal distribution curve depends on the size of σ. As shown in Figure L-1, the bell shape of the normal distribution is wider if σ is large and narrower if σ is small.

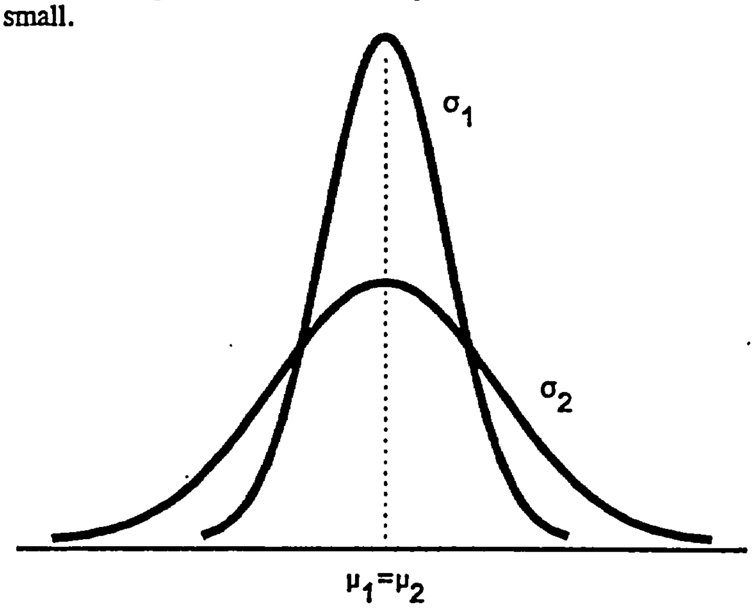


Figure L-1
Variation of the Normal Distribution Curve With σ, $\sigma_1 < \sigma_2$

A highly-peaked, narrow distribution with a small value of σ corresponds to a precise data set in which the individual data points are concentrated near the same value. A wider distribution corresponds to a less precise data set or a data set with significant variation in the individual values.

The mean, μ, represents the central point of the normal distribution curve. Figure L-2 shows the result for two normally distributed functions with equal standard deviations, but different means.

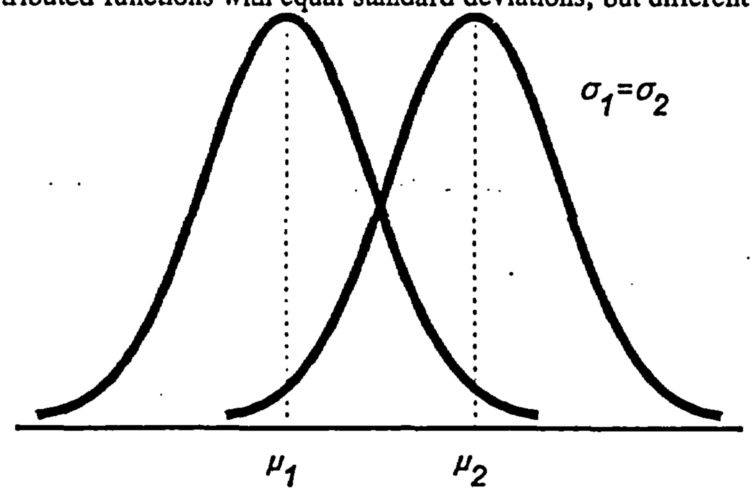


Figure L-2
Variation of the Normal Distribution Curve With μ, $\mu_1 < \mu_2$

The normal distribution curve can assume a variety of shapes depending on the value of the mean and the standard deviation, but it will always have the bell-shaped appearance. Figure L-3 shows the curves for two distributions with different means and standard deviations.

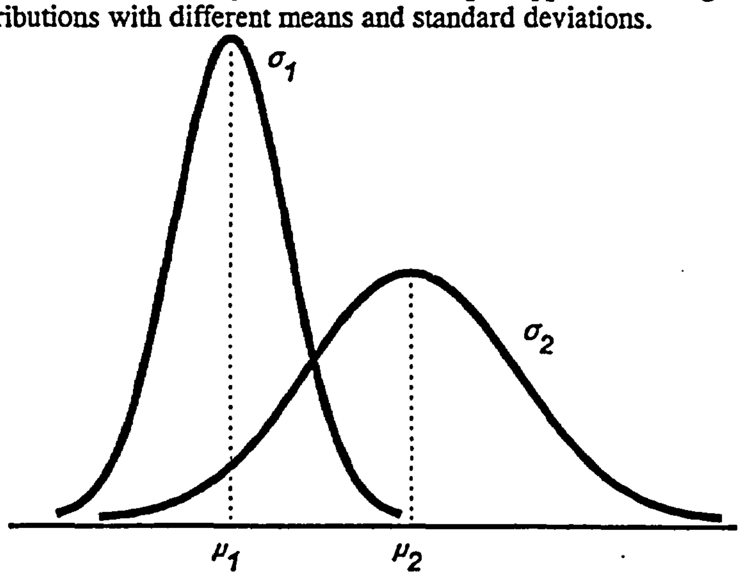


Figure L-3
Variation of the Normal Distribution Curve, $\sigma_1 < \sigma_2$ and $\mu_1 < \mu_2$

L.3.2 Areas Under the Normal Distribution Curve

The normal distribution curve is a probability density curve of the data and the total probability contained under the curve is equal to 1. This is easily verified by evaluating the integral of the normal distribution exponential function from $-\infty$ to $+\infty$. As given by Equation L.3, the normal distribution is described by:

$$f(x;\ \mu,\ \sigma) = \frac{1}{\sqrt{2\pi}\sigma}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

If we assume, for the sake of simplifying this example, that $\mu=0$ and $\sigma=1$, the exponential expression for the normal distribution simplifies to:

$$f(x;\ \mu,\ \sigma) = \frac{1}{\sqrt{2\pi}}\, e^{-\frac{(x)^2}{2}}$$

The integral of the above expression is given by:

$$\frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} e^{-\frac{(x)^2}{2}}\, dx = \frac{\sqrt{2\pi}}{\sqrt{2\pi}} = 1$$

This means that there is a 100% probability that each data point will be contained somewhere within the curve. The bell-shaped appearance shows that there is a much greater likelihood that a data point will be located near the center value, or mean, and a lesser likelihood that it will be located in the extreme ends, or tails, of the curve. This feature in the normal distribution is also appealing to analysts because it is likely that a given data point will be near the mean value of the population. The probability that a data point will lie within a certain interval can be calculated by use of the standard deviation, σ. For example, the probability that a point will lie within the interval of $\pm 1\sigma$ is approximately 68%. This interval is shown in Figure L-4.

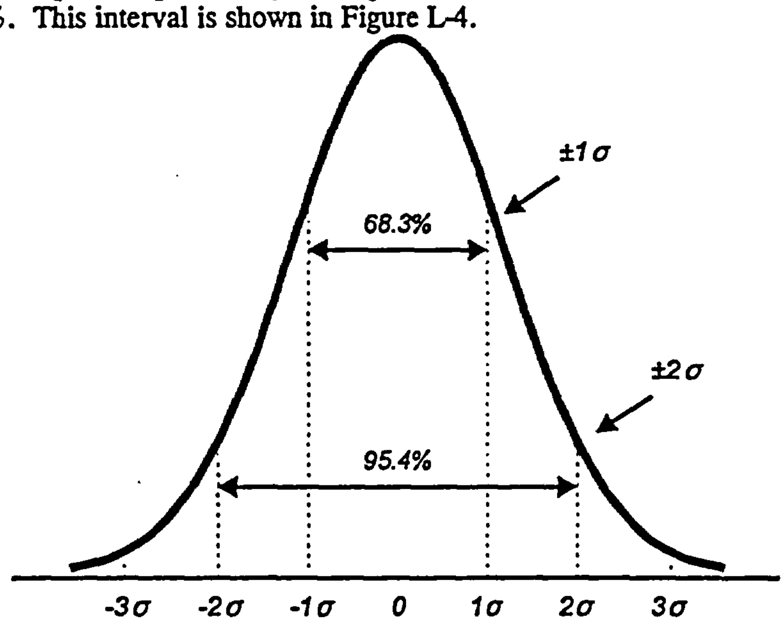


Figure L-4
Probability of a Measurement Within $\pm 1\sigma$

As the number of standard deviation, $t\sigma$, increases, there is an ever-increasing probability that a given data point will be contained within the interval $t\sigma$. The normal distribution probabilities for various multipliers of the standard deviation are shown in Table L-1. For example, referring to Table L-1, the probability that a data point will lie within 2 standard deviations, 2σ, is about 95.45%.

t	Probability for $t\sigma$, %
0.000	0.000
0.250	19.740
0.500	38.290
0.674	50.000
0.750	54.670
1.000	68.270
1.500	86.640
2.000	95.450
2.500	98.760
3.000	99.730
3.500	99.590
4.000	99.9994

Table L-1
Probability That an Individual Data Point Will Lie Within $\pm t\sigma$

Statistics performed for uncertainty analyses are often performed at a 2σ, or approximately 95%, probability. As shown in Table L-1, the probability that a data point will lie outside the stated interval decreases as the number of standard deviations increases.

Given a normal distribution, the probability of obtaining a value X between any two points, x_1 and x_2, can be determined by calculating the area under the curve defined by these two points. The area is calculated by the integral

$$P\ (x_1 < X < x_2) = \frac{1}{\sqrt{2\pi}\sigma} \int_{x_1}^{x_2} e^{-\frac{(x-\mu)^2}{2\sigma^2}}\, dx \qquad \text{Eqn. L.4}$$

The are under the curve defined by x_1 and x_2 is shown on Figure L-5.

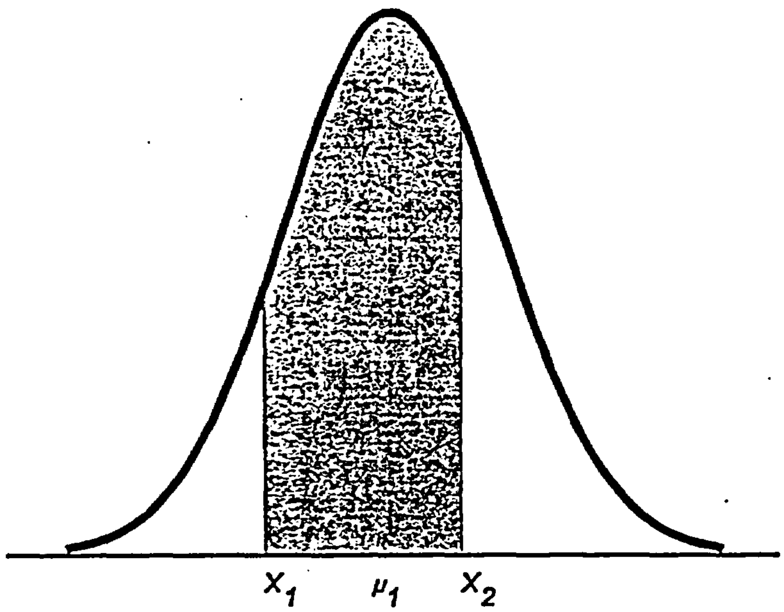


Figure L-5
$P(x_1 < X < x_2)$ Described by Shaded Area

In practice, lookup tables are used to determine the probabilities associated with different areas under the curve; evaluating the integral of the normal density function can quickly become tiresome. However, lookup tables are not prepared for every possible combination of mean and standard deviation. Instead, a single table is provided with $\mu=0$ and $\sigma=1$. Any observations of a normal random variable, X, are transformed to a standardized normal random variable Z with $\mu=0$ and $\sigma=1$ by the following transformation.

$$z = \frac{X - \mu}{\sigma} \qquad \text{Eqn. L.5}$$

The distribution of Z with $\mu=0$ and $\sigma=1$ is called the *standard normal distribution*. If the random variable X assumed a specific value x, the transformed value of Z is given by $z = (x-\mu)/\sigma$. Referring to Figure L-5, if X falls between the values $x = x_1$ and $x = x_2$, the random variable Z will fall between the corresponding values $z_1 = (x_1-\mu)/\sigma$ and $z_2 = (x_2-\mu)/\sigma$, or

$$P\,(x_1 < X < x_2) = \frac{1}{\sqrt{2\pi}\sigma}\int_{x_1}^{x_2} e^{-\frac{(x-\mu)^2}{2\sigma^2}}\,dx$$

$$= \frac{1}{\sqrt{2\pi}}\int_{z_1}^{z_2} e^{-\frac{(z)^2}{2}}\,dz$$

$$= P\,(z_1 < Z < z_2)$$

By transforming any random variable X into the standard normal distribution Z, with $\mu=0$ and $\sigma=1$, only a single table is required to determine the probability associated with the area under the curve, regardless of the value of μ and σ for X. Table L-1 provides the area under the curve corresponding to $P(Z<z)$. The probability $P(z_1<Z<z_2)$ is simply $P(Z<z_2) - P(Z<z_1)$. The following examples illustrate the use of the standard normal distribution and Table L-2.

Example L-1

Given a standard normal distribution, find the area of the curve that lies a) to the left of $z = 1.96$, b) to the left of -1.96, and c) between $z = -1.96$ and $z = 1.96$.

a) Referring to Table L-2, locate the value of $z = 1.9$ in the left column and move across the row to the column under 0.06 to find $z = 1.96$. Obtain the value 0.9750. This is the answer. The area contained to the left of $z = 1.96$ is 0.9750, or

$$P\ (Z < 1.96) = 0.9750$$

b) Referring to Table L-2, locate the value of $z = -1.9$ in the left column and move across the row to the column under 0.06 to find $z = -1.96$. Obtain the value 0.0250. This is the answer. The area contained to the left of $z = -1.96$ is 0.0250, or

$$P\ (Z < -1.96) = 0.0250$$

c) The area contained between $z = -1.96$ and $z = 1.96$ is simply the difference between the results obtained in parts a) and b) above, or 0.9750 - 0.0250 = 0.9500. Another way of stating the problem is:

$$P\ (-1.96 < Z < 1.96) = P\ (Z < 1.96) - P\ (Z < -1.96) = 0.9750 - 0.0250 = 0.95$$

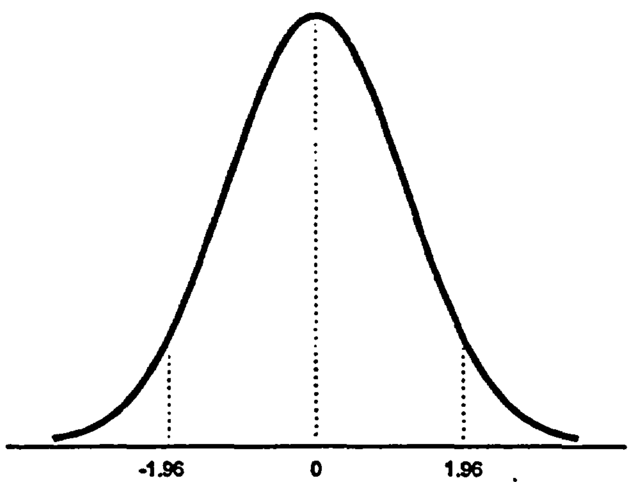


Figure L-6
Example L-1 Areas

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
-3.4	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0002
-3.3	.0005	.0005	.0005	.0004	.0004	.0004	.0004	.0004	.0004	.0003
-3.2	.0007	.0007	.0007	.0006	.0006	.0006	.0006	.0005	.0005	.0005
-3.1	.0010	.0010	.0010	.0009	.0008	.0008	.0008	.0008	.0007	.0007
-3.0	.0013	.0013	.0013	.0012	.0012	.0011	.0011	.0011	.0010	.0010
-2.9	.0019	.0018	.0017	.0017	.0016	.0016	.0015	.0015	.0014	.0014
-2.8	.0026	.0025	.0024	.0023	.0023	.0022	.0021	.0021	.0020	.0019
-2.7	.0035	.0034	.0033	.0032	.0031	.0030	.0029	.0028	.0027	.0026
-2.6	.0047	.0045	.0044	.0043	.0041	.0040	.0039	.0038	.0037	.0036
-2.5	.0062	.0060	.0059	.0057	.0055	.0054	.0052	.0051	.0049	.0048
-2.4	.0082	.0080	.0078	.0075	.0073	.0071	.0069	.0068	.0066	.0064
-2.3	.0107	.0104	.0102	.0099	.0096	.0094	.0091	.0089	.0087	.0084
-2.2	.0139	.0136	.0132	.0129	.0125	.0122	.0119	.0116	.0113	.0110
-2.1	.0179	.0174	.0170	.0166	.0162	.0158	.0154	.0150	.0146	.0143
-2.0	.0228	.0222	.0217	.0212	.0207	.0202	.0197	.0192	.0188	.0183
-1.9	.0287	.0281	.0274	.0268	.0262	.0256	.0250	.0244	.0239	.0233
-1.8	.0359	.0352	.0344	.0336	.0329	.0322	.0314	.0307	.0301	.0294
-1.7	.0446	.0436	.0427	.0418	.0409	.0401	.0392	.0384	.0375	.0367
-1.6	.0548	.0537	.0526	.0516	.0505	.0495	.0485	.0475	.0465	.0455
-1.5	.0668	.0655	.0643	.0630	.0618	.0606	.0594	.0582	.0571	.0559
-1.4	.0808	.0793	.0778	.0764	.0749	.0735	.0722	.0708	.0694	.0681
-1.3	.0968	.0951	.0934	.0918	.0901	.0885	.0869	.0853	.0838	.0823
-1.2	.1151	.1131	.1112	.1093	.1075	.1056	.1038	.1020	.1003	.0985
-1.1	.1357	.1335	.1314	.1292	.1271	.1251	.1230	.1210	.1190	.1170
-1.0	.1587	.1562	.1539	.1515	.1492	.1469	.1446	.1423	.1401	.1379
-0.9	.1841	.1814	.1788	.1762	.1736	.1711	.1685	.1660	.1635	.1611
-0.8	.2119	.2090	.2061	.2033	.2005	.1977	.1949	.1922	.1894	.1867
-0.7	.2420	.2389	.2358	.2327	.2296	.2266	.2236	.2206	.2177	.2148
-0.6	.2743	.2709	.2676	.2643	.2611	.2578	.2546	.2514	.2483	.2451
-0.5	.3085	.3050	.3015	.2981	.2946	.2912	.2877	.2843	.2810	.2776
-0.4	.3446	.3409	.3372	.3336	.3300	.3264	.3228	.3192	.3156	.3121
-0.3	.3821	.3783	.3745	.3707	.3669	.3632	.3594	.3557	.3520	.3483
-0.2	.4207	.4168	.4129	.4090	.4052	.4013	.3974	.3936	.3897	.3859
-0.1	.4602	.4562	.4522	.4483	.4443	.4404	.4364	.4325	.4286	.4247
0.0	.5000	.4960	.4920	.4880	.4840	.4801	.4761	.4721	.4681	.4641

Table L-2
Areas Under the Normal Curve

z	.00	.01	.02	.03	.04	.05	.06	.07	.08	.09
0.0	.5000	.5040	.5080	.5120	.5160	.5199	.5239	.5279	.5319	.5359
0.1	.5398	.5438	.5478	.5517	.5557	.5596	.5636	.5675	.5714	.5753
0.2	.5793	.5832	.5871	.5910	.5948	.5987	.6026	.6064	.6103	.6141
0.3	.6179	.6217	.6255	.6293	.6331	.6368	.6406	.6443	.6480	.6517
0.4	.6554	.6591	.6628	.6664	.6700	.6736	.6772	.6808	.6844	.6879
0.5	.6915	.6950	.6985	.7019	.7054	.7088	.7123	.7157	.7190	.7224
0.6	.7257	.7291	.7324	.7357	.7389	.7422	.7454	.7486	.7517	.7549
0.7	.7580	.7611	.7642	.7673	.7704	.7734	.7764	.7794	.7823	.7852
0.8	.7881	.7910	.7939	.7967	.7995	.8023	.8051	.8078	.8106	.8133
0.9	.8159	.8186	.8212	.8238	.8264	.8289	.8315	.8340	.8365	.8389
1.0	.8413	.8438	.8461	.8485	.8508	.8531	.8554	.8577	.8599	.8621
1.1	.8643	.8665	.8686	.8708	.8729	.8749	.8770	.8790	.8810	.8830
1.2	.8849	.8869	.8888	.8907	.8925	.8944	.8962	.8980	.8997	.9015
1.3	.9032	.9049	.9066	.9082	.9099	.9115	.9131	.9147	.9162	.9177
1.4	.9192	.9207	.9222	.9236	.9251	.9265	.9278	.9292	.9306	.9319
1.5	.9332	.9345	.9357	.9370	.9382	.9394	.9406	.9418	.9429	.9441
1.6	.9452	.9563	.9474	.9484	.9495	.9505	.9515	.9525	.9535	.9545
1.7	.9554	.9564	.9573	.9582	.9591	.9599	.9608	.9616	.9625	.9633
1.8	.9641	.9649	.9656	.9664	.9671	.9678	.9686	.9693	.9699	.9706
1.9	.9713	.9719	.9726	.9732	.9738	.9744	.9750	.9756	.9761	.9767
2.0	.9772	.9778	.9783	.9788	.9793	.9798	.9803	.9808	.9812	.9817
2.1	.9821	.9826	.9830	.9834	.9838	.9842	.9846	.9850	.9854	.9857
2.2	.9861	.9864	.9868	.9871	.9875	.9878	.9881	.9884	.9887	.9890
2.3	.9893	.9896	.9898	.9901	.9904	.9906	.9909	.9911	.9913	.9916
2.4	.9918	.9920	.9922	.9925	.9927	.9929	.9931	.9932	.9934	.9936
2.5	.9938	.9940	.9941	.9943	.9945	.9946	.9948	.9949	.9951	.9952
2.6	.9953	.9955	.9956	.9957	.9959	.9960	.9961	.9962	.9963	.9964
2.7	.9965	.9966	.9967	.9968	.9969	.9970	.9971	.9972	.9973	.9974
2.8	.9974	.9975	.9976	.9977	.9977	.9978	.9979	.9979	.9980	.9981
2.9	.9981	.9982	.9982	.9983	.9984	.9984	.9985	.9985	.9986	.9986
3.0	.9987	.9987	.9987	.9988	.9988	.9989	.9989	.9989	.9990	.9990
3.1	.9990	.9991	.9991	.9991	.9992	.9992	.9992	.9992	.9993	.9993
3.2	.9993	.9993	.9994	.9994	.9994	.9994	.9994	.9995	.9995	.9995
3.3	.9995	.9995	.9995	.9996	.9996	.9996	.9996	.9996	.9996	.9997
3.4	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9997	.9998

Table L-2, continued
Areas Under the Normal Curve

Example L-2

Given a standard normal distribution, find the area of the curve that lies to the right of $z = 1.55$.

Notice that Table L-2 is configured to describe the are to the left of z. The total area under the standard normal distribution equals 1. Therefore, the area to the right of $z = 1.55$ is 1 minus the area to the left of $z = 1.55$, or $P(Z>1.55) = 1 - P(Z<1.55)$. Referring to Table L-2, $z = 1.55$ corresponds to 0.9394. The area to the right of $z = 1.55$ is

$$P\ (Z > 1.55) = 1 - P\ (Z < 1.55) = 1 - 0.9394 = 0.0606$$

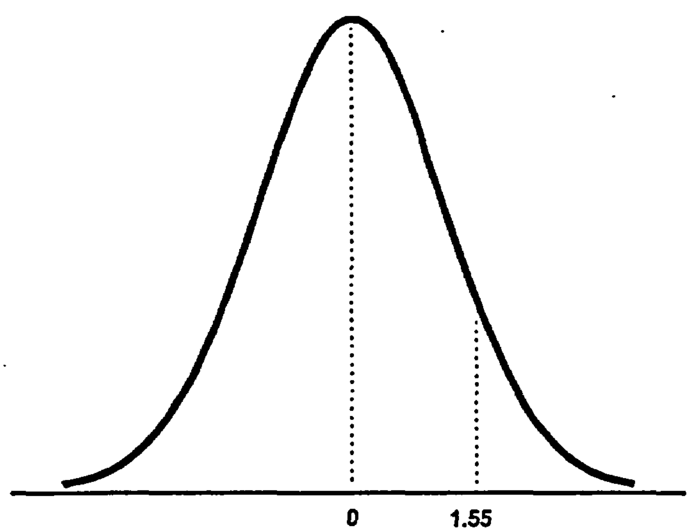


Figure L-7
Example L-2 Area

Example L-3

Given a normal distribution, determine the probability of obtaining a value of X within three standard deviations, 3σ, of the mean.

First, compute the z-values corresponding to $x_1 = \mu - 3\sigma$ and $x_2 = \mu + 3\sigma$.

$$z_1 = \frac{(\mu - 3\sigma) - \mu}{\sigma} = -3$$

$$z_2 = \frac{(\mu + 3\sigma) - \mu}{\sigma} = 3$$

The problem statement has now been reworded so that Table L-2 can be used directly. The problem to be solved is:

$$P\ (\mu - 3\sigma < X < \mu + 3\sigma) = P\ (-3 < Z < 3)$$

$$= P\ (Z < 3) - P\ (Z < -3) = 0.9987 - 0.0013 = 0.9974$$

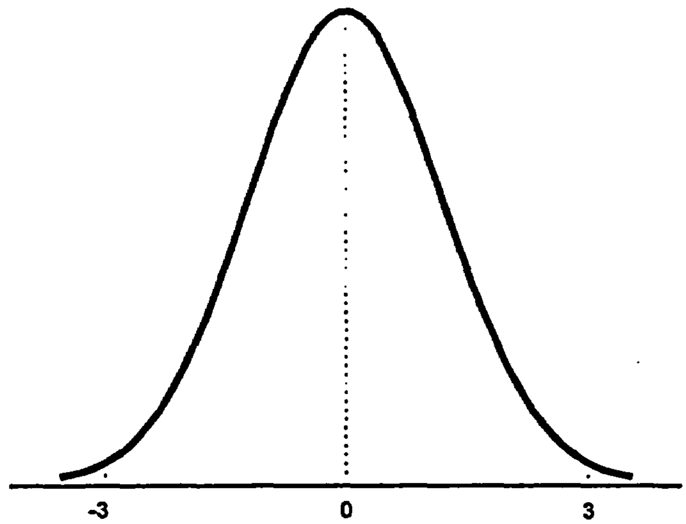


Figure L-8
Example L-3 Area

L.3.3 Confidence Intervals

The mean, μ, represent the best estimate of the parameter X. The standard deviation is one measure of how the data varies about the mean. Now, let's consider how accurate is our estimation of the mean. As might be expected from any discussion of uncertainty analysis, we do not expect to know the mean exactly. For any population, there is a value for the mean that precisely defines the average value. However, we are usually dealing with a sample taken from a population with an unknown mean and standard deviation. For this reason, we calculate the sample mean from the available data and establish bounds that are expected to contain the actual population mean. These bounds that are expected to contain the actual mean is known as a *confidence interval.*

Consider several random samples taken from a single population. Because the samples represent random subsets of the population, we expect to observe some variation in the mean. Figure L-9 shows the potential variation that might be observed in a set of samples. The solid dot on each line represents the sample mean and each line represents a confidence interval about the sample mean that is expected to contain the true population mean. Notice that the true mean is usually, but not always, contained within the confidence interval.

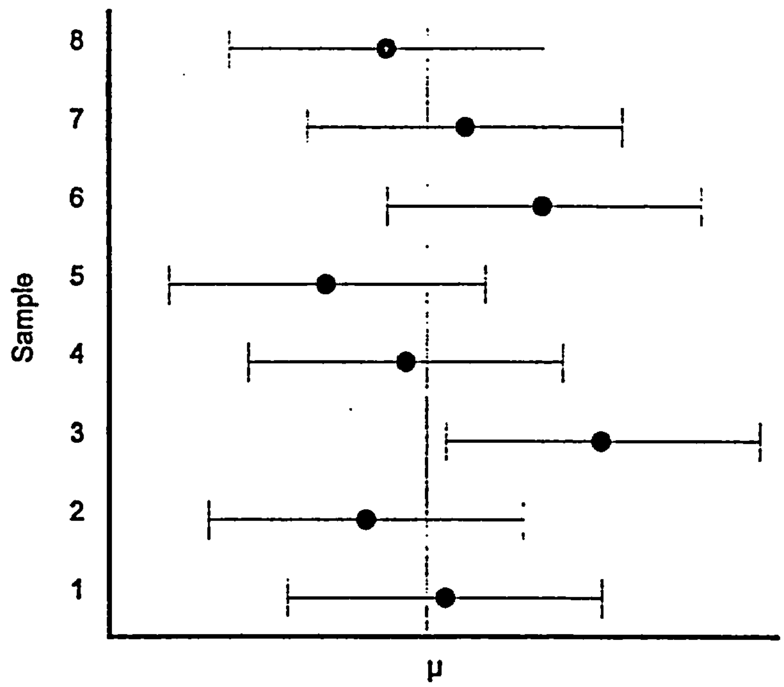


Figure L-9
Potential Confidence Intervals About the True Mean

A confidence interval is a statement of probability that the mean is contained within a given interval. For example, a confidence interval can be defined at the 80%, 95%, 99%, or any other probability. As the confidence level increases, the interval about the mean will become larger, reflecting the larger uncertainty about the mean as the statement of probability approaches 100%. For example, we may be 50% certain that a given confidence interval contains the true mean. In order to be 90% confident that our interval contains the mean, the width of the interval will be substantially larger.

The following sections discuss the confidence interval in more detail. Section L.3.3.1 describes the case in which the population standard deviation is known. Section L.3.3.2 describes the much more likely case in which the population standard deviation is not known.

L.3.3.1 Confidence Interval for a Known Standard Deviation

If $\bar{x}$ is the mean of a random sample of size n from a population with known standard deviation, σ, a $(1-\alpha)100\%$ confidence interval for μ is given by:

$$\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}} \qquad \text{Eqn. L.6}$$

where $z_{\alpha/2}$ is the standard normal distribution value from Table L-2 that leaves an area of $\alpha/2$ to the right.

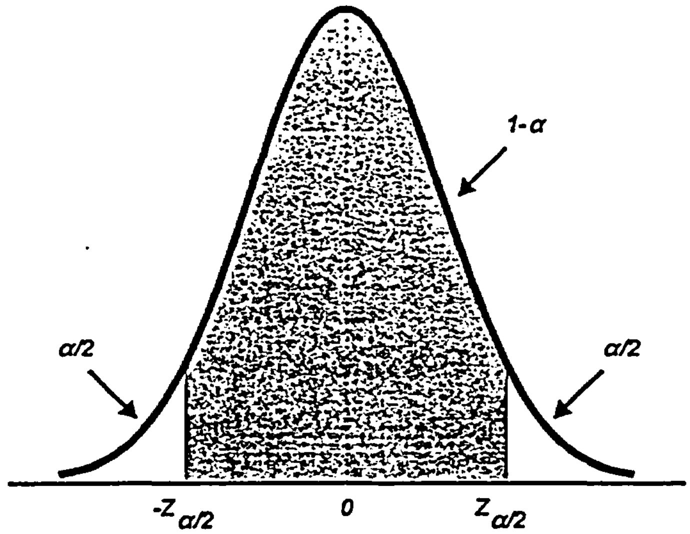


Figure L-10
$P(-z_{\alpha/2} < Z < z_{\alpha/2}) = 1-\alpha$

Example L-4

The sensitivity of a number of identical design bistables is checked by monitoring the trip (pickup) point actuation current. The average pickup current at a particular point for 25 bistables was 12 mA. Find the 95% and 99% confidence intervals for the bistable pickup current given that the population standard deviation is 0.32 mA.

To find the 95% confidence interval, first determine the z-values corresponding to 95% of the area under the curve shown in Figure L-10. The are containing 0.95 leaves areas of 0.025 in both tails. As previously shown in Example L-2, the corresponding z-value is 1.96. Therefore, the 95% confidence interval is:

$$\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$$

$$12 - 1.96 \times \frac{0.32}{\sqrt{25}} < \mu < 12 + 1.96 \times \frac{0.32}{\sqrt{25}}$$

or,

$$11.87 < \mu < 12.13$$

To find the 9% confidence interval, determine the z-values corresponding to 0.005. Using Table L-2, $z_{0.005} = 2.575$. Therefor, the 99% confidence interval is:

$$\bar{x} - z_{\alpha/2}\frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + z_{\alpha/2}\frac{\sigma}{\sqrt{n}}$$

$$12 - 2.575 \times \frac{0.32}{\sqrt{25}} < \mu < 12 + 2.575 \times \frac{0.32}{\sqrt{25}}$$

or, $$11.84 < \mu < 12.16$$

L.3.3.2 Confidence Interval for an Unknown Standard Deviation

The previous section applies for those instances in which the population standard deviation is already known. Unfortunately, we are more often attempting to estimate the mean of a population when the standard deviation is also unknown. This leads to the use of the *t*-distribution. If we obtain a random sample of size n from a normal distribution, the random variable *T* has a *t*-distribution with ν=n-1 degrees of freedom, or

$$T = \frac{\bar{x} - \mu}{s/\sqrt{n}} \qquad \text{Eqn. L.7}$$

The distribution of *T* is similar to the distribution of *Z* in that it is symmetric about a mean and is bell-shaped. The significant difference between the two distributions is that the distribution of *Z* only depends on the variability of $\bar{x}$ because the standard deviation is already known. The *t*-distribution varies with both $\bar{x}$ and the sample standard deviation, *s*. As the sample size becomes large, the *t*-distribution converges to the *Z* distribution.

If $\bar{x}$ is the mean of a random sample of size *n* from a population with unknown standard deviation, *s*, a (1-α)100% confidence interval for μ is given by:

$$\bar{x} - t_{\alpha/2}\frac{\sigma}{\sqrt{n}} < \mu < \bar{x} + t_{\alpha/2}\frac{\sigma}{\sqrt{n}} \qquad \text{Eqn. L.8}$$

where $t_{\alpha/2}$ is the critical value of the t-distribution from Table L-3 leaving an area of $\alpha/2$ to the right. Figure L-11 shows the t-distribution.

v	α=0.05	α=0.025
1	6.314	12.076
2	2.920	4.303
3	2.353	3.182
4	2.132	2.776
5	2.015	2.571
6	1.943	2.447
7	1.895	2.365
8	1.860	2.306
9	1.833	2.262
10	1.812	2.228
11	1.796	2.201
12	1.782	2.179
13	1.771	2.160
14	1.761	2.145
15	1.753	2.131
16	1.746	2.120
17	1.740	2.110
18	1.734	2.101
19	1.729	2.093
20	1.725	2.086
21	1.721	2.080
22	1.717	2.074
23	1.714	2.069
24	1.711	2.064
25	1.708	2.060
26	1.706	2.056
27	1.703	2.052
28	1.701	2.048
29	1.699	2.045
30	1.697	2.042
40	1.684	2.021
60	1.671	2.000
120	1.658	1.980
-	1.645	1.960

Table L-3
Probabilities of the t-Distribution

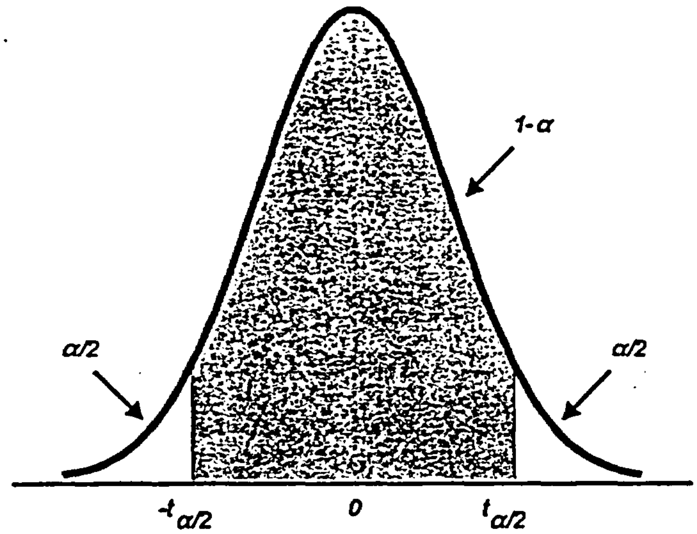


Figure L-11
$P(-t_{\alpha/2} < Z < t_{\alpha/2}) = 1-\alpha$

Example L-5

Rework Example L-4 for the 95% confidence interval if the population standard deviation is not known. The average pickup current for 25 bistables is 12 mA. Find the 95% confidence interval if the sample standard deviation is 0.32 mA.

Using Table L-3, $t_{0.025} = 2.064$ with $\nu = 24$ degrees of freedom. The 95% confidence interval is:

$$12 - 2.064 \times \frac{0.32}{\sqrt{25}} < \mu < 12 + 2.064 \times \frac{0.32}{\sqrt{25}}$$

or,

$$11.87 < \mu < 12.13$$

Notice that the answer is the same to two decimal places as Example L-4. The t-distribution asymptotically approaches the standard normal distribution as the sample size becomes large.

L.3.4 Tolerance Intervals

A tolerance interval is a statement of probability that a certain proportion of the population is contained within a defined interval. The tolerance interval description also includes an assessment of the level of confidence in the statement of probability. For example, a 95%/95% tolerance interval indicates a 95% level of confidence that 95% of the population is contained within the stated interval. A 95%/99% tolerance interval means that 99% of the population is contained within the stated interval with a 95% confidence.

The tolerance interval is defined as follows. For a normal distribution of measurements with unknown mean and unknown standard deviation, the tolerance interval is given by

$$\bar{x} \pm ks \qquad \text{Eqn. L.9}$$

The tolerance factor, k, is determined so that one can assert with 100γ% confidence that the given interval contains at least the proportion P of the measurements where,

$\bar{x}$ = Sample mean

k = Tolerance factor

s = Sample standard deviation

γ = Desired confidence level

P = Proportion of population contained within the tolerance interval

The tolerance interval is sometimes referred to as a tolerance limit because the calculated interval establishes upper and lower bounds within which is contained the stated proportion of the population. Some sources refer to a tolerance interval as a statistical tolerance content interval.

The tolerance interval is important for verifying that a stated proportion of the population is contained within a given interval. If the population mean and standard deviation are precisely known, approximately 95% of the population would be contained within the interval $\mu \pm 2\sigma$. However, precise knowledge of the mean and standard deviation is usually not available. Instead, the mean and standard deviation are estimated from a sample of the population.. The tolerance interval, $\bar{x} \pm ks$, is a larger interval than for the case in which μ and σ are known, thereby reflecting our greater uncertainty in the actual distribution of the data. As the sample size increases to infinity, the tolerance interval factor asymptotically approaches the ideal case in which the population mean and standard deviation are known.

Tolerance interval factors, k, are tabulated in Table L-4 for 95%/95% and 95%/99% tolerance intervals. Note that the appropriate tolerance factor depends on the sample size. As the sample size grows larger, the tolerance factor becomes smaller demonstrating a statistical confidence that the larger sample size is more representative of the total population. Refer to statistical texts for a more complete listing or for tolerance interval factors for other tolerance intervals.

Sample Size	95/95 Percent Tolerance Factor	95/99 Percent Tolerance Factor
10	3.38	4.43
20	2.75	3.62
30	2.55	3.35
40	2.45	3.21
50	2.38	3.13
75	2.29	3.00
100	2.23	2.93
150	2.18	2.86
200	2.14	2.82
300	2.11	2.77
400	2.08	2.74
500	2.07	2.72
600	2.06	2.71
800	2.05	2.69
1000	2.04	2.68
∞	1.96	2.58

Table L-4
Tolerance Interval Factors for Normal Distributions

Example shows how to determine a tolerance interval.

<u>Example L-6</u>

Assume the following instrument data statistics for $n = 50$ sample points:

$x = 0.0$ (sample mean)
$s = 0.5$ (sample standard deviation)

Calculate a 95/95 tolerance interval for this data set ($\gamma = 0.95$, $P = 0.95$)

By use of Table L-4, the tolerance factor $k = 2.38$. Therefore, the tolerance interval $x \pm ks =$ $0 \pm 2.38 \times (0.5) = \pm 1.19$. Our conclusion in this case is that we are 95% confident that 95% of the total population is contained within the interval from -1.19 to +1.19 based on our sample size of 50 points.

Some features of the tolerance interval as defined here are worth noting:

- The tolerance interval is based on the data being normally distributed.
- The tolerance factor, k, is selected based upon the sample size, the desired confidence level γ, and the proportion of the population P. Standard statistics texts provide tabulated values for the tolerance factor for various values of γ and P.
- The tolerance interval is two-sided and is centered about the sample mean. It defines an upper and a lower limit that is expected to contain a proportion of the population to a certain confidence.
- The tolerance interval establishes bounds on the entire population, not just the sampled data.

L.4 Square Root of the Sum of the Squares (SRSS) Methodology

The basic approach used to determine the overall uncertainty for a given channel or module is to combine all terms that are considered random using the Square Root of the Sum of the Squares (SRSS) methodology, then adding to the result any terms that are considered nonrandom.

The basic formula for the uncertainty calculation takes the form of:

$$CU = \pm\sqrt{A^2 + B^2 + C^2} \pm \sum |F| + \sum L - \sum M \qquad \text{Eqn. L-10}$$

where,

A, B, C = Random and independent uncertainty terms. The terms are zero-centered, approximately normally distributed, and are indicated by a sign of ±.

F = Arbitrarily distributed uncertainties (biases that do not have a specific known direction). The term is used to represent limits of error associated with uncertainties that are not normally distributed and do not have a known direction. The magnitude of this term is assumed to contribute to the total uncertainty in both directions and is indicated by a ± sign.

L and M = Biases (terms that are not random) with known direction. The terms can impart an uncertainty in a specific direction and, therefore, have a specific + or - contribution to the total uncertainty. Also, a negative (positive) bias is not combined with the positive (negative) uncertainty factors to reduce their overall effect unless the negative (positive) bias can be guaranteed to always be at the specified value. An example of such a bias is a static head on a pressure transmitter that was not corrected for by the calibration process.

CU = Resultant uncertainty.

The SRSS methodology allows combining the random and independent terms within the square root radical as shown above. This methodology is well established as an acceptable method of determining an instrument loop uncertainty. ISA-67.04, *Setpoints for Nuclear Safety-Related Instrumentation*, Section 4.4.1, states that it is acceptable to combine uncertainties that are random, normally distributed, and independent by the SRSS method. ISA-RP67.04, Methodologies for the Determination of Setpoints for Nuclear Safety-Related Instrumentation, provides additional information regarding the SRSS methodology. Although it does not directly apply to setpoint calculations, ANSI/ASME PTC 19.1, *Measurement Uncertainty*, provides additional information regarding the basis of the SRSS methodology. Anyone performing uncertainty calculations should be familiar with the above documents in addition to the information provided in this engineering standard.

One alternative to the SRSS methodology would be to simply algebraically add the random and independent terms. This approach is often stated to provide a 99%/99% confidence for the calculated uncertainty, i.e., we should have a 99% confidence that the result contains the actual value 99% of the time. The algebraic addition of errors assumes that all errors occur in the same direction simultaneously. We would expect that some errors occur in one direction while other errors occur in the opposite direction. Or, there should be some beneficial canceling of errors. The SRSS allows for this effect and is often stated to provide a 95%/95% confidence for the calculated uncertainty, i.e., we should have a 95% confidence that the result contains the actual value 95% of the time. Actually, a 95%/95% confidence is achievable only if the inputs to the calculation are known to this level.

Finally, the general equation for the SRSS method is often treated as an indisputable fact as if it exactly describes some physical process. Fortunately, engineering experience has demonstrated that the SRSS methodology does provide conservative and acceptable results if applied properly.

L.5 An Empirical Method of Confirming the SRSS Methodology

The SRSS method of determining instrument is widely used because it seems to work. The methodology does have a mathematical and statistical basis; however, there is a simpler method of confirming its applicability that does not require one to have an advanced degree in statistics. An example can readily demonstrate one way to gain a more intuitive feel for the analysis methodology. Consider the indication circuit in Figure L-12. The pressure transmitter sends a pressure signal to an isolator which retransmits the isolated signal to an indicator.

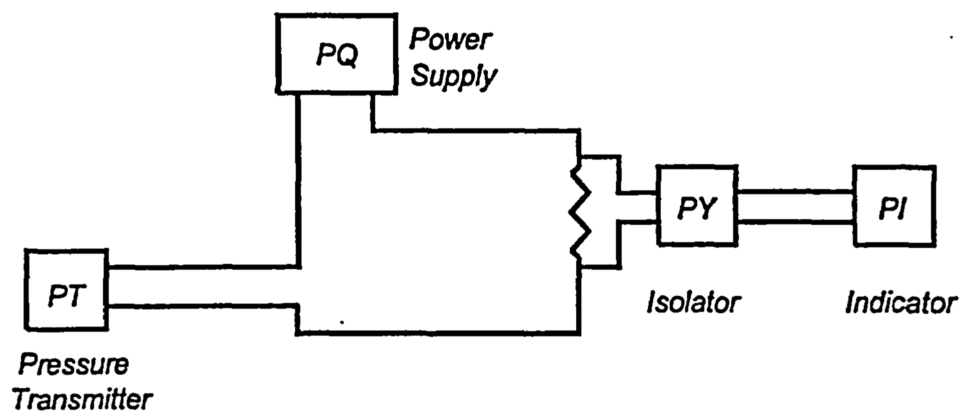


Figure L-12
Example Instrument Loop to Demonstrate SRSS Methodology

Assume for this example that the true process value is at 50% of span and assume the following uncertainties in the above instruments:

Pressure transmitter: ±1%
Isolator: ±0.5%
Indicator: ±1.5%
Power supply: negligible
Input resistor: negligible

The above uncertainties will each be assumed to be normally distributed about the true value or the input signal as appropriate. For example, the pressure transmitter senses the true value of 50% but provides an output of 50% ±1% with the ±1% normally distributed about the 50% point as shown on Figure L-13.

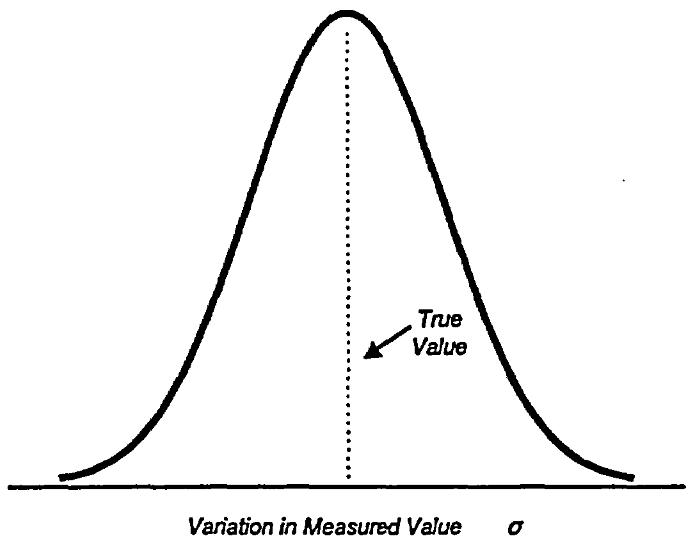


Figure L-13
Assumed Distribution of Uncertainties

Any spreadsheet program such as Excel or Quattro-Pro can be set up to perform a quick Monte Carlo study of the predicted indicated error. Normally-distributed random numbers are generated. The pressure transmitter provides an output signal in which the true value (50%) is varied by the a random number times the 1% uncertainty. This signal is provided to the isolator which then provides an output signal that is varied by another random number times the isolator's 0.5% uncertainty. The isolator's output signal is provided to the indicator which then provides an indication that is varied by another random number times the indicator's 1.5% uncertainty. If this process is repeated many times, an estimate of the total indication uncertainty can be obtained. For example, the above process was completed in an Excel spreadsheet in which a single Monte Carlo study consisted on the above process performed 5,000 times. The standard deviation of the 5,000 runs were then computed with the results shown below.

	Standard Deviation
Monte Carlo study #1	1.85%
Monte Carlo study #2	1.86%
Monte Carlo study #3	1.84%

Applying the SRSS methodology for these random uncertainties provides the following result:

$$Uncertainty = \sqrt{PTU^2 + ISU^2 + INDU^2} = \sqrt{1\%^2 + 0.5\%^2 + 1.5\%^2} = 1.87\%$$

Notice that the SRSS method predicts an uncertainty very close to that obtained by the Monte Carlo method. The advantage of the Monte Carlo method here is that it provides additional insight into the SRSS methodology. The following observations can now be made regarding the methodology:

- The methodology assumes that the uncertainties are normally distributed, or at least approximately normally distributed, about some mean value. For example, the Monte Carlo study yields a different result if the uncertainties have a uniform distribution. Industry experience is that an assumption of a normal distribution produces acceptable results.

- Notice above that the SRSS method in this example produced a predicted uncertainty of $\pm 1.87\%$. Texts and standards typically state that this value generally represents a 95% probability with a 95% confidence. The Monte Carlo study also produced similar results; however, note that the Monte Carlo results are the standard deviation of the variation. Thus, the calculated standard deviation represents a 95%/95% value if, and only if, the input uncertainties are known to a 95%/95% level. This is an area that can be commonly overlooked by the analyst. The uncertainties must be known to a defined probability and confidence. Manufacturers typically define performance specifications at the 2σ or the 3σ level, but the meaning of a manufacturer's performance statement should be verified.

ATTACHMENT M
STATISTICAL ANALYSIS OF SETPOINT INTERACTION

Frequently, there is more than one setpoint associated with a process control system. For example, a tank may have high and low level setpoints that are designed to prevent overfilling or completely emptying the tank. Each setpoint has a lower and upper actuation uncertainty and, in some cases, two or more setpoint can be very close to one another (or overlap) when all uncertainties are included. A calculation that involves multiple setpoints should also confirm that the setpoints are adequate with respect to one another.

Setpoints that are prepared in accordance with this engineering standard represent a 95% probability with a high confidence (approximately 95%) that the setpoint will actuate within the defined uncertainty limit. The uncertainty variation about the setpoint is assumed to be approximately normally distributed. If two setpoints are close together, it could appear that they have an overlap region as shown in Figure -1.

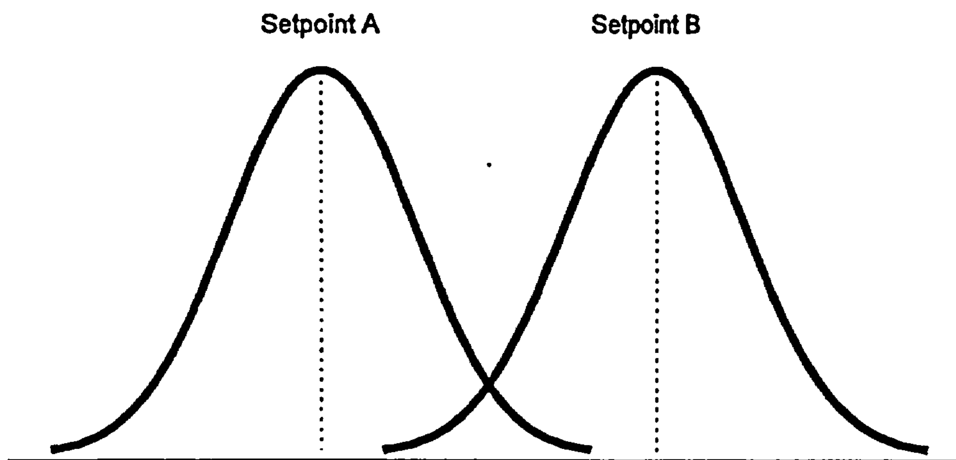


Figure M-1
Distribution of Uncertainty About Two Setpoints

As shown in Figure M-1, setpoint overlap can occur when Setpoint A drifts high at the same time that Setpoint B drifts low. The probability of this occurrence can be estimated based on the behavior of the normal distribution. For a normal distribution, 68.3% of the total probability is contained within $\pm 1.0\sigma$ of the mean, with 15.85% in either tail. Because the setpoints have been statistically determined, it is reasonable to evaluate the possibility of setpoint overlap statistically also. It is highly unlikely for one setpoint to drift by the 1.0σ value in the high direction when the other setpoint simultaneously drifts low by the 1.0σ value. The probability, P_T, of this occurring is:

$$P_T = P_A \times P_B = (0.1585) \times (0.1585) = 0.0251 = 2.51\%$$

The above probability readily shows the low likelihood of setpoint overlap even at the 1.0σ level. The probability becomes virtually insignificant at the 1.5σ level. In this case, 86.64% of the total probability is contained within ±1.5σ level, with 6.68% in either tail. The probability of one setpoint to drift high by 1.5σ when the other setpoint drifts low by 1.5σ is:

$$P_T = P_A \times P_B = (0.0668) \times (0.0668) = 0.0045 = 0.45\%$$

The above approach can be used to demonstrate the low likelihood of setpoint overlap. If setpoints appear to have a higher-than-desired probability of overlap, the electrical circuits should be reviewed to determine the possible consequences of the overlap.

ATTACHMENT N
INSTRUMENT LOOP SCALING

N.1 Introduction

A process instrumentation loop (circuit) typically consists of three distinct sections:

1. Sensing: The parameter to be measured is sensed directly by some mechanical device. Examples include a flow orifice for flow, a differential pressure cell for level, a bourdon tube for pressure, and a thermocouple for temperature measurement. The sensing element may include a transmitter that converts the process signal into an electrical signal for ease of transmission.

2. Signal Processing: The electrical signal sent by the sensor/transmitter may be amplified, converted, isolated, or otherwise modified for the end-use devices.

3. Display or Actuation: The process signal is used somehow, either as a display, an actuation setpoint above or below some threshold, or as part of some final actuation device logic.

Figure N-1 shows a typical instrument application. As shown, a level transmitter monitors a tank's water level. A power supply provides a constant voltage to the transmitter and the transmitter outputs a current proportional to the tank level. The indicator displays a tank level corresponding to the electrical current. If the electrical current is above (below) a predetermined level, indicative of a high (low) tank level, the bistable actuates. The current is provided to the controller for some control action.

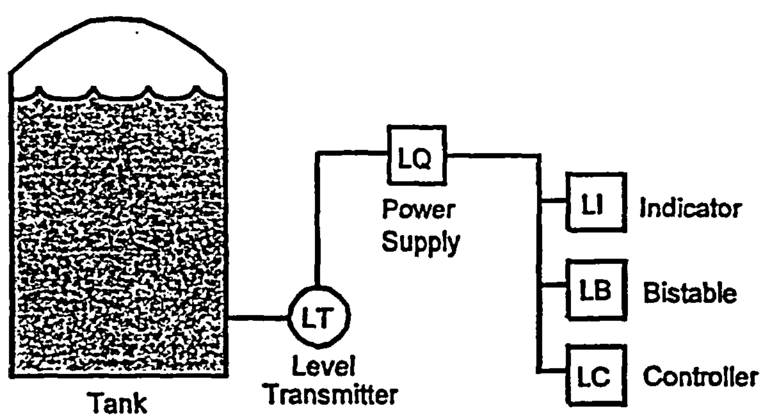


Figure N-1
Simple Instrument Loop for Level Measurement

The above example of a tank level measurement illustrate the various elements of an instrument loop. Regardless of the application, an instrument loop measures some parameter - temperature, pressure, flow, level, etc. - and generates signals to monitor or aid in the control of the process. The instrument loop may be as simple as a single indicator for monitoring a process, or can consist of several sensor outputs combined to create a control scheme.

An instrument and control engineer will usually design an instrument circuit such that the transmitter (or other instrument) output is linearly proportional to the measured process. Consider the tank level instrument loop just described. As tank level varies from 0% to 100%, we want a transmitter electrical output that can be scaled in direct proportion to the actual tank level. A typical transmitter output signal is shown in Figure N-2. The output signal varies linearly with the measured process parameter with a low value of 4 milliamps (mA) to a high limit of 20 mA. Under ideal conditions, a zero tank level would result in a 4 mA transmitter output and a 100% level would correspond to a 20 mA output (or 10 to 50 mA, respectively).

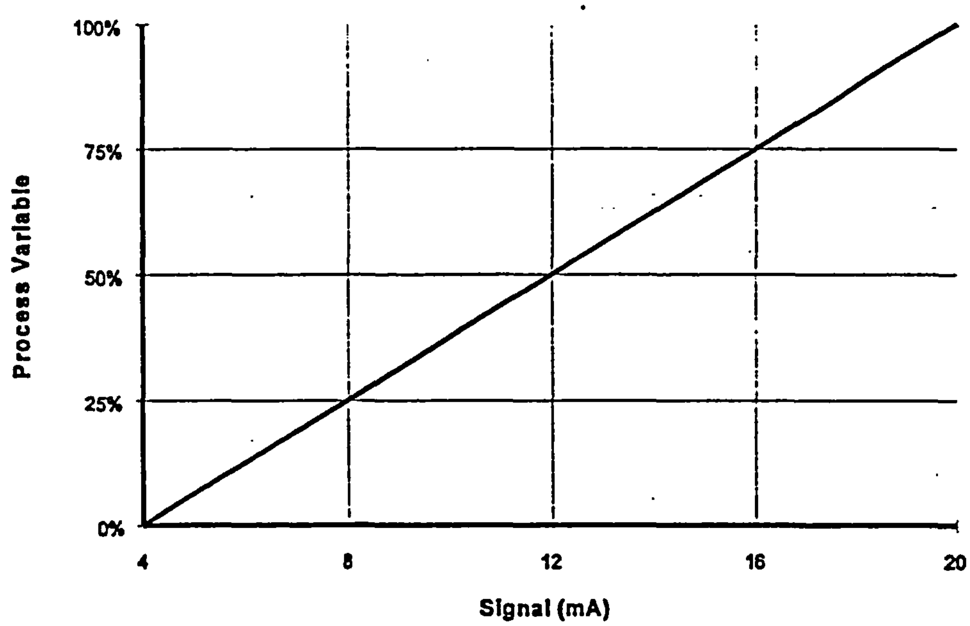


Figure N-2
Desired Relationship Between Measured Process and Sensor Transmitter Output

Example N-1

Referring to Figure N-2, what is the expected transmitter output signal if tank level is 50%? The tank level varies from 0% to 100% for a transmitter output span of 16 mA (4 to 20 mA). The transmitter output signal should be:

$$Transmitter\ Output\ =\ 4\ mA\ +\ 0.50\times(16\ mA\ span)\ =\ 12\ mA$$

As expected, the transmitter output is at the half-way point of its total span. The above equation will be developed in more detail in the following section.

Example N-2

Referring again to Figure N-2, what is the expected tank level is the transmitter signal is 18 mA?

$$Tank\ Level\ =\ \frac{18\ mA\ -\ 4\ mA}{16\ mA\ span}\times 100\%\ =\ 87.5\%$$

N.2 Scaling Terminology

Instrument scaling, applied to a process instrumentation, is a method of establishing a relationship between a process sensor input and the signal conditioning devices that transmit/condition the sensor's output signal. The goal is to provide an accurate representation of the measured parameter throughout the measured span. In its simplest perspective, scaling converts process measurements (temperature, pressure, differential pressure, etc.) from engineering units (°F, psig, etc.) into analog electrical units (VDC, mADC, etc.).

A typical instrument loop consists of a sensor, power supply, and end-use instruments as shown in Figure N-3. Whereas Figure N-1 showed the functionality of the circuit, Figure N-3 shows the instrument loop as an actual circuit. All components are connected in a series arrangement. The power supply provides the necessary voltage for the pressure transmitter to function. In response to the measured process, the pressure transmitter provides a 4 to 20 mA output current.

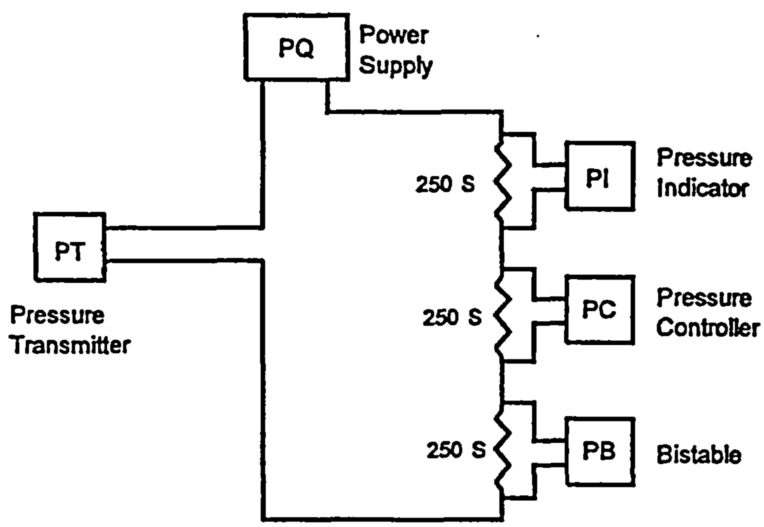


Figure N-3
Simplified Instrument Loop Schematic

Suppose the pressure transmitter shown in Figure N-3 monitors pressurizer pressure and is designed to operate over a process range of 1700 to 2500. The transmitter has an elevated zero or *pedestal* of 1700 psig. The transmitter has an analog output signal of 2 to 20 mADC, which also has a pedestal of 4 mADC.

Other components in Figure N-3 include a pressure indicator, controller, and bistable, each sensing the same 4 to 20 mA signal from the transmitter. Notice that each of these instruments senses the voltage developed across a 250 ohm input resistor; this arrangement is typical. As the current through the input resistors varies from 4 to 20 mA, the voltage developed across the resistor is 1 V to 5 V, maintaining a linear relationship between the measured process and the resultant output signal. The only purpose of the resistors is to convert the current signal to a voltage signal.

As configured in this example, the 1700 to 2500 psig process signal has a span of 800 psig which corresponds to the 1 to 5 VDC (or 4 VDC span) across the input resistor. The *scale factor* is defined as the ratio of the analog electrical signal span to the process span, or 4 VDC/800 psig = 0.005 VDC/psig. Accounting for the 1700 psig input pedestal and the 1 VDC output pedestal, the *scaling equation* that relates the input to the output is given by:

$$E_p = [0.005\ V/psig \times (P - 1700\ psig)] + 1\ V \qquad \text{Eqn. N.1}$$

where,

E_p = Voltage corresponding to the input pressure

P = Input pressure value between 1700 and 2500 psig

The above scaling equation provides an exact relationship between the process variable and the voltage developed across an input resistor for the stated configuration.

N.3 Process Algorithm

Section N.2 provides a simple example of a single instrument loop and how the electrical signal is scaled with respect to the input process signal. Sometimes, the signal from one instrument loop will be combined in some manner with the signal from another instrument loop in accordance with a specific process algorithm. An example of a process algorithm is the reactor coolant system average temperature, T_{avg}, which is calculated from a hot leg temperature measurement, T_{hot}, and a cold leg temperature measurement, T_{cold}, as follows:

$$T_{avg} = \frac{T_{hot} + T_{cold}}{2} \qquad \text{Eqn. N.2}$$

The scaling equation that implements the above calculation is called the *process equation* and starts first with the process parameters and associated ranges. The necessary input information is provided below:

Parameter	Process Range
T_{hot}	530 to 650°F
T_{cold}	510 to 630°F
T_{avg}	530 to 630°F
Parameter	Analog Range
ET_{hot}	1 to 5 V
ET_{cold}	1 to 5 V
ET_{avg}	1 to 5 V

Before the process equation can be developed, the individual loop scaling equations must first be defined. Starting with T_{hot}, it has an input span of 120°F for an electrical span of 4 VDC. The scaling equation is given by:

$$E_{T_{hot}} = [\frac{4}{120} \times (T_{hot} - 530)] + 1 \qquad \text{Eqn. N.3}$$

By a similar approach, the scaling equations for T_{cold} and T_{avg} are given by:

$$E_{T_{cold}} = [\frac{4}{120} \times (T_{cold} - 510)] + 1 \qquad \text{Eqn. N.4}$$

$$E_{T_{avg}} = [\frac{4}{100} \times (T_{avg} - 530)] + 1 \qquad \text{Eqn. N.5}$$

Notice that the above scaling equations describe the expected output voltage in response to input process variations. But the process algorithm is defined in terms of T_{avg}, not ET_{avg}. For this reason, the above scaling equations have to be solved for T_{hot}, T_{cold}, and T_{avg}, respectively, before proceeding with the development of the process algorithm. The equations are rewritten below:

$$T_{hot} = [\frac{120}{4} \times (E_{T_{hot}} - 1)] + 530 \qquad \text{Eqn. N.6}$$

$$T_{cold} = [\frac{120}{4} \times (E_{T_{cold}} - 1)] + 510 \qquad \text{Eqn. N.7}$$

$$T_{avg} = [\frac{100}{4} \times (E_{T_{avg}} - 1)] + 530 \qquad \text{Eqn. N.8}$$

The process algorithm was given by:

$$T_{avg} = \frac{T_{hot} + T_{cold}}{2}$$

Substituting Equations N.6 through N.8 into the process algorithm yields:

$$[\frac{100}{4}\times(E_{T_{avg}}-1)]+530 = \frac{[\frac{120}{4}\times(E_{T_{hot}}-1)]+530 + [\frac{120}{4}\times(E_{T_{cold}}-1)]+510}{2} \qquad \text{Eqn. N.9}$$

Simplifying terms and solving for T_{avg} yields the following result:

$$E_{T_{avg}} = 0.6 \times (E_{T_{hot}} + E_{T_{cold}} - 2.667) + 1 \qquad \text{Eqn. N.10}$$

The above example shows the development of a process algorithm and its conversion to an actual scaling equation.

N.4 Module Equations

Module equations are commonly referred to as *transfer functions*. They define the relationship between a modules' input and output signals and are just scaling equations that describe this input/output relationship. Transfer functions are typically classified as either static or dynamic.

Static transfer functions are time-independent and can be either linear or nonlinear. Modules that typically have static transfer functions include:

- Input resistors (I/V modules)
- Isolators
- Summators

The module equation of a static device will sometimes include a gain adjustment also. For example, a simple summator may have the following module equation:

$$E_{out} = G(k_1E_1 + k_2E_2 + k_3E_3) + 1\ V \qquad \text{Eqn. N.11}$$

where,

k_1, k_2 = Input signal gains

k_B = Bias input gain

E_1, E_2 = Input voltages

E_B = Bias voltage

G = Output gain

E_{out} = Output voltage

Dynamic transfer functions are time-dependent and are commonly expressed as a function of time. The time-dependent nature tends to cause these types of modules to have more complex module equations. A lead/lag controller is an example of a dynamic module. For example, if it is configured as a lag unit, the output signal is delayed in accordance with the following module equation:

$$E_{out} = G\left(\frac{1}{1 + \tau_2 s}\right) E_1 \qquad \text{Eqn. N.12}$$

where,

E_1 = Input voltage

τ_2 = Lag time constant

s = Laplace transform variable

G = Output gain

E_{out} = Output voltage

A dynamic module can have its response to an input signal change, depending on the nature of the signal. For example, if a step change is applied to the input, the output signal changes in accordance with the following expression:

$$E_{out} = G\ E_1(1 - e^{-\frac{t}{\tau_2}}) \qquad \text{Eqn. N.13}$$

If a linear ramp is applied as the input signal, the module equation changes as follows:

$$E_{out} = G\ R[t - \tau_2(1 - e^{-\frac{t}{\tau_2}})] \qquad \text{Eqn. N.14}$$

Laplace transforms are used to simplify the use of dynamic transfer functions. A Laplace transform converts a dynamic transfer function from the time domain to the Laplace domain where it is more easily solved. Laplace domain functions are expressed using the Laplace transform variable s. Once in the Laplace domain, the equations can be solved algebraically.

N.5 Scaling Calculation

After the process algorithm, module equations, and required ranges have been determined, the scaling calculation can be completed. The scaling factor is used with the scaling equation to derive the voltage equation from the process equation. An overall system equation can be developed by combining module equations, as applicable. For example, assume the use of two modules in an instrument loop.

The first module has two inputs, E_1 and E_2, that are summed together with a module gain of G_1. The simplified equation for this module is given by:

$$E_A = G_1 (E_1 + E_2) \qquad \text{Eqn. N.15}$$

Now, assume that the output, E_A, is summed with another input, E_3, which has a module gain of G_2. The resulting module equation is:

$$E_A = G_2 (E_3 + E_A) \qquad \text{Eqn. N.16}$$

or, substituting in for E_A,

$$E_{out} = G_2 [E_3 + G_1(E_1 + E_2)] \qquad \text{Eqn. N.17}$$

The expression for each voltage above can be complex also. But, the result is an overall scaling equation that defines the system operation. Once a scaling equation has been developed and the scaling calculation performed, the equation should be checked by inputting typical process values and determining if reasonable analog values are calculated. Each module should be tested separately to ensure its accuracy before combining it with other modules. As part of the test process, include minimum and maximum process values to ensure that the limits work as expected.

ATTACHMENT O
RADIATION MONITORING SYSTEMS

Radiation monitoring systems have unique features that complicate an uncertainty analysis. The system design, detector calibration, and display method all can reduce the system accuracy. Whenever evaluating a radiation monitoring system, review the following references for additional information:

ANSI N42.18, *American National Standard for Specification and Performance of On-Site Instrumentation for Continuously Monitoring Radioactivity in Effluents* (Reference 3.1.6)

EPRI TR-102644, *Calibration of Radiation Monitors at Nuclear Power Plants* (Reference 3.4.11)

Radiation monitoring system operation and maintenance manual

Radiation monitoring system calibration procedures

The following should be considered as part of any uncertainty analysis:

<u>Detector Measurement Uncertainty</u>

A radiation monitoring system detector's response varies with the following parameters:

- Energy level of the incident particles.
- Count rate of the detected particles.
- Type of particle being counted (depending on application, the particles may be gamma photons, neutrons, or beta particles).

<u>Detector Count Rate Measurement Uncertainty</u>

The detector's measurement uncertainty can be affected by the following:

- On the low end of scale, the uncertainty in count rate response is affected by signal to noise ratio effects.
- On the high end of scale, the uncertainty in count rate is affected by pulse pile-up in which discrete pulses are missed.
- Throughout the detection range, the alignment of the source to the detector geometry can impact the measurement uncertainty. For example, the containment high range radiation monitors need an unobstructed view of the containment dome. Blockages such as concrete walls can degrade the measurement capability of the detector.

<u>Detector Energy Response Uncertainty</u>

The detector energy response uncertainty can be affected by the following:

- On the low end, the discriminator setting and the energy sensitivity of the detector.
- On the high end, the point at which a rise in incident particle energy does not result in a change in pulse height output.
- Throughout the detection range, by a degrading failure of the system.

For most permanently installed radiation detectors, the detectors is designed to respond to incident particles over a certain range of energies. The output of count rate is then correlated to a mR/hr or

μC/cc indication by the application of a conversion factor, without regard to differing incident particle energies.

When the plant is shutdown, the detector indicated count rate is generally derived from lower energy particles. When the plant is operating, the particle energy tends to be higher. In this case, a typical detector will display a higher count rate, even if the number of incident particles per unit time remain the same. As the incident particle energy level changes, the probability of detection changes for a given count rate. During initial calibration, this difference is accounted for by exposing the detector sample streams of different radio-isotopes and measuring the detector's response. After in-plant installation, the calibration is checked by exposing the detector to fixed external sources of different radio-isotopes.

Whenever evaluating the uncertainty of a radiation monitoring system, the periodic calibration methods are particularly important to consider. EPRI TR-102644, *Calibration of Radiation Monitors at Nuclear Power Plants* provides additional guidance. Also, the applicable system engineer should be contacted for additional expertise.