ASME PTC 19.22-2007

[Revision of ANSI/ASME PTC 19.22-1986 (R1998)]

Data Acquisition Systems

Performance Test Codes

REAFFIRMED 2012

FOR CURRENT COMMITTEE PERSONNEL
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AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

ASME
SETTING THE STANDARD

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Date of Issuance: June 30, 2008

This Code will be revised when the Society approves the issuance of a new edition. There will be no addenda issued to ASME PTC 19.22-2007.

ASME issues written replies to inquiries concerning interpretations of technical aspects of this document. Periodically certain actions of the ASME PTC 19.22 Committee may be published as Code Cases. Code Cases and interpretations are published on the ASME Web site under the Committee Pages at http://cstools.asme.org as they are issued.

The American Society of Mechanical Engineers
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Nonmandatory Appendices

NOTICE

All Performance Test Codes must adhere to the requirements of ASME PTC 1, General Instructions. The following information is based on that document and is included here for emphasis and for the convenience of the user of the Supplement. It is expected that the Code user is fully cognizant of Sections 1 and 3 of ASME PTC 1 and has read them prior to applying this Supplement.

ASME Performance Test Codes provide test procedures that yield results of the highest level of accuracy consistent with the best engineering knowledge and practice currently available. They were developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis.

When tests are run in accordance with a Code, the test results themselves, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. ASME Performance Test Codes do not specify means to compare those results to contractual guarantees. Therefore, it is recommended that the parties to a commercial test agree before starting the test and preferably before signing the contract on the method to be used for comparing the test results to the contractual guarantees. It is beyond the scope of any Code to determine or interpret how such comparisons shall be made.

FOREWORD

The scope of the Instruments and Apparatus Supplements (PTC 19 Series) is to describe the various types of instruments and methods of measurement likely to be prescribed in the ASME Performance Test Codes. Such details as the limits and sources of error, methods of calibration, precautions, etc., as will determine their range of application are usually given.

PTC 19.22, Data Acquisition Systems, represents an extension of the purpose of the Supplements into the realm of digital systems. These are increasingly becoming an integral part of modern testing practice. In order that the ASME Performance Test Codes continue to provide test procedures characterized by the highest level of accuracy consistent with the best current engineering practice, it became necessary to develop and maintain a PTC document on this topic.

Accordingly, on November 18, 1969, the Performance Test Codes Standing Committee (now the Performance Test Codes Standards Committee) authorized the organization of a Technical Committee to develop a Supplement on instrumentation for computer information. However, at that time it was difficult to obtain the services of qualified Committee personnel due to the relative novelty of applying digital systems to testing procedures. Nevertheless, a chairman was appointed by November 1972 and a report on the object and scope was issued on November 20, 1974. Regular Committee meetings began in 1976 and are held periodically.

The previous edition, PTC 19.22-1986, Digital Systems Techniques, was adopted by the American National Standards Institute as an American National Standard on January 3, 1986.

This revision, PTC 19.22-2007, Data Acquisition Systems, was approved by ASME Committee PTC 19.22 on April 20, 2007. It was then approved by the American National Standards Institute (ANSI) as an American National Standard on September 12, 2007.

ASME PTC COMMITTEE
Performance Test Codes

(The following is the roster of the Committee at the time of approval of this Standard.)

CORRESPONDENCE WITH THE PTC 19.22 COMMITTEE

General. ASME Codes are developed and maintained with the intent to represent the consensus of concerned interests. As such, users of this Supplement may interact with the Committee by requesting interpretations, proposing revisions, and attending Committee meetings. Correspondence should be addressed to:

Secretary, PTC 19.22 Standards Committee
The American Society of Mechanical Engineers
Three Park Avenue
New York, NY 10016-5990

Proposing Revisions. Revisions are made periodically to the Supplement to incorporate changes that appear necessary or desirable, as demonstrated by the experience gained from the application of the Supplement. Approved revisions will be published periodically.

The Committee welcomes proposals for revisions to this Supplement. Such proposals should be as specific as possible, citing the paragraph number(s), the proposed wording, and a detailed description of the reasons for the proposal, including any pertinent documentation.

Proposing a Case. Cases may be issued for the purpose of providing alternative rules when justified, to permit early implementation of an approved revision when the need is urgent, or to provide rules not covered by existing provisions. Cases are effective immediately upon ASME approval and shall be posted on the ASME Committee Web page.

Requests for Cases shall provide a Statement of Need and Background Information. The request should identify the Code, the paragraph, figure or table number(s), and be written as a Question and Reply in the same format as existing Cases. Requests for Cases should also indicate the applicable edition(s) of the Code to which the proposed Case applies.

Interpretations. Upon request, the PTC 19.22 Committee will render an interpretation of any requirement of the Supplement. Interpretations can only be rendered in response to a written request sent to the Secretary of the PTC 19.22 Standards Committee.

The request for interpretation should be clear and unambiguous. It is further recommended that the inquirer submit his/her request in the following format:

Subject:	Cite the applicable paragraph number(s) and the topic of the inquiry.
Edition:	Cite the applicable edition of the Supplement for which the interpretation is being requested.
Question:	Phrase the question as a request for an interpretation of a specific requirement suitable for general understanding and use, not as a request for an approval of a proprietary design or situation. The inquirer may also include any plans or drawings, which are necessary to explain the question; however, they should not contain proprietary names or information.

Requests that are not in this format will be rewritten in this format by the Committee prior to being answered, which may inadvertently change the intent of the original request.

ASME procedures provide for reconsideration of any interpretation when or if additional information that might affect an interpretation is available. Further, persons aggrieved by an interpretation may appeal to the cognizant ASME Committee or Subcommittee. ASME does not “approve,” “certify,” “rate,” or “endorse” any item, construction, proprietary device, or activity.

Attending Committee Meetings. The PTC 19.22 Standards Committee regularly holds meetings, which are open to the public. Persons wishing to attend any meeting should contact the Secretary of the PTC 19.22 Standards Committee.

INTRODUCTION

The purpose of this Code is to define the scope and application of data acquisition systems for use with ASME Performance Test Codes. The code is based on the use of data acquisition systems covering a wide range of capability from simple data gathering equipment to multipurpose online or offline data acquisition systems.

Use of this Code with any of the applications of ASME Performance Test Codes should include a review of the following documents:

(a) PTC 1

(b) PTC 19.1

(c) Appropriate ASME Performance Test Codes

(d) Appropriate ASME Performance Test Code Reports and Guides

(e) Appropriate Instruments and Apparatus Supplements

The appropriate sections of the Instruments and Apparatus Supplements of the PTC 19 series and specifically PTC 19.1, Measurement Uncertainty are essential when selecting or developing data acquisition systems.

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DATA ACQUISITION SYSTEMS

Section 1
Object and Scope

1-1 OBJECT

The object of this Code is to provide guidance for design, selection, and application of the data acquisition systems used in ASME Code Performance Tests. This Code provides descriptions of the various data acquisition system architectures and information on determining system uncertainties and to assist in selecting and applying these data acquisition systems. The Code is intended to address data acquisition systems used for ASME Code Performance Testing but may also be used for guidance in selecting systems for any test application. These systems include systems specifically installed for a test and plant Distributed Control Systems (DCS) which also provide the ability to monitor sensors during a test. The Code is not intended to address long term Performance Monitoring but may provide guidance for such applications.

1-2 SCOPE

The scope of this Code includes signal conditioning, signal multiplexing, analog-to-digital signal conversion, and data processing. This Code addresses stand-alone data acquisition systems, typified by a sensor with an integral digital display, data acquisition systems that link multiple sensors to a common digital processor tied to a computer or printer, and systems that link multiple digital processors to one or more stand-alone or networked computers.

This Code incorporates instrumentation practices covered by other Instruments and Apparatus Supplements (PTC 19 Series) as well as by the equipment Performance Test Codes. It also provides a means to determine the uncertainty associated with the data acquisition system, and its impact on the overall uncertainty of the performance test. The Code does not directly address specific sensors or instruments used for ASME Performance Testing. These are addressed in other ASME Performance Test Codes.

Section 2
Definitions and Descriptions of Terms

The following definitions are provided to clarify the terms used in this document:

accuracy: the closeness of agreement between a measured value and the true value [1].

analog signal: a nominally continuous electrical signal that varies in some direct correlation with another signal impressed on a transducer [2].

analog-to-digital (A/D) converter: a device that converts an analog signal to a digital signal that represents equivalent information [2].

binary word: the maximum number of bits treated as a unit and capable of being stored in one location [3].

bit: a contraction of the words "binary" and "digit" [3].

calibration: the process of comparing the response of an instrument to a reference standard over some measurement range.

channel: a single path through a transmission media intended to carry the signal of an instrument reading. Typically, it carries the raw electrical signal of the instrument, or the output of a multiplexing function.

checksum bit (check bit): a bit, such as a parity bit, derived from and appended to a bit string for later use in error detection and possibly error correction [2].

contact resistance: the resistance between the closed contacts of a relay in a multiplexer.

crosstalk: the undesired signal appearing in one signal path as a result of coupling from another signal path [3].

data acquisition system: any device or collection of devices capable of accepting information, converting this information to corresponding digital information, applying prescribed processes to the information, and supplying the results of the processes [3].

data compression: the method of filtering data, by exception or other means, and storing it only if meeting specified criteria. The primary function of this method is to optimize data storage space by limiting the amount of data being stored.

data reduction: the method by which raw test data being collected by the data acquisition system is summarized through simple calculations to produce more meaningful information.

digital signal: data represented by discrete values or conditions [2].

double precision: use of two digital words together to increase the resolution of a digital signal that could not be represented by a single digital word.

drift: a change in system output over time independent of the input signal.

filtering: electric, electronic, acoustic, optical, or software devices used to reject signals, vibrations, or radiations of certain frequencies while allowing others to pass [2].

full range (FR): the absolute value of the algebraic difference between the minimum and maximum values for which the system is capable of measuring or generating.

full scale: an instrument's maximum reading or output for each of its ranges [4]. May have a higher numeric value than the range setting due to overrange capability.

gain error (scale error): error in a signal due to nonlinearity in a device's response.

least significant bit (LSB): right most bit in a binary word whose value contributes the least to the overall value of the binary word and also represents the resolution of the digital word.

multiplexer: a device that combines two or more information channels onto a common transmission medium [2].

noise: a disturbance that affects a signal and that may distort the information carried by the signal [2].

primary variables: those used in calculations of test results. They are further classified as:

(a) Class 1: primary variables are those which have a relative sensitivity coefficient of 0.2 or greater

(b) Class 2: primary variables are those which have a relative sensitivity coefficient of less than 0.2 [5].

random error: sometimes called precision; the true random error which characterizes a member of a set of measurements. The random error varies in a random, Gaussian-normal manner, from measurement to measurement [1].

range: an area between two limits within which a quantity is measured [6]. Instrument setting used in order to measure or supply a set of input or output values [4].

raw data: unreduced data prior to the application of any calculations.

reference standard: a traceable instrument or process to which a system is compared during calibration.

relative sensitivity coefficient: a nondimensionalized sensitivity coefficient.

resolution: the minimum difference between two discrete values that can be distinguished by a measuring device [2].

scaling: the method by which raw data is converted into engineering values.

scan: collection of data by a data acquisition system via a single sequential interrogation of devices, usually obtained through a multiplexer.

scan rate: the frequency at which a data acquisition system performs scans. Also known as sample rate.

sensitivity coefficient: ratio of the change in a result to a unit change in a parameter [1].

signal conditioning: to modify a signal to make it suitable for measurement by data acquisition systems.

span: the difference between the two limits of a nominal range of a data acquisition system.

systematic error: sometimes called bias; the true systematic or fixed error which characterizes every member of any set of measurements from the population. It is the constant component of the total measurement error [1].

systematic uncertainty: the 95% confidence level estimate of the limits of a true systematic error, often determined by judgment.

temperature coefficient: a factor used to calculate the change in output of an instrument due to change in ambient temperature [6].

time synchronization: adjusting the system time on one or more data acquisition systems to ensure consistency among all systems.

transducer: a device that converts signals from one form to another.

transmitter: a device used to broadcast a signal that is usually a function of an input to the device.

uncertainty: the interval about the measurement or result that contains the true value for a given confidence level [1].

zero offset: the magnitude of the output signal when the input signal is zero [3].

Section 3
Guiding Principles

This Section discusses the fundamental elements to be considered when designing/selecting a data acquisition system.

3-1 CAPABILITY

Data acquisition systems are capable of improving testing in many ways.

(a) Data quality can be improved in basic data acquisition systems through the use of digital displays that reduce human error often incurred when recording data manually.

(b) More sophisticated data acquisition systems can reduce human recording error by recording and storing data digitally.

(c) Test personnel can be reduced by replacing manual data collectors with automated data acquisition systems when sampling multiple data points.

(d) Automated data acquisition systems may have the capability of online data reduction and results calculations. With this feature, dissemination of data must be considered to accommodate validation of the data acquisition system.

(e) Test duration can be reduced by recording data more frequently than manual methods, allowing for a sufficient number of samples to be obtained in a shorter period of time.

(f) Data acquisition systems can be designed to allow for remote, real time access of test data. The incorporation of networked computers into data acquisition systems permits transmission of test data to remote locations.

3-2 TYPICAL DATA ACQUISITION SYSTEMS

To better understand the scope and types of data acquisition systems, this subsection categorizes and describes the functions of each category. Three groups are defined to differentiate among levels of complexity: basic, intermediate, and advanced data acquisition systems. Figures 3-2-1 through 3-2-3 provide a representation of these systems based on the individual functions of the data acquisition systems. These figures do not necessarily represent the components of the systems since multiple functions may be contained in and performed by a single component. The order in which these functions are executed may vary from one system to the next.

3-2.1 Basic Data Acquisition System

The basic data acquisition system is characterized by the following features that are the minimum required to be considered a data acquisition system:

(a) signal conditioning

(b) analog to digital conversion

(c) multiplexing

(d) data logging (digital or hard output)

A schematic representation of a basic data acquisition system is shown in Fig. 3-2-1.

The basic data acquisition system is appropriate for tests that require a minimal number of data points due to the labor-intensive data reduction that is required with this system. The basic data acquisition system typically requires longer test periods so that a sufficient number of data samples can be recorded to meet the required measurement uncertainty. Therefore, the basic system is ideal for tests with a small number of measurements that can be performed under steady conditions for a long period of time.

3-2.2 Intermediate Data Acquisition System

The intermediate data acquisition system is distinguished from the basic system by digital data storage capability. This is shown in Fig. 3-2-2, illustrations (a) and (b). The features of the intermediate data acquisition system include the basic data acquisition system and the following capabilities:

(a) Elementary Calculations. This is an optional feature that includes engineering unit conversion, scaling, and calibration corrections.

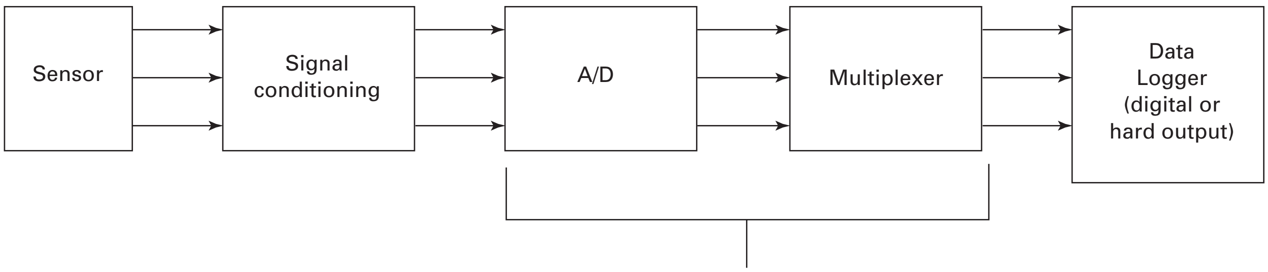
(b) Digital data storage.

(c) Digital data output.

Elementary calculations can be executed in various stages of the intermediate data acquisition system. For example, calculations may be performed by a central processor after the multiplexing component or before the multiplexing component in a transmitter.

The intermediate system is ideal for high frequency data collection. Since this system records and stores data digitally, the frequency of data collection is increased significantly over the basic data acquisition system. This means that a sufficient number of measurements can be taken in a shorter amount of time. Digital storage allows the possibility of transferring data directly into a separate computer application, which improves data reduction time. Elementary calculations can further reduce data reduction time by performing unit conversions,

Fig. 3-2-1 Basic Data Acquisition System Flowchart



scaling, and/or applying calibration corrections to the raw data.

A limitation of the intermediate data acquisition system is that it does not handle data from multiple sources. When data from multiple sources is required, separate data acquisition systems are required. Use of multiple data acquisition systems necessitates careful attention to time synchronization and data reduction techniques.

3-2.3 Advanced Data Acquisition System

The advanced data acquisition systems shown in Fig. 3-2-3 are characterized by the capability to collect data from multiple sources, perform advanced calculations, and/or communicate remotely.

Advanced data acquisition systems can consolidate data from multiple sources such as basic, intermediate, and even other advanced data acquisition systems and provide a single source of output. Advanced calculations may include online data averaging, and statistical analysis. Advanced calculations may also include results calculations. This feature should be used with caution to avoid neglecting possible errors that can only be diagnosed by inspecting calculation input data and intermediate calculations. Communication features such as networking or software that allows remote online data access also distinguishes the advanced system from an intermediate system. Like the intermediate system, the advanced system can record many measurements at high frequencies. Advantages of the advanced system include the ability to collect from multiple data sources. The advanced system can connect multiple basic and/or intermediate systems to consolidate all test data into a single storage location. This, along with results calculations significantly reduces data reduction time. Because of its data consolidation and remote communication capabilities, the advanced data acquisition may require fewer test personnel at the test location.

3-3 SYSTEM PLANNING

Data acquisition systems have become an integral and sometimes necessary part of performance testing. To successfully select the data acquisition system to be used for a particular test, several operational considerations should be evaluated.

3-3.1 Test Plan

Prior to selecting a data acquisition system, it is best to have the test plan in place. The test plan should dictate the type of system to be used. As a minimum, the following items should be considered:

(a) The Number of Data Points Needed. This will determine whether or not digital data storage or advanced calculations for data reduction are necessary.

(b) The Length of the Test. This is necessary to determine the data storage capability required.

(c) The Number of Samples Required. This parameter would also set the size of the data storage capability and the need for elementary or advanced calculations.

(d) The Frequency of Data Collection. Along with test duration this parameter determines the processor capability including speed and storage capacity.

(e) Target Test Uncertainty. Advanced calculation capabilities can assist in online determinations of test uncertainty via statistical calculations. The use of a data acquisition system may be necessary for increased data sampling frequency required to achieve test uncertainty targets.

(f) Ambient Conditions. Hardware components of the data acquisition system must be chosen to minimize the effects of ambient conditions on the data quality.

(g) Site Layout. Location of sensors with respect to data output components must be considered. This will determine whether digital signals must be used and how the signal should be transmitted.

(h) Data Output. Data acquisition software must be designed or selected to accommodate the output or accessibility of all data required by subsection 7-2.

(i) Data Distribution. Users of the data should be considered with respect to software compatibility, hard copy versus soft copy preferences, etc.

3-3.2 Hardware

Selection of hardware for a data acquisition system is extremely dependent on the test plan. The following

Fig. 3-2-2 Intermediate Data Acquisition System Flowcharts

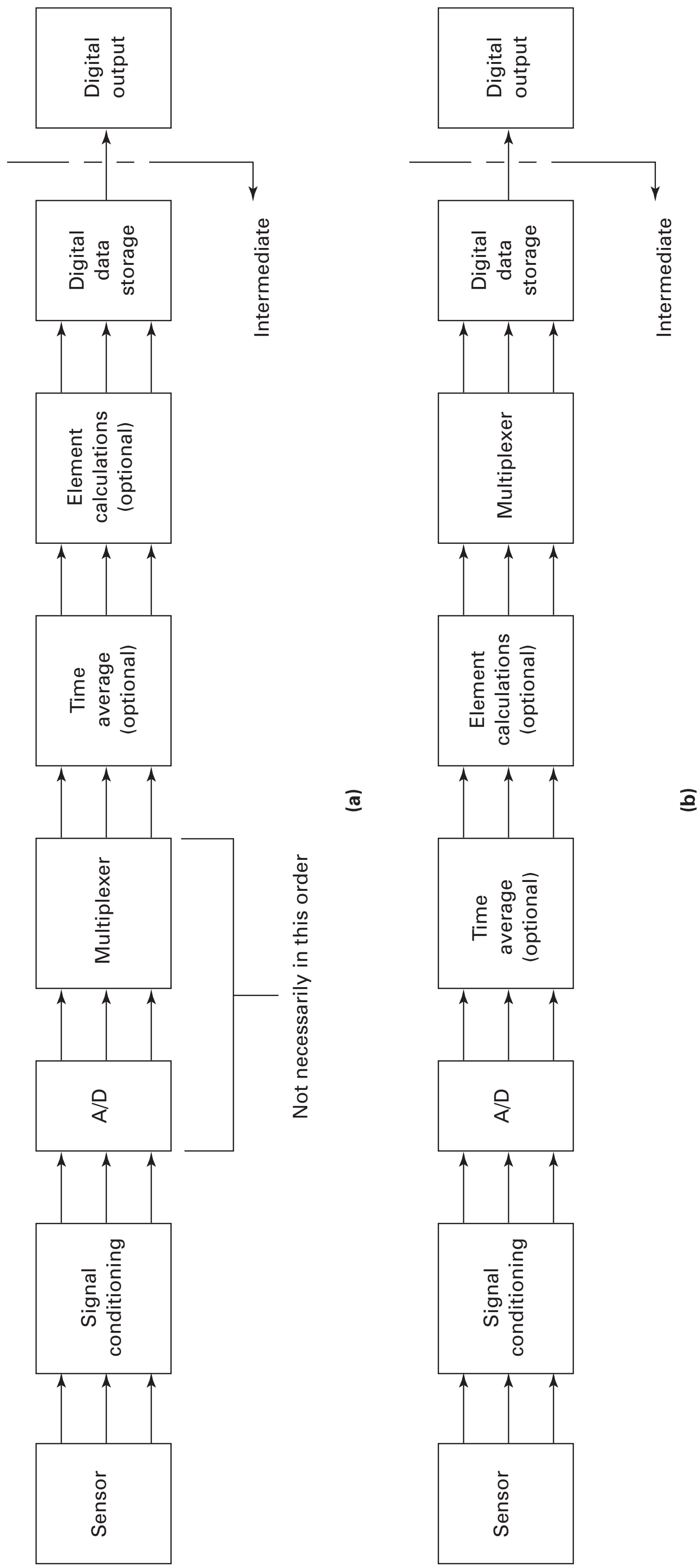
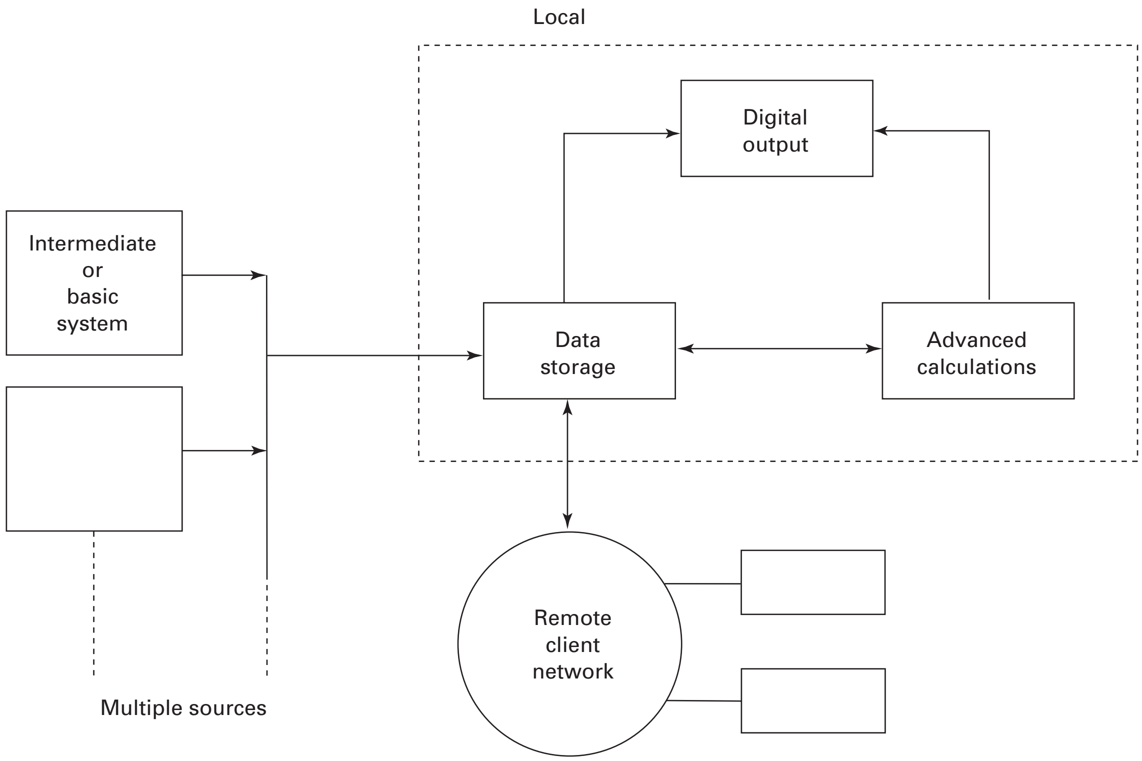


Fig. 3-2-3 Advanced Data Acquisition System Flowchart



components should be chosen carefully based on the considerations described in para. 3-3.1:

(a) Central Processing Units. Data storage capacity, processing speed (for calculations and data retrieval), and ruggedness required by the test must be evaluated.

(b) Multiplexers. The number of data points to be collected and site layout will determine the size and quantity of multiplexers required for the system. Ambient conditions dictate the type of enclosure required for this type of equipment (i.e., waterproof, explosion proof, etc).

(c) Cables/Connections. Site layout and ambient conditions must be considered when determining the type of cables and connections required. Multiple cables are typically required in temporary installations. Temporary cables and their connectors should be selected to withstand or minimize the impact of any stresses, interferences, or ambient conditions to which they may be exposed.

(d) Signal Type. The type of signal being transmitted is dependent upon test goals and site layout. Certain analog signals, for example, are not acceptable for transmitting across large distances due to the impact on system accuracy. Signal conditioning devices must be selected to accommodate data transmission distances and test accuracy goals.

3-3.3 Software

Software for data acquisition systems must be selected or designed to meet the needs of the test. One of the most important items to consider is the user interface. For a basic system, the user interface may consist only of hard output from a printer. This type of interface is useful in applications where the number of data points is small and manual data reduction is not a concern.

Software considerations for the intermediate data acquisition system are more involved. With a digital storage device, the methods of data access must be specified. Specifically, online versus offline access, output compatibility with spreadsheet applications, and data sorting (by time/date, description, tag number, etc.) must be considered.

When recording and storing data used in performance testing, it is imperative that all sampled data be available to the user. Data acquisition software must be selected or designed to record and access data at a user specified frequency without applying compression or exception techniques.

Data acquisition system software must also have the capability to access data as defined in subsection 7-2.

Time synchronization is critical in advanced data acquisition systems where multiple data sources are used. This can be addressed as part of the system software design. Synchronization must be performed manually when using multiple basic or intermediate data acquisition systems for the same test.

Planning for data retrieval is equally important in the advanced data acquisition system. Flexibility in performing advanced calculations is also a consideration.

Compatibility with spreadsheet applications provides this flexibility and is universally user friendly. Operating system selection for advanced data acquisition systems should be considered for systems that are to be used for remote communications.

3-4 OPERATIONAL CONSIDERATIONS

3-4.1 Calibration

Calibration requirements vary based on the type of data acquisition system used. Systems that are entirely digital, for instance, may require only calibration of the sensor. Field or in situ calibration of data acquisition systems can be used as a check but is not recommended for determining calibration corrections. The types of calibration references available for use in the field may not be sensitive enough to discern the small differences that may exist between laboratory and field installations and laboratory reference standards are not reliable in field environmental conditions. Calibration of the data acquisition system should be performed in a laboratory on all components that have a significant impact to the uncertainty of the system. This topic is discussed further in Section 5 of this Code.

3-4.2 System Validation

After installation of the data acquisition system, functional checks should be made. As a minimum, a pretest data run should be performed to verify the following:

(a) Sensors have not failed and are communicating properly. This can be verified by making sure the data logger output matches expected process values, by redundant instrumentation, or by application of a known condition to a sensor.

(b) All data acquisition systems being used for the same test are time synchronized.

(c) Calculations are applied correctly. This can be verified by comparing input data values to the calculated value at a given sample time.

(d) Data is being stored properly. Data collection for a specified time interval followed by a data retrieval test is sufficient to verify proper data storage.

Section 4
Signal Conversion

Signal conversion involves the reading of sensor values and converting them to a digital form for use in the data acquisition system. The basic elements are sensors, signal conditioning, and multiplexing.

4-1 SENSORS

Sensors provide the primary input signal to data acquisition systems. It is this signal that is converted by the data acquisition system into useful information. The selection of sensors is guided by the requirements of the application. The appropriate Instruments and Apparatus Supplements and other recognized standards should be reviewed to first determine if the instrument selected meets the minimum requirements.

4-1.1 Sensor Considerations

The following should be considered when evaluating the suitability of a sensor for use in a data acquisition system:

(a) Care must be exercised to ensure that the ranges of the sensor signals are compatible with the capability provided by the data acquisition system.

(b) Accuracy of the sensor selected for the particular measurement must be considered in order to meet the overall system uncertainty requirements.

4-1.2 Sensor Signal Types

Paragraphs 4-1.2.1 through 4-1.2.4 describe commonly used sensor signal types.

4-1.2.1 Analog Signals. Analog signals from sensors or transducers used primarily for control or indication are sometimes used jointly as inputs to data acquisition systems. Caution should be exercised to ensure control and signal circuit integrity as well as calibration accuracy to meet the test requirement. For maximum accuracy, input signals to data acquisition systems should be obtained from primary sensors.

Some measurements use the average signal from multiple sensors. This paralleling circuit introduces an error due to the difference in individual sensor outputs. This error can be difficult to determine with reasonable accuracy since the differences may be random and the characteristics nonlinear. In most cases it is desirable to provide separate inputs and obtain averaged values via software in the data acquisition system.

4-1.2.2 Digital Signals. Sensors with digital signal outputs typically require less or no signal conditioning. Use of digital signal output from sensors can reduce overall data acquisition system uncertainty, especially when transmitting signals over long distances.

4-1.2.3 Pulse Inputs. Integrating pulses over a specified period of time, such as pulses from watthour or linear flow meters, tends to be more accurate than frequency measurement because it eliminates the A/D conversion errors.

4-1.2.4 Contact Input Signals. The use of contact inputs in data acquisition systems is limited, since measured data is normally transmitted via analog, digital, or pulse type signals. Contact inputs may be used to automatically condition the acceptance or rejection of data, or to change the operational range of a sensor input. For example, the gathering of data may be triggered by a status change contact input. The opening and closing of a valve may time the filling of a weigh tank by the use of separate open and close limit switch contact input signals to the data acquisition system. The scan frequency should be considered to ensure that an unacceptable timing error is not introduced. When the data acquisition system allows and timing accuracy requires, computer interrupts can be utilized to initiate software action.

4-2 SIGNAL CONDITIONING

Signal conditioning as used in this Code is a term that in a broad sense means to modify a signal to make it suitable for measurement by data acquisition systems. Various types of signal conditioning are described in paras. 4-2.1 through 4-2.7. Because of the diversity in available commercial data acquisition systems, it is not a requirement to fully understand the details of signal conditioning, but it is necessary to understand the type of signal being measured and the requisite accuracy and frequency of measurement when selecting data acquisition hardware. As a result, it may not be necessary to specify the type of signal conditioning required, but the requirements of the measurement may in turn dictate the requirements for signal conditioning and hence the ultimate hardware configuration utilized.

4-2.1 A/D Conversion

Six common electrical types of A/D conversion are counter or ramp type, successive approximation type, dual slope integrating type, voltage to frequency integrating type, parallel type, and Sigma-Delta type.

4-2.1.1 Counter or Ramp Type. This type of A/D converter is one of the simplest. To perform a conversion, this type of converter gates on an internal pulse generator (clock), which produces a series of pulses that are accumulated by a digital counter. As the digital counter accumulates pulses, the output of an internal D/A converter increases and is compared to the input signal voltage. Each clock pulse produces an equal change at the output of the D/A converter. When the D/A converter output is equal to (or slightly larger than) the input signal voltage, the internal comparator changes state which inhibits (gates off) any further clock pulses to the counter. At this time the conversion is complete and the output digital number is stored in the output register of the counter for use by the data acquisition system. This method is also referred to as a staircase ramp converter.

This type of conversion features simplicity, low cost, and good accuracy, but has the disadvantage of slow speed. Conversion time is proportional to input voltage and frequency of pulse generation and is longest for a full-scale voltage conversion.

4-2.1.2 Successive Approximation Type. This conversion method is widely used in general practice due to its combination of high resolution and high speed. The successive approximation converter operates with a fixed conversion time per bit, independent of the value of the analog input. This type of converter operates by comparing an input voltage to the output from an internal D/A converter, one bit at a time. At the start of the conversion cycle, the D/A converter's most significant bit (MSB) is turned on. This generates a feedback voltage from the D/A converter equal to one-half the input full-scale range. If the MSB voltage is larger than the input, it is turned off prior to turning the next bit on. If smaller than the input, it is left on and the next bit is tried. This process of comparison is continued with bit weightings of $\frac{1}{4}$, $\frac{1}{8}$, $\frac{1}{16}$,. . ., $(\frac{1}{2})^{N-1}$ until the least significant bit (LSB) is compared, after which the output register contains the complete output data digital number in a binary format.

Both serial and parallel output data can be brought out of this type converter and the converter can be synchronized to an external clock if desired. High speeds can be achieved using this method. Successive approximation converters can also be quite accurate, but the accuracy depends on the stability of the reference, the switches used to turn on the digital bits, the ladder network of the D/A section, and the internal comparator.

4-2.1.3 Dual Slope Integrating Type. There are several types of converters using the integrating or ramp principle. The most popular and widely used at the present time is the dual ramp or dual slope type. It is used extensively in digital voltmeters.

The dual slope A/D converter operates by the indirect method of converting a voltage to a time period that is then converted to a digital number. Conversion starts with the analog input signal voltage switched to the input of an integrator. It is integrated for a fixed period of time, which is determined by counting clock pulses for a predetermined number of counts. This fixed time period T is chosen to equal the period of the power system frequency (or a multiple of it) so that this common source of noise is integrated out. After time T, the integrator input is switched from the analog input signal to a reference voltage, which has the opposite polarity of the analog input. At the instant of switching, the integrator output voltage is proportional to the analog input signal and the reference voltage of opposite polarity will cause it to be ramped to zero. Since the reference voltage is constant, the ramp rate (or slope) during the ramping to zero is constant. The time required to ramp to zero is then directly proportional to the analog input signal voltage. The digital counter is used to time the fixed time period, is reset at the end of the fixed time period T and is used to count during the time period t_1. The comparator detects when the integrator reaches zero, and the counting is stopped with the counter containing the digital word representing the analog input. In practice, the input voltage is frequently offset by half of the reference voltage to provide a bipolar converter.

With the dual slope method, the conversion accuracy is independent of the clock frequency and integrator component values as long as they are stable within a conversion period. Therefore, conversion accuracy is dependent only on the accuracy and stability of the voltage reference. Resolution is basically limited by the analog resolution of the converter. This converter gives excellent noise reduction because of the integration operation. The normal mode noise rejection is infinite when the integration period is equal to a multiple of the period of the interfering noise. In practice, this time is usually a multiple of 60 Hz. The disadvantage of this method is that it is relatively slow.

4-2.1.4 Voltage to Frequency Integrating Type. The voltage to frequency integrating A/D converter consists of an integrator, comparator, and a counter. An analog input signal voltage is applied to the input of the integrator. The integrator output integrates up to a predetermined voltage level, which causes the comparator to change state. The control logic then resets the integrator and the process is repeated for a fixed period of time. The number of integration cycles (or pulses) during this fixed period of time is a function of the input voltage and is accumulated in the counter for the digital output.

Similar to the dual ramp integrating type, the voltage to frequency type has excellent noise rejection because the integration period is chosen to reject a multiple of the line input frequency. Typical of integrating type A/D converters, the voltage to frequency type provides high resolution. The conversion speed is relatively slow. Since short-term drift of the clock frequency, integrator components, or reference voltage will affect accuracy, care must be exercised in selecting these components.

4-2.1.5 Parallel Type. This method is sometimes referred to as the *simultaneous technique* and is capable of significantly higher conversion rates. The parallel method has the advantage of the fastest speed, but is limited to a relatively few bits, usually about four, due to the large number of comparators required. To convert a large number of bits, it is necessary to employ a hybrid technique whereby a parallel conversion stage is followed by a fast D/A converter, the output of which is subtracted from the input voltage, the difference amplified and then converted using another parallel stage. This results in a speed compromise but high resolution.

4-2.1.6 Sigma–Delta Type. Sigma–Delta conversion is based on oversampling, noise shaping, and decimation filtering of the data stream. This technology relies on digital signal processing with anti-aliasing filters that are less complex than other conversion types and less susceptible to external noise factors since all of the digital filtering techniques are behind the A/D conversion. One advantage of the Sigma–Delta converter is a higher resolution over the SAR or dual slope type converters. Other conversion methods typically utilize a Nyquist sampling method where the sampling rate is approximately twice the maximum input signal frequency. The Sigma–Delta converter utilizes significant oversampling of the input signal frequency (e.g., over sixty four times the input signal frequency) to achieve a higher resolution, however the resulting conversion speed is slower for a given input signal.

4-2.2 Signal Amplification

Many applications of data acquisition systems with low-level input signals require amplification to the input voltage range of the A/D converter(s). The low level signals are commonly in the millivolt range (i.e., 10, 50, l00 mV). A common A/D input range is 0 V to 10 V, and amplifiers are frequently required.

Many low level amplifiers are provided with multiple input ranges, which are selected by the data acquisition system software to match the input signal range. Generally, an amplifier is associated with each A/D converter. Some systems include the low level amplifier function as an integral part of the A/D converter.

The present day low-level instrumentation systems are normally of the differential type. Being sensitive only to differential voltage (or voltage difference) at its input terminals, this type of system will inherently minimize common-mode voltages.

4-2.3 Current to Voltage

Generally, analog input equipment is designed with high impedance devices and has DC input voltage ranges that may be as low as 0 mV to 10 mV or as high as 0 V to 10 V. Thus, a current signal, say in the range of 4 mA to 20 mA, must be converted to an appropriate input voltage range. This conversion can be accomplished simply with a series resistor in the current loop. The resistor selected for this application should have an accurately known resistance and a low temperature coefficient.

When selecting the resistor, two precautions should be taken. The loading of the transducer should be considered. If the loop resistance is too high, the transducer may not be able to provide the required current. The transducer specifications should be consulted and the total resistance in the loop considered. When more than one device is used in series in a current loop, care must be taken that the devices do not affect the circuit current flow.

4-2.4 Voltage Divider

A voltage divider provides a simple means of reducing a voltage source to a voltage that is compatible with the analog input equipment range. The voltage equation is

$$V_o = (R_2 \times V_i)/(R_1 + R_2)$$

The values of R_1 and R_2 should be selected by considering the loading of the source and the input impedance of the analog input equipment.

The transducer specifications should be consulted to determine the minimum value of $R_1 + R_2$. Be sure to consider any other instruments in parallel with the divider. The input impedance of the analog input equipment is used to determine the maximum value of R_2. As an example, for analog input equipment with a 10 MΩ input impedance, an R_2 of less than 10 kΩ is satisfactory. The impedance of the analog input equipment will not have a significant loading effect on the divider.

4-2.5 AC to DC Conversion

Commercial data acquisition systems have the ability to measure low-level AC voltage signals, and internally convert the signal into an appropriate format for A/D conversion.

Alternative approaches to measuring AC signals would be to employ an isolating AC to DC transducer located at the AC signal source or convert AC voltage to DC by providing a simple rectifying and filter circuit as part of the signal conditioning equipment. The circuit consists of a bridge or a half-wave rectifier with a filter capacitor and a resistor divider. The RC combination should be chosen large enough to provide filtering of the AC component and yet small enough that it will not increase the time constant of the input signal. The divider reduces the voltage to be compatible with the analog input equipment. This method may be relatively imprecise due to the forward voltage drop of the diodes. Hardware or software may be necessary to compensate for this diode voltage drop. The AC signal source may be a high power circuit that may introduce common-mode voltage; therefore, caution should be exercised when this method is employed. Examples of field devices that process AC are: power meters, speed transducers, and pulse rate meters.

4-2.6 Filtering

Many analog signals include transient signals that alter the characteristics of the measured signal. Filtering reduces electrical and process noise that exists in an industrial environment. Electrical noise cannot be completely eliminated by proper cabling practices. Generally this is electromagnetic noise at the system power frequency and also capacity-coupled spikes caused by solenoid operation or other sources. Analog filtering is frequently included as part of the data acquisition system. If the signal being measured includes frequencies at or near the frequency of the signal being measured, the filter will introduce an additional error, called aliasing that may not be quantifiable. Because filtering by its nature alters the data stream, care should be exercised to assure that the filter characteristics are compatible with the signal being measured and do not introduce an unacceptable error into the measurement. Therefore, the use of filters, while not requiring specific knowledge of the filter mechanics, does require knowledge of the filter effects and knowledge of the frequency components of the measured signal. This is especially important where the measured signal is at or near the power line frequency. In such cases, it may be necessary to employ an alternate measurement scheme that provides electrical isolation from the power lines.

Two types of hardware filters are discussed: passive and active. Software filtering can also be employed by integrating each reading over multiple power line cycles to minimize this effect.

4-2.6.1 Passive Filters. Passive filters generally consist of resistance, inductance, and capacitance (RLC) circuits, which are designed to remove-noise at some base frequency with a bandwidth of frequencies above or below this base.

For signal measurements taken only at steady state conditions, an RC filter can be used. If the dynamics of the process are important, the characteristic of this type of filter may cause undesirable attenuation at the frequencies of concern. A two-stage filter can be effectively used to eliminate power frequency noise and not attenuate desired process signal frequencies. For high frequency noise, the RC (or LC) is very effective.

4-2.6.2 Active Filters. An active filter is a filter network, which makes use of gain elements with feedback. Active filters may be used when the roll-off or attenuation associated with passive filters is a problem. Since the filter is active, the roll-off can be designed to approach any desired characteristic and can, if desired, provide amplification of the signal.

4-2.7 Digital Signal Conditioning

Signal conditioning equipment of the type discussed with analog signals is usually not necessary with digital inputs except for electrical isolation. Typically, the digital input circuit is designed to receive most digital signals without state conversion.

4-3 SIGNAL MULTIPLEXING

A signal multiplexer is any device that connects a number of signals to a common transmission medium. Multiplexers are used for both analog and digital input signals.

4-3.1 Analog Signal Multiplexing

Analog multiplexers vary in switching speeds from as few as 5 points per second to as many as 20,000 points per second or more. The desirable characteristics of a multiplexer are low contact resistance, low thermal noise, high or infinite resistance when off (or open) to reduce crosstalk, low contact noise, short settling time, and protection against (or immunity to) high overload voltages. Multiplexers typically have two conductors per input point. Three basic types of analog multiplexers are switches, electromechanical relays, and solid state.

4-3.1.1 Switch Type Multiplexing. This type of multiplexer is defined as any type of mechanical device, which can be used to switch signals. These include stepping switches, rotating switches, and crossbar switches. These switches are usually driven by an electrical coil(s) that, in turn, mechanically selects the desired input. Switch type multiplexers usually have gold or silver plated contacts to reduce resistance and thermal noise and to give long contact life.

4-3.1.2 Relay Type Multiplexing. A relay type multiplexer, as contrasted to the mechanical switch type multiplexer, usually has one electrical-mechanical relay for each analog input signal. The relays used are chosen for low contact resistance and low thermal noise characteristics. Some have gold plated contacts sealed in glass to prevent oxidation and are referred to as reed relays.

Another relay type uses a small amount of mercury to wet the contact surfaces for low contact resistance, reliability, and longer life. Relays give excellent point-to-point isolation, which prevents crosstalk between signals, and also have good overload voltage capabilities. They can be randomly addressed. Their switching speeds vary depending upon design.

4-3.1.3 Solid State Multiplexing. These are multiplexers that use semiconductor devices to switch the analog input signals. When the devices are turned on, they connect the input signal to be routed to the output. These may be of a discrete or integrated design.

These multiplexers have high switching speeds – 20,000 points per second or higher. Theoretically they have an infinite life. Unlike mechanical relays, they have a relatively high resistance in the "ON" state and should not be used for low-level signal devices, such as thermocouples, without individual amplification for each low-level signal. Solid state multiplexers are also more susceptible to failure due to high overload voltages.

4-3.2 Digital Signal Multiplexing

This type of multiplexer is used to select digital input signals. Generally, the digital inputs are selected in groups depending on the hardware considerations. This type is also used to select the outputs of multiple A/D converters.

When the digitized output data from an A/D converter is selected by a digital multiplexer, the problems of crosstalk, over-voltage, and threshold voltage levels encountered with solid-state analog multiplexers are avoided. The switching speeds are comparable to solid-state analog multiplexers.

Section 5
Data Acquisition System Calibration

Calibration procedures for data acquisition systems vary based on the type of system to be used and the target test accuracy. This Section discusses the various methods of data acquisition system calibration.

5-1 SYSTEM CALIBRATION

System calibration involves the comparison of the data acquisition system (or system component) output with a reference standard, documentation of this comparison, and application of the difference to the output as a correction, when necessary. System or component output should agree with the reference value within the accuracy requirements of the test and the accuracy limits of the reference.

5-1.1 Reference Standards

The data acquisition system should be calibrated against reference standards traceable to the National Institute of Standards and Technology (NIST), other recognized international standard organization, regulatory requirements, or recognized physical constants. All reference standards should be calibrated at a frequency specified by the manufacturer. Deviations from the manufacturers' calibration frequency are acceptable if sufficient data is available to support the deviation. Sufficient data is historical calibration data that demonstrates a calibration drift less than the accuracy of the reference standard for the desired calibration period.

The reference standards should have an uncertainty at least four times less than the test instrument to be calibrated. This is to ensure that the uncertainty of the standard has an insignificant impact on the total uncertainty of the instrument being calibrated. In this case, the uncertainty of the standard can be disregarded when estimating the uncertainty of the instrument being calibrated.

A reference standard with a higher uncertainty may be employed but the uncertainty of the standard must be included as a component of uncertainty in the instrument being calibrated. This is acceptable if the uncertainty of the standard combined with the uncertainty of the instrument being calibrated is less than the accuracy requirement of the test measurement.

5-1.2 Quality Assurance Program

Each calibration must be performed in accordance with a quality assurance program. This program should include the following documentation:

(a) calibration procedures
(b) calibration technician training
(c) reference standard calibration records
(d) reference standard calibration schedule
(e) instrument calibration histories

The quality assurance program should be designed to ensure that the reference standards are calibrated as required to support the accuracy requirements of the system to be calibrated.

The opportunity to observe the calibration process and/or audit the calibration lab should be provided as a part of the quality assurance program and agreed to by all parties. The quality assurance documentation should also be made available to all parties.

5-1.3 Ambient Conditions

Ideally, the calibration of a data acquisition system should be performed in a manner that replicates the condition under which the instrument will be used to make the test measurements. Due to inability to accurately calibrate systems in the field and duplicate field conditions in the laboratory, other methods must sometimes be employed to account for ambient condition effects. Consideration must be given to all process and ambient conditions which may affect the measurement including temperature, pressure, humidity, electromagnetic interference, radiation, etc. When these effects cannot be calibrated, the impacts to the system accuracy must be estimated and included in the system uncertainty analysis.

5-1.4 Calibration Points and Ranges

The number of calibration points should be based on manufacturer's recommended procedures. Where manufacturer's data is not available the number of calibration points should be based on the order of the calibration curve fit equation. For systems used to measure Class 1 primary variables, the minimum number of calibration points required is two plus the order of the curve fit equation. For systems used to measure Class 2 primary variables, the minimum number of calibration points is equal to the order of the curve fit equation. Data acquisition systems with mechanical analog components should be calibrated such that the measuring point is approached in an increasing and decreasing manner. This exercise minimizes any hysteresis effects. Hysteresis effects in digital systems (or system components) are negligible.

If the system or any of its components are built with a mechanism to alter the range once it is installed, it must be calibrated over each range to be used during the test period. The calibration points must include the expected or encountered range of input values. In some cases, increased accuracy can be achieved by narrowing the span to that needed for the specific application.

5-1.5 Timing of Calibration

Data acquisition systems shall be calibrated per manufacturers' recommended frequency and/or data obtained from calibration history to meet the required test uncertainty. No mandate is made regarding quantity of time between the initial calibration, the test period, and the recalibration. The quantity of time between initial and recalibration should, however, be kept to a minimum to obtain an acceptable calibration drift.

5-1.6 Drift

Drift can result from system malfunction, and/or transportation, installation effects, or removal of any component of the data acquisition system. When the post-test calibration indicates the drift is less than the data acquisition system systematic uncertainty, the drift is considered acceptable. Occasionally the calibration drift is unacceptable. Should the drift, combined with the reference standard accuracy as the square root of the sum of the squares, exceed the required accuracy of the data acquisition system, it is unacceptable.

5-1.7 Calibration Corrections

Calibration corrections may be applied to the output to reduce the overall uncertainty of the measurement. Calibration corrections should only be applied if the uncertainty of the reference standard is at least four times better than the target measurement uncertainty based on test goals. Otherwise, additional uncertainty may be incorporated into the output with the application of a correction developed from a reference with higher uncertainty.

Corrections may be applied at the component level or an overall system correction may be applied to the output. When adjustments or corrections are applied to individual components, the estimated uncertainty is reduced.

5-1.8 Documentation and Traceability

All calibrations must be documented sufficiently to provide information required to perform test uncertainty analyses, apply calibration corrections, and trace each system to reference standards. Documentation should include the range for which the system is calibrated.

5-2 CALIBRATION METHODS

5-2.1 Loop Calibration

Loop calibration involves the calibration of the data acquisition system from sensor to output. This may be accomplished by calibrating the entire system either in a laboratory or on site during test setup before the instrument is connected to process. The advantage of the loop calibration method is that it captures the effects, if any, of the components' interactivity. Where loop calibration is not practical, the uncertainty analysis must confirm that the combined uncertainty of the measurement system meets the accuracy requirements of the test.

5-2.2 Component Calibration

This method calibrates components of the data acquisition system individually, independent of the assembled data acquisition system. All components that have significant contribution to the overall system measurement uncertainty must be calibrated. Components that only handle digital signals typically add negligible uncertainty to the system relative to less accurate components such as sensors. Overall system uncertainty is determined by combining the component uncertainties using the methods of PTC 19.1.

Component calibration can also be used to determine the source of error if a loop calibration yields unacceptable results. Calibration certificates for each component should be provided to all test parties.

5-3 FIELD CALIBRATION

Field calibration refers to calibration of the data acquisition system in the location where it is to be used for testing. Advantages of field loop calibrations include the ability of capturing the effects of system installation, ambient conditions, cable lengths, and component interactivity. Since reference accuracies are typically based on specific, controlled ambient conditions, the effects of field ambient conditions must be included in the reference accuracy when used outside laboratories. Otherwise, field calibrations are best used for functionality checks of the system.

Field calibrations can be used for development of calibration corrections if the reference accuracy, adjusted for environmental effects, is at least four times better than the accuracy required for the test.

5-4 LABORATORY CALIBRATION

Laboratory calibration provides the benefit of controlled environment necessary to achieve the highest accuracy results when field ambient and installation effects are negligible. Laboratory environments can be adjusted to simulate field conditions to the extent they are known prior to the test. Laboratory calibrations are recommended for determination of calibration corrections to the data acquisition system.

Section 6
System Uncertainty

The purpose of this Section is to provide guidance on estimating the uncertainty of a data acquisition system and reducing the uncertainties. This Section is limited to discussion of the systematic uncertainty associated with a data acquisition system. It is more practical and recommended that these effects be analyzed for the entire measurement loop as part of the test data reduction using the techniques described in ASME PTC 19.1.

6-1 SYSTEM UNCERTAINTY CONTRIBUTORS

The systematic uncertainty of the data acquisition system will be a combination of the base uncertainty of each individual component and any additional uncertainty resulting from the system application. Components of data acquisition systematic uncertainty contributors may include but are not limited to sensors, signal conditioning, wire shielding, signal grounding, multiplexing, and A/D conversion.

Since data acquisition systems may be comprised of many different combinations of equipment and components, the uncertainty of a typical data acquisition system cannot be quantified as a specific representative number. Instead, the uncertainty contributors will be discussed in a manner such as to allow the user to determine what effects, if any, should be accounted for in the overall systematic uncertainty of a specific data acquisition system.

6-1.1 Component Base Uncertainty

The base uncertainty of a component is the estimated error for a given confidence interval under controlled situations that represents the minimum uncertainty that will be applied to the component. The uncertainty may be as specified by the manufacturer or based on calibration in a laboratory. The component uncertainty should take into account the expected measurement range of the input signal. For example, a component with a base uncertainty expressed as a percent of reading, the base uncertainty of the component in percentage terms is as stated and the uncertainty in terms of engineering units will be the test reading multiplied by the base uncertainty. For a component whose base uncertainty is expressed as a percent of the span, the uncertainty expressed in engineering units will be calculated as the span multiplied by the stated uncertainty, and the uncertainty in percentage terms would be the uncertainty in engineering units divided by the measurement as a percentage. Some component base uncertainties may be expressed as a combination of the two.

When the base uncertainty of a component is based upon a calibration tolerance, the uncertainty should take into account the contribution of the standards used in the calibration process. A typical calibration tolerance value applied to instruments that are calibrated is four times the overall uncertainty of the standard used in the calibration process. For applications where the manufacturer's specifications or other reference accuracies are applied in conjunction with the calibration uncertainty or where the calibration tolerance becomes statistically significant relative to the applied tolerance, then the two contributors should be combined as the root-sum-squared of the applied calibration tolerance and the calibration uncertainty by

$$U_{\text{Base}} = \sqrt{U^2_{\text{Calibration Uncertainty}} + U^2_{\text{Calibration Tolerance}}}$$

In the above equation, the calibration tolerance can be considered negligible when there is no change in the result when the calibration tolerance is included. For example, a calibration uncertainty of 3.3 to 1 ratio between the applied tolerance and the calibration standard is required in order to achieve a base uncertainty that does not change unless the result is carried to three significant digits (e.g., 1.04%). If the base uncertainty is derived from manufacturer's specifications, then the confidence interval associated with the specification should be taken into account. For example, if the specification is a 3σ value and the component uncertainty is being evaluated as a 2σ confidence, then the specification should be converted from the 3σ value to a 2σ value. Guidance on interval conversion is provided in PTC 19.1.

6-1.2 System Application Uncertainty

System application can have additional effects on the uncertainty of the data acquisition system. The effects discussed in the following paragraphs describe fundamental system application errors, each of which may or may not be applicable for a given data acquisition component/system.

6-1.2.1 Environmental Effects. Environmental effects on the data acquisition system due to changes in the ambient conditions (e.g., temperature, humidity, pressure, etc.) from the calibration or reference conditions at which the base uncertainty of the component was established. The accuracy of many components is affected by environmental conditions. The location of the various components of the data acquisition system should be examined to determine if the environmental conditions are such that the accuracy of the component will change significantly. The quantification of this effect may be included in the specification of the base uncertainty provided by the manufacturer. This effect may also be quantified by running tests on the system/component to characterize its behavior over varying environmental conditions.

In-situ calibration can incorporate environmental conditions in the base component uncertainty, however; the environmental conditions may also affect the accuracy of the calibration standards. This effect can also be minimized by locating components in a climate controlled area or limiting the times at which data can be taken to periods when the environmental conditions are within acceptable ranges.

6-1.2.2 Drift Effects. Drift effects may be included with the component base uncertainty by using manufacturer's specifications that include drift effects such as 24-hr, 90-day, or 1-yr accuracies. This effect can also be quantified using either component manufacturer's specifications or by running tests on the system/component to characterize the drift behavior. Drift effects may be applicable regardless of the calibration methodology employed, depending on the elapsed time between the calibration and the performance test. Reducing the time between calibration and test data acquisition can minimize drift effects. Using a pre- and post-test calibration will help quantify any drift that does occur or validate any assumed drift values.

6-1.2.3 Measurement Resolution. The strength of the sensor input signal or changes in the input signal in relation to the ability of the data acquisition system's ability to measure the signal affect the accuracy of the measurement. One primary example of this is the resolution of A/D conversion. For signals whose strength or change in strength for a desired measurement accuracy is small compared to the data acquisition system's resolution for a given range setting, this effect can be large. An example would be a 50 mV signal input to a signal conditioner with a resolution of 5 mV. The resulting resolution uncertainty is 10% of the input signal. This situation would occur with a 50 mV signal input to a data acquisition system with a 100 V range and $5\frac{1}{2}$-digit accuracy.

This effect can be reduced or eliminated by increasing the resolution of the system, reducing the measurement range, or amplifying the input signal to increase the size of the signal such that it is not at the lower extreme of the measurement range. Any modifications to the signal to reduce this effect should be examined for other sources of uncertainty due to additional equipment or equipment changes.

6-1.2.4 Measurement Methodology. Measurement methodology uncertainties are associated with the technique and/or methods used in the data acquisition process. This does not include effects that are random in nature. Examples of measurement methodology uncertainties are effects due to cabling such as parasitic voltages and parasitic currents.

Parasitic resistances may be induced by lead wires, lead wire imbalances, circuit connections, and multiplexing relays. This effect can be reduced or eliminated by following proper installation using manufacturer's recommendations or standard industry practices. For example, using four-wire connections for resistance measurements will effectively eliminate any parasitic resistances induced by system application.

Parasitic voltages may be introduced by noise and thermal EMFs associated with connections. As with parasitic resistances, this effect can be reduced or eliminated by following proper installation using manufacturer's recommendations or standard industry practices such as shielded cables, proper grounding, and guarded integrating A/D converters. Continuing the example above, a four-wire resistance measurement using offset compensation will reduce or eliminate any noise from the measurement system. Two common sources of thermal EMFs are across circuit connections and multiplexer relays. These affects can be influenced by the quality of the connections as well as any temperature differentials.

Another example of measurement methodology uncertainty is any effect due to signal conditioning not accounted for in the calibration methodology. Ensuring that all components are properly calibrated will eliminate this effect.

Measurement methodology biases can be reduced or minimized by ensuring that the measurement methodology incorporates standard recommended industry practices such as guidelines published by ASME, ANSI, IEEE, etc., for each component of the data acquisition system. These practices include location of components relative to other equipment, cabling practices such as lengths and types for the respective signals, equipment orientation, shielding, grounding, etc., as well as ensuring that all signal conditioning is included in the calibration methodology. Issues associated with thermocouple cold junctions should be assessed using the guidance of ASME PTC 19.3. If these guidelines are followed, the resulting measurement methodology uncertainty due to cabling techniques can often be negligible with respect to the remaining uncertainty contributors for the data acquisition system. Field calibrations can also incorporate the effects of any methodology uncertainty due to installation effects into the calibration uncertainty.

6-1.2.5 Transient Effects. Transient effects are those errors introduced into the system by rapid changes in the measured signal inputs during the course of the test.

Transient measurements are difficult to quantify, but can be considered negligible if the test is conducted under steady-state conditions as established by the applicable test code. If transient measurements are required, the effects can be minimized or reduced by ensuring that the data acquisition system components are designed for the types of signals being measured. Measurements whose signals vary significantly with time should be measured with components designed for such operation with appropriate response times.

6-1.3 Analytical Uncertainty

Analytical uncertainty is uncertainty in calculations whose result depends on values obtained with inexact relationships such as regressions, interpolations, or correlations (e.g., thermodynamic properties).

Minimization of these effects may be accomplished by refining analysis techniques to include more accurate calculation methodologies or calculations that reflect more accurately a specific test setup rather than general test conditions.

6-2 OVERALL SYSTEM UNCERTAINTY

The overall systematic uncertainty of the data acquisition system should be determined by combining the individual uncertainty contributors using the methods of ASME PTC 19.1. In general the process for determining the systematic uncertainty of a data acquisition system consists of five steps.

(a) Determine the target uncertainty of the system including the confidence level (e.g., 95% vs. 99%).

(b) Identify system uncertainty contributors that will apply for the system for each measurement type (e.g., voltage, resistance).

(c) Evaluate identified system uncertainty contributors based on actual or expected input values.

(d) Determine combined overall system uncertainty to determine an overall system uncertainty for each measurement type.

(e) Compare the resulting system uncertainty with the target uncertainty.

The presentation of the data acquisition uncertainty should be in a manner such that it is unambiguous as to its application for a given signal input and measurement range.

6-2.1 Combination of Individual Component Uncertainties

The overall uncertainty for each system component will be a combination of the individual component uncertainty contributors. Assuming that the uncertainty contributors are independent (uncorrelated), these uncertainties are typically combined using a root-sum-squared (RSS) methodology.

$$U_{\text{component}} = \sqrt{B^2_{\text{base}} + B^2_{\text{environment}} + B^2_{\text{drift}} + B^2_{\text{resolution}} + B^2_{\text{method}} + B^2_{\text{transient}} + B^2_{\text{analytical}}}$$

The uncertainty for each system component can then be similarly combined to provide an overall system uncertainty.

$$U_{\text{system}} = \sqrt{\sum U^2_{\text{component}}}$$

In cases where there are correlations between component uncertainties, such as a common standard used for calibration of multiple components, it may be necessary to calculate the overall system uncertainty by combining all of the individual component uncertainties at once using a RSS methodology for independent uncertainty contributors and the square root of the square of the sum of dependent uncertainty contributors. ASME PTC 19.1 provides further guidance on combining elemental uncertainties, especially where there are correlations between one or more contributors.

6-2.2 Overall Measurement System Loop Uncertainty

The overall system uncertainty should also be combined with the uncertainties of the individual sensor input uncertainties to provide a total measurement loop uncertainty in terms of each measured parameter. The sensor uncertainties should be evaluated per the applicable ASME PTC or equivalent document. This may involve performing a sensitivity analysis to propagate the uncertainties from the sensor input to the final output result.

The overall uncertainty of the system may be reduced through a total loop calibration of the system, which effectively combines the calibration uncertainty for all components and the sensor in to a single value instead of separate values for each component and the sensor. Other uncertainty contributors will still need to be examined to determine any effect on the system, regardless of whether a loop calibration or nonloop calibration is performed.

Section 7
Data Management

Performance test data required by data acquisition systems are internally stored and manipulated in the form of binary words. This Section will introduce the subject and highlight the limitations imposed by the length of the binary word (i.e., the data resolution) and its consequential impact on test accuracy and precision. The intermediate and advanced categories of data acquisition systems have the capability to store and manipulate the test data. This Section will give guidance on how to derive the most benefit from this capability.

7-1 DIGITAL DATA REPRESENTATION

The digital values equivalent to test data readings are represented internally in the data acquisition system by a series of bits-on (1's) and bits-off (0's) contained within a binary word. Individual components are designed to handle specific binary word lengths (e.g., 8-bit, 16-bit, 32-bit, etc.). The number of bits, or the data resolution, impacts the selection of components for the data acquisition system. This section discusses the various aspects to be considered when making this selection.

7-1.1 Data Resolution

Generally speaking, the greater the number of A/D converter data bits, the less the instrument signal must change to effect a change in the measured value.

Also, in many cases, not all of the bits in a binary word are entirely utilized for input data storage. One bit is frequently used to indicate instrument signals that exceed the A/D converter range, often referred to as an overload bit. Another bit is ordinarily a sign bit indicating whether the data value is positive or negative. Bits may be used to ensure the data integrity by always maintaining an even or odd bits-on count; these are known as parity bits or checksum bits and are generally an additional bit provided in excess of the basic binary word length. The remaining bits are used to represent the actual data value in a binary arithmetic code.

7-1.2 Computational Accuracy and Precision

Data resolution influences, among other things, computational accuracy and precision. The conversion of the output digital value from the A/D converter into engineering units, the addition of a calibration correction factor, or adjustment for zero offset, such as fluid head, are all affected by data resolution as well as by mode of arithmetic computations. Data resolution effects ultimately propagate through to the calculated results of the performance test.

Insufficient data resolution of a fixed-point value may also result in error due to truncation of digits from a number. For example, the product of two numbers using 16-bit data words including sign could not exceed ±32,767; otherwise, a truncated number would result. However, some data acquisition systems may use two words (double precision) to implement fixed-point arithmetic, which increases resolution somewhat.

To aid in computations and programming, floating point arithmetic has been developed whereby the data acquisition system keeps track of the decimal point in binary format. This decreases numerical precision if the same binary word length is kept, since some of the bits must now be used to indicate the binary point location. A commonly used floating point representation defined by the IEEE Standard 754 [7].

In more powerful components of a data acquisition system, most of the data is capable of being stored and manipulated as floating-point values. In this case, the fixed-point arithmetic is typically limited to integer values where the binary point is always to the right of the least significant bit (LSB).

7-2 DATA OUTPUT REQUIREMENTS

Depending on the types of instrumentation and modes of measurement, much of the data collected must be manipulated in a way to provide meaningful test results. Whether the manipulation is through signal conditioning, conversions, or other calculations, certain data must be preserved as a "roadmap" so that calculation results can be verified post test. This is especially important where there are multiple methods by which to measure and calculate various parameters.

(a) Examples of required outputs:
  (1) Flow calc – DP, P, T
  (2) Chromatograph — constituents
  (3) Engineering units — uncorrected
  (4) Every data sample — access to this data required for validation of averages

(b) Examples of outputs not required:
  (1) T/C mV
  (2) RTD resistance
  (3) Thermistor resistance
  (4) Transducer mV

7-3 MANUALLY PREPARED DATA

Not all measurements are appropriately monitored by data acquisition systems, and it may be more desirable, practical, or economical to manually obtain a measurement. In order to manually enter or substitute values into a data acquisition system that is capable of calculating test results, the capability to accept, store, and reuse the data should be considered. Several needs for manually prepared data arise.

Some fluid flows are generally more practical to measure by the use of weigh tanks or by extraction from equipment design curves (e.g., blowdown and makeup flows, steam seal flows, other leakages). Manually prepared flow rates may then be entered into the data acquisition system capable of calculating results. This is especially important when establishing a steam cycle water balance prior to running a cycle heat rate test for a steam turbine.

Depending upon the relative importance of the results, provisions to enter manually substituted values should be considered. Whenever manually substituted values are used in calculations by the data acquisition system, these entries should be flagged or otherwise distinguished for easy identification.

7-4 CALCULATIONS

Intermediate and advanced data acquisition systems may include the capability to perform calculations on the collected test data. The calculations can be as simple as unit conversions or as complex as equipment performance calculations. This subsection discusses the various types of calculations to be considered for a data acquisition system.

7-4.1 Data Reduction

Data reduction is the method by which test data being collected by the data acquisition system is summarized through simple calculations to produce more meaningful information. This can include scaling, engineering unit conversions, averaging, and corrections for calibration. Software signal conditioning is another example of data reduction. The data system can have the capability to allow test personnel to reject certain parts of the data (e.g., if non-steady-state conditions existed for part of a steady-state test). The averages may be calculated based only upon the unrejected data.

Several methods of data reduction are discussed in para. 7-4.1.1 through 7-4.1.7.

7-4.1.1 Scaling. Scaling is the method by which raw data is converted into engineering unit values. For example, the digital readout from an A/D converter is a linear representation of the voltage applied to the analog input subsystem. To present this information in engineering units, a subsequent conversion or scaling operation is required.

The conversion of measurement signals to engineering units may require linear, polynomial, logarithmic, or other functions.

Standard recognized equations should be used for the scaling to engineering units of measure. Standard tables for conversion of thermocouples are available. For example, polynomial equations describing the conversion of thermocouple signal levels to engineering units of measure are defined in the National Bureau of Standards Monograph 125.

Various programming techniques can be used to represent the nonlinear conversion factors accurately. Where there exists a nonlinear relationship between instrument signal level and the corresponding engineering units of measure, it is acceptable to fit piecewise linear segments of the conversion equation or to use polynomial curve fits. The piecewise linear segments should be chosen so that there is continuity at the boundaries. A greater number of segments will provide a more accurate conversion over the test data range. Any approximations should be accounted for in the analytical uncertainty as discussed in Section 6.

Digital techniques are ideal for pulse counting applications, such as calculating megawatt-hours. The engineering unit value per pulse must first be accurately determined for use as the conversion factor.

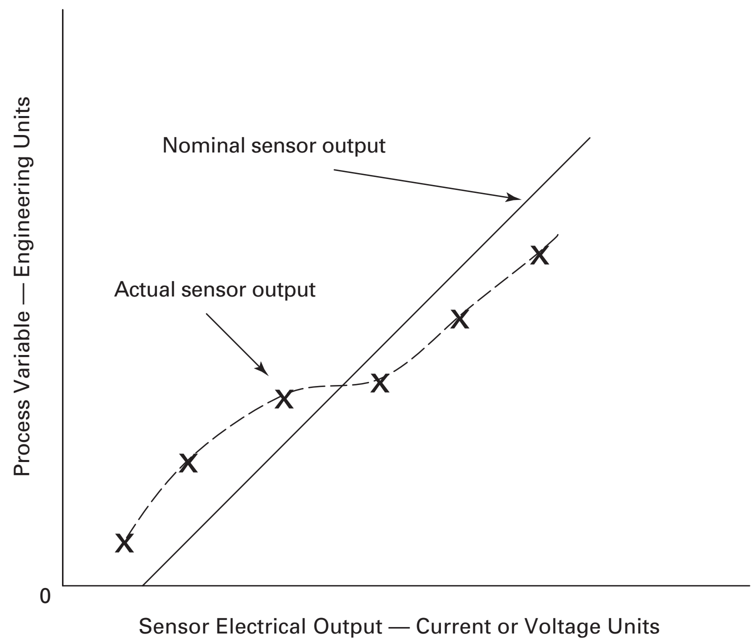
7-4.1.2 Unit Conversions. Unit conversions are necessary where subsequent calculations or test reports require specific engineering units which are different from the scaled or recorded value. Since there exists the potential for many converted values to be used as inputs to a calculation, it is important that the units conversions are as accurate as possible. Utilizing a data acquisition system with this capability can significantly help in reducing any errors resulting from manual calculations.

A common units conversion in performance testing is from psig (gauge) to psia (absolute). This conversion is necessary for many calculations which use pressure as an input, including various steam and gas property functions.

7-4.1.3 Calibration Corrections. This paragraph discusses three basic methods of applying calibration corrections that are applicable to the entire data acquisition system.

(a) *Total Curve Fit.* This method is illustrated in Fig. 7-4.1.3-1. The actual data acquisition system output curve is derived from several calibration points and replaces the output curves of the system components in converting the sensor electrical output into engineering unit values. The nominal sensor output curve is the set of points that one would expect from sensor outputs with no error. The actual sensor output is represented as a curve such as a polynomial of the form $y = a_o + a_1x + a_2x^2 + \ldots + a_nx^n$. It is desirable that the zero offset as represented by the a_o coefficient be

Fig. 7-4.1.3-1 Total Curve Fit



independently adjustable. A transducer zero shift usually does not affect the characteristic shape of its actual output curve.

The data acquisition system may be programmed with the capability of deriving this polynomial from the calibration point data. Care must be taken in the selection of the polynomial order to prevent undesirable points of inflection. The number of calibration points must be at least two greater than the polynomial order. The actual sensor output curve should be checked at its operational range extremities to assure continuity.

The measurement accuracy using this method depends upon the number of points selected, their relative position to each other, and how well the polynomial curve fits the calibration points.

(b) Offset Curve Fit. This method is illustrated in Fig. 7-4.1.3-2. An offset value is the difference between an actual sensor output value and the nominal or expected sensor output value at the same sensor electrical output value. An actual sensor output value is obtained by either adding the offset value to or subtracting it from the associated nominal value. The offset curve is derived similarly to the total curve and the same precautions should be observed.

(c) Offset Straight Line Segments. This method is illustrated in Fig. 7-4.1.3-3. An offset value is defined similarly to that described in the offset curve fit method. Line segments are selected from the calibration point values. These segments are represented by independent linear equations of the form $y = mx + b$. The length of each segment is usually equal but may be selected to best fit the calibration points. Five segments are frequently selected to represent the offset curve in the sensor's operational range. The total and offset curve fit methods require more elaborate software than the line segment method due to the derivation of the polynomials. Compared to using the total curve fit method, a higher resolution may be obtained over the operational range of the sensor by using either offset method. This is due to the offset curves being more nearly linear, and the lack of fit error being reduced.

7-4.1.4 Other Corrections. Corrections to raw test data are used when an instrument is used in conditions different from that when calibrated. Examples can include

(a) compensating for water leg

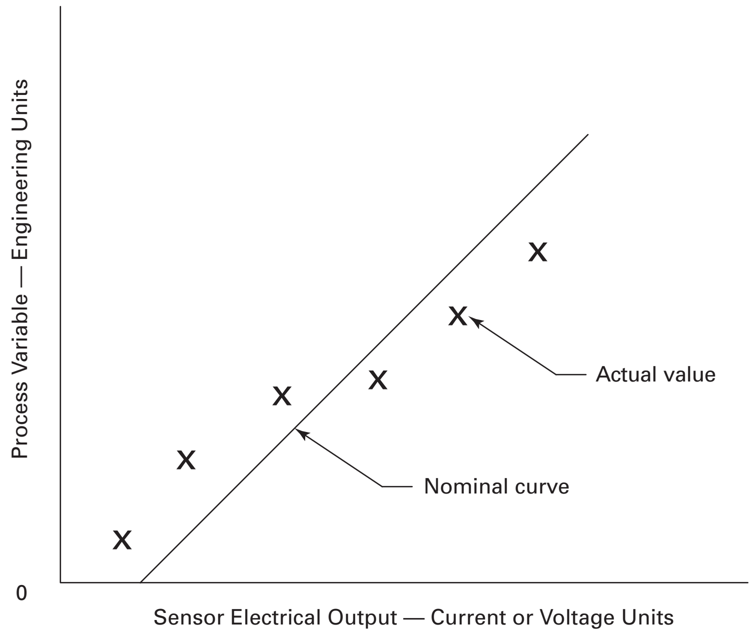
(b) correcting for local gravity

Intermediate and advanced data acquisition systems may be capable of performing correction calculations automatically, provided that the current conditions are properly input to the system.

7-4.1.5 Averaging. Average test data is used to provide a summary of the test over a certain period of time. Averaging can be more efficiently performed within the data acquisition system. Data acquisition systems may have the capability of performing performance calculations at each sample point (or scan) prior to averaging. Caution should be exercised to ensure that software averaging techniques are only applied with full knowledge and concurrence of the parties to the test.

Care should be taken that certain data should always remain available as required by subsection 7-2.

Fig. 7-4.1.3-2 Offset Curve Fit



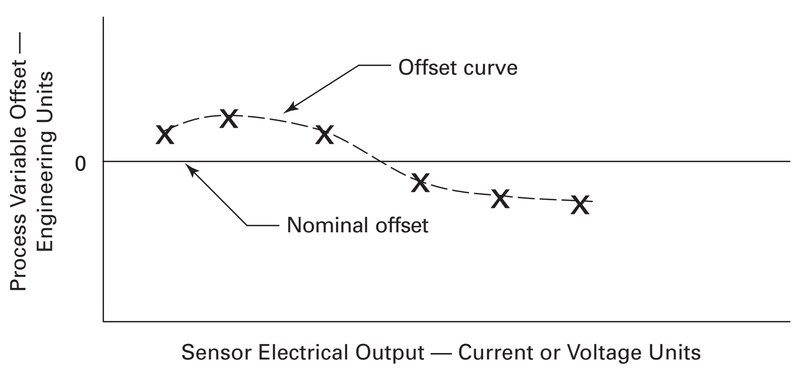
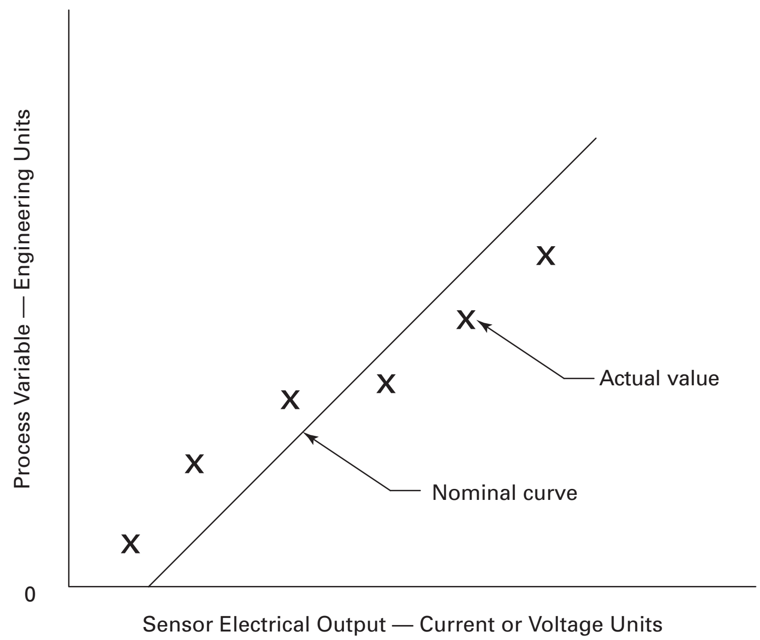
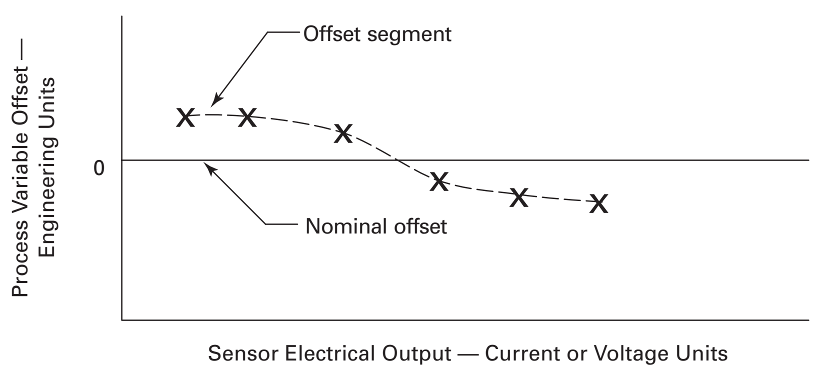


Fig. 7-4.1.3-3 Offset Straight Line Segments





7-4.1.6 Statistical. Data acquisition systems may also be programmed with various statistical calculations, such as standard deviation, ultimately to be used to perform an uncertainty analysis of the test.

7-4.1.7 Signal Conditioning: Software Filtering or Data Smoothing. Some data acquisition systems are programmed with the capability to minimize noise effects by arithmetically "dampening" or "smoothing" sharp variations in process inputs. Caution should be exercised to ensure that software data smoothing techniques are only applied with full knowledge and concurrence of the parties to the test.

Care should be taken that certain data should always remain available as required by subsection 7-2.

7-4.2 Results

7-4.2.1 Test Results. Advanced data acquisition systems may be capable of performing test result calculations directly from data gathered from instrumentation as well as manually entered data. In advanced data acquisition systems, various tools such as gas and steam property calculation packages can be incorporated into the results.

Calculations specified by other PTC's can also be programmed into the system to provide the automatic calculation of test results. An example of this includes application of test corrections to measured values.

An evaluation should be made whether to perform calculations on instantaneous versus averaged data, based on the linearity of the system. This also depends on whether or not the system is in steady-state, as not all test requirements specify steady-state operations.

7-4.2.2 Test Uncertainty. Test results uncertainty calculations can also be incorporated into the system to provide automatic uncertainty results. Care must be taken when manually inputting component uncertainties to avoid typographical errors.

7-4.3 Validation

One should be able to validate the results by following an audit trail of the calculation using the input data to come up with the same answer. Therefore, all calculations in a data acquisition system should leave all input data intact.

Manually prepared design data may be substituted into the equations to demonstrate their correctness. Design data for all variables may be entered and the resultant values compared with the design resultant values. These test case data may be entered for several design load points to demonstrate the credibility of the equations throughout the range of the test loads.

7-5 DATA STORAGE GUIDELINES

In both the intermediate and advanced data acquisition systems, data storage is used to store both input data as well as calculated results. This subsection provides guidelines for saving test data.

7-5.1 Storage Capacity

The amount of data to be stored must be considered when choosing or designing a data acquisition system since data compression is not acceptable for PTC tests. Length of data collection (time), number of data points, number of data point attributes, and frequency of collection will determine the amount of data that needs to be stored. Hard drive capacity, spreadsheet row and column limitations, and archive sizes are examples of limitations on data storage capacity.

7-5.2 Stored Attributes

When storing test data, the following attributes need to be retained to make the data meaningful:

(a) The basic attribute is the data value itself. This is the value after appropriate signal conditioning and scaling has been applied. Storage of the raw data (such as the mV signal from an instrument) can be valuable for diagnostic purposes but is not required. Data output requirements are presented in subsection 7-2.

(b) Every piece of data needs to be assigned a time stamp. The resolution of the time stamp needs to be at least that of the time interval between data samples collected either by the data acquisition system or manually. Also, calculated values need to be stored with a time stamp that matches the raw data from which it is calculated unless calculated from averages.

(c) A tag name and engineering units must be stored to give the value meaning. The tag name should reflect what is being measured or calculated. An additional tag description is recommended.

(d) Some indication of the quality of the data should be stored when available. Quality can be used to indicate if that data is valid or not. For example, a "bad" status could indicate that a transmitter reading 0.0 has failed as opposed to the process actually being at a zero state.

(e) Calibration coefficients, if incorporated into calculations performed by the data acquisition system, should be stored.

(f) Channel number (if applicable) should be stored with each data point to assist in troubleshooting and provide calibration traceability.

7-5.3 Data Compression

Storing data leads to capacity issues, particularly for longer tests with large amounts of data. Many data archiving systems have the capability to compress the data. A common compression technique is storage by exception where a value is only stored after it has changed by a certain amount. Another technique involves not storing values that can be calculated from previously stored data. Both of these methods introduce an uncertainty since data cannot be matched exactly with other data at any one time stamp. Also, calculations to back calculate data to a certain time stamp will introduce additional uncertainties.

7-6 REPORTING

The data acquisition system may be provided with the capability of producing tabular listings or graphs of calibration data, test data, and results. The electronic output is faster, more accurate, and more legible than that obtained by manual reporting. Extraction of records from stored data of a data acquisition system eliminates human transcribing error. In the case where data output is required to be reported, providing the large files digitally is more convenient than pages of hardcopy tables of data.

Permanent records can be stored on magnetic or optical media requiring minimum storage space and providing for ease of data retrieval.

Data acquired during the test should be available for use by test personnel and can be available to other data acquisition systems. Consequently, all data incorporated into the final report of the test should be recorded by the data acquisition system if that lies within the system capability.

When presenting data for inspection by test personnel, the data acquisition system should mark the individual data readings by some method that uniquely identifies the parameter.

The data system may also have the capability to average all appropriate valid data during the test period. The average reading of each individual variable may be printed out and appropriately identified.

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NONMANDATORY APPENDIX A DATA ACQUISITION SYSTEM COMPONENT ERRORS AND OVERALL SYSTEM UNCERTAINTY REPRESENTATION

A-1 INTRODUCTION

The purpose of this Appendix is to describe the uncertainties associated with each component in a data acquisition system, and how each of these component uncertainties are presented and considered together to determine the overall system uncertainty. Where possible, recommendations and methods are given for minimizing the error contributors in a data acquisition system.

It should be noted that the discussion below is general in nature and does not represent all possible contributors or representations thereof. Furthermore, due to the wide variety of component combinations and system/component boundaries, the representation of system accuracies cannot be fully encompassed. Rather, the reader should note the variety of contributors that affect the accuracy of a system and then determine whether the information provided encompasses the individual contributors.

A-2 SYSTEM COMPONENT ERRORS

The errors associated with each of the major elemental components of a DAS are discussed in paras. A-2.1 through A-2.3.

A-2.1 Sensors

Sensors, primary elements, and in the case of thermocouples, the lead wire external to the data acquisition system are elements involved in the overall accuracy consideration. The errors associated with individual sensors are addressed in the PTC 19 Series — Instruments and Apparatus Supplements, as well as other industry standards and manufacturer's specifications.

A-2.2 Signal Conditioning

The signal conditioning and filtering elements of the data acquisition system include the types of signal conditioning addressed in Section 4 of this Code. Each signal condition type discussed in Section 4 will have an associated error.

A-2.3 Multiplexing

Errors introduced by multiplexing vary with the type of multiplexer used. The following are some typical error sources that may be introduced by a relay type multiplexer. It should be noted that the calibration procedure for a data acquisition system often does not include the multiplexer and assumes that the uncertainty due to the multiplexer relays and associated contacts is negligible. Caution should be taken if the multiplexer is not included in the calibration, since a partial failure in the multiplexer may go unnoticed and affect the overall system accuracy.

Error Source
Contact resistance
Crosstalk
Long-term drift
Noise (thermal, switching, etc.)
Thermal coefficients
Zero offset

A-2.4 A/D Conversion

The A/D conversion function is generally provided by either an integrating type A/D converter or a successive approximation type. Since the successive approximation converters require low level differential amplifiers for the low level inputs, they are included here in the accuracy considerations for the A/D converter function. Errors that may be encountered in the A/D conversion process include resolution, linearity, gain, and zero offset.

Table A-2.4-1 shows the resolution range of A/D converters typically encountered in data acquisition systems and differing methods of presenting the resulting accuracy. The A/D component uncertainty decreases with higher resolution, higher-bit conversion.

Table A-2.4-1 DAS A/D Converter Resolution

Percent	PPM	Digits	Bits	dB	Portion of 10 V
10%	100 000	1	3.3	−20	1 V
1%	10 000	2	6.6	−40	100 mV
0.1%	1 000	3	10	−60	10 mV
0.01%	100	4	13.3	−80	1 mV
0.001%	10	5	16.6	−100	100 μV
0.0001%	1	6	19.9	−120	10 μV
0.00001%	0.1	7	23.3	−140	1 μV
0.000001%	0.01	8	26.6	−160	100 nV
0.0000001%	0.001	9	29.9	−180	10 nV

A-2.5 Data Processing Errors

Some error is introduced by the conversion of the A/D converter output in digital form to engineering units. The general term "conversion to engineering units" is intended to include all aspects of flow calculation, thermocouple linearization, and other nonlinear conversions as well as linear conversions. Error can also be introduced by the representation of calibration data when using a curve fitting approach, which may not provide a good regression fit in between calibration points if the lack of fit is not accounted for in the calibration methodology. This error must be considered in addition to the error resulting from conversion to engineering units. An example is a flow measurement that uses a K-Factor to convert from pulses to engineering units.

In many cases the unit conversion error is included as part of the calibration. In this case, the calibration data and reported uncertainty would typically account for any unit conversion errors.

A-3 SYSTEM APPLICATION ERRORS

In addition to the error contributors associated with the base system components discussed in subsection A-2, the application of the system components will have additional contributors.

A-3.1 Zero Offset Errors

The zero offset will change as a function of ambient temperature. Long-term drift will also cause zero offset error. It is common practice to specify the long-term drift and thermal coefficients for the system including both elements.

Many data acquisition systems include an autozero feature that automatically recalibrates the DAS to correct for zero offset errors. This is done by periodically scanning shorted inputs to determine the offset correction. With multigrain amplifiers, the zero offset for each gain and polarity should be checked. This correction will include zero offset errors from the A/D converter as well as multiplexing.

A-3.2 Gain Errors

The thermal coefficient of gain error is typically represented as a ratio of the percent full range (FR) divided by the difference in the ambient temperature a some reference temperature or temperature range (e.g., ±% FR/°C). Some data acquisition systems incorporate automatic recalibration for full range to minimize the gain errors due to drift. Another approach in identifying gain drift is to periodically scan a reference (or multiple references) input, checking against very narrow limits. An alarm output may be given whenever the reference alarm dead band tolerance is exceeded, indicating the need for manual recalibration. The manual or automatic recalibration of bipolar A/D converters should check both polarities. With multigain amplifiers, each gain should be checked for both polarities.

A-3.3 Reference Voltage Errors

The most common sources of reference voltage errors are the inaccuracy of the voltage regulation circuitry, its thermal coefficient, and long-term drift. Reference voltages are used in A/D converters, bridge circuits (such as RTDs), and for the standard or reference for automatic gain calibration or gain error monitoring. Reference voltages errors associated with A/D converters and bridge circuits are generally included in the accuracy statements for those devices. Errors in the reference voltages used as the standard for automatic recalibration of gain directly affect the accuracy of the data acquisition system. Issues associated with thermocouple cold junctions should be assessed using the guidance of ASME PTC 19.3.

A-3.4 Common Mode Errors

Common mode error is caused by voltage (noise), which appears equally between each input signal wire and ground. The ability of the analog input system to reject the common mode voltage while processing the desired differential input signal is referred to as the common mode rejection (CMR). The CMR is usually expressed in decibels by the equation

$$CMR = 20 \log_{10} V_{CM}/V_{CMO}$$

where

CMR = common mode rejection, dB
V_{CM} = common mode voltage on signal wires
V_{CMO} = common mode signal component in output reading

A-3.5 System Noise Error

The analog portions of a data acquisition system characteristically have an ambient noise level associated with the measurement. For systems with multiranged low level differential amplifiers, the error is typically defined as a voltage referred to input (RTI) and its error calculated in percent full range for each amplifier range. For a fixed range system, the error is defined in percent full range. Ensuring that the input signal strength is much larger than the error associated with the system noise (signal-to noise ratio) can minimize noise errors.

A-4 OVERALL DATA ACQUISITION SYSTEM ERRORS

When determining the overall uncertainty or component uncertainty of a DAS, the individual contributors identified in subsections A-2 and A-3 may not be available. Instead, the system/component accuracies may be expressed as a combination of error sources that may encompass some or all of the contributing errors. As a result, the available information must be examined to determine if any contributors are not included and evaluate them for inclusion in the overall system uncertainty. For example, system accuracy may be stated as % Reading ± % Range (for a given A/D range setting and operating environment for a 1-yr interval).

This specification includes contributors due to zero offset, A/D resolution, drift and gain errors. Depending on the operating environment, an additional temperature coefficient may also be required or may be included in the specification.

Alternately, the specification may be provided as % Reading (over a given span).

This specification may also include contributors due to zero offset, A/D resolution, drift and gain errors depending on the stated measurement range (e.g., 10 psi to 20 psi or 50°F to 100°F) and whether any drift effects and/or environmental effects are included.

Note that accuracy specifications provided in terms of percent of full range (% FR) is different than a specification in terms of a percent of span (% Span), which covers the range of readings over which the system is calibrated.

The method of calibration may also affect the system accuracy. This can be seen especially in instances where a complete loop calibration of the measurement loop is performed over a narrow range of inputs, where the demonstrated accuracy of the system may shown to be better than the individual specifications. In such instances, the calibration accuracy may supersede some or all of the previous accuracy information for the system provided that all relevant contributors are still accounted for.

A-5 SUMMARY

In summary, this type of analysis demonstrates the need for an understanding of the separate component error contributors in order to understand the variety of means of stating system and component uncertainties. This will assist in the comparison of different systems as well as combining individual component uncertainties. This will, in turn enable the selection and analysis of a data acquisition system that best meets the requirements of the particular test.

NONMANDATORY APPENDIX B
DATA ACQUISITION SYSTEM UNCERTAINTY CALCULATION EXAMPLES

B-1 PURPOSE

The purpose of this example is to provide a detailed example of an uncertainty analysis for several common measurement types. For each type of measurement, the individual contributors from Section 6 are considered. For the purposes of this Appendix, the primary units of measure are assumed to be English units. Units used in the development of intermediate and supporting calculations will use units typically found for the instrument specification such as Ω/°C for the nominal RTD coefficient, °C for temperature coefficient temperature differences, mW/°C for power dissipation, etc.

B-2 UNCERTAINTY OF FOUR-WIRE RESISTANCE MEASUREMENT

The following paragraphs describe the uncertainty calculations for the four-wire resistance measurements.

B-2.1 System Configuration/Specifications

(a) The following data acquisition system configuration will be examined: four-wire RTD inputs into a multiplexing data logger with signal conditioning and A/D conversion with subsequent conversion to engineering units.

(b) The data logger accuracy for the resistance measurements is as follows: ±(0.008% of reading + 0.001% of range) for 1 kΩ range.

(c) The temperature coefficient for the resistance measurement is as follows: ±(0.0006% of reading + 0.0001% of range)/°C.

B-2.2 Assumptions

(a) The RTDs are calibrated, to a repeatable accuracy of ±0.15°F with sensor specific coefficients using the ITS-90 calculation methodology [8].

(b) All instruments are installed using good handling practices and correct calibration and measurement techniques are followed.

(c) The RTDs are wired to the multiplexers with shielded, twisted pair instrument cable. The cable length is assumed to provide no effect on the measurement.

(d) Circuit connections are made with clean copper-to-copper or copper to lead/tin junctions, and the maximum temperature differential across any connection in the measurement circuit is limited to no more than 1°C.

(e) Thermal equilibrium is obtained for all measurements by exposing the entire system to the same environment and allowing suitable instrument warm-up periods.

(f) Methodology systematic uncertainty due to sensor location or installation technique with respect to the measured parameter, spatial effects, and random uncertainties will not be considered in this calculation. Such uncertainties require further evaluation using actual test data or site-specific information.

(g) The system is operated at ambient conditions that are ±10°C (18°F) from the calibration conditions.

(h) The system is pre- and post-test calibrated to verify the stability of the system.

(i) Measurements are made under steady-state conditions. Therefore, transient effects will not be considered in this analysis.

B-2.3 Analysis

The following sections identify and analyze the individual uncertainty contributors identified for the overall systematic uncertainty of the measurement loop. For this analysis, the individual contributors are grouped into three categories; contributors to the DAS itself, contributors to the input sensor, and analytical uncertainties.

B-2.3.1 DAS Systematic Uncertainty Contributors. The following paragraphs discuss the systematic uncertainty contributors for the DAS.

B-2.3.1.1 Base Systematic Uncertainty. The DAS is calibrated to ±(0.008% of reading + 0.001% of range) accuracy. Assuming a maximum test temperature reading of 200°F, the corresponding resistance at this temperature is 135.97 Ω. This value corresponds to the highest uncertainty expected in the measurement range for the test conditions. Therefore, the base systematic uncertainty associated with the DAS is conservatively calculated as

$$B_{\text{DAS\_Base}} = (0.008\% \cdot 135.97\ \Omega + 0.001\% \cdot 1\,000\ \Omega) \cdot 100 = \pm 0.0208\ \Omega$$

(a) Resistance Error Sensitivity Coefficient. A resistance error sensitivity coefficient is required to convert the DAS base systematic uncertainty from resistance to temperature. ASME PTC 19.1 defines sensitivity as the error

propagated to the resulting measurement due to a unit error in the measurement parameter. The sensitivity coefficient in this case is determined analytically by

$$\theta_{r,\,P_i} = \frac{\partial r}{\partial P_i}$$

where

P_i = measurement parameter
r = resulting measurement
$\theta_{r,\,P_i}$ = sensitivity coefficient for the resulting measurement with respect to a measurement parameter

(b) The sensitivity can then be applied as:

$$B_{\text{DAS\_Base}}(°\text{F}) = B_{\text{DAS\_Base}}(\Omega) \bullet \theta_{T,R}$$

(c) The sensitivity coefficient may be approximated using a nominal RTD temperature coefficient of 0.385 Ω/°C as

$$\theta_{T,\,R} = (1/TC) \bullet C$$

where

C = factor for converting °C to °F (1.8°F/°C)
TC = 0.385 Ω/°C

(d) The sensitivity coefficient, $\theta_{T,\,R}$, is calculated to be

$$\theta_{T,\,R} = \frac{1}{0.385\ \Omega/°\text{C}}\, 1.8°\text{C}/°\text{F} = 4.675°\text{F}/\Omega$$

(e) Applying this sensitivity to the DAS base systematic uncertainty yields a base systematic uncertainty in terms of the measured temperature of

$$B_{\text{DAS\_Base}} = \pm 0.0208\ \Omega \bullet 4.675°\text{F}/\Omega = 0.10°\text{F}$$

B-2.3.1.2 Environmental Effects. Operation of the DAS in environmental conditions that differ from those in which it was calibrated can potentially introduce additional uncertainty. Manufacturer's specifications often provide temperature coefficients, which may be used to derate the performance of the instrument based on the expected operating temperature range.

(a) The DAS systematic uncertainty due to environmental effects may be calculated from the equation

$$B_{\text{DAS-env}} = TC \bullet \Delta T$$

where

TC = temperature coefficient used to derate the accuracy specifications, given by the manufacturer for the proper resistance range
ΔT = the difference between the ambient temperature range during calibration and the ambient temperature range during operation, evaluated for the worst-case difference

(b) For this example, a temperature difference of 10°C is assumed and the DAS has a temperature coefficient of

$$TC = [\pm 0.0006\%\text{ of reading} + 0.0001\%\text{ of range}]/°\text{C}$$

(c) Substituting the values of the temperature coefficient and temperature differential of 10°C into the equation for the DAS environmental systematic uncertainty yields

$$B_{\text{DAS-env}} = [\pm(0.0006\%\text{ of reading} + 0.0001\%\text{ of range})/°\text{C}]^*(10°\text{C})$$

$$B_{\text{DAS-env}} = [\pm(0.006\%\text{ of reading} + 0.001\%\text{ of range})]$$

(e) From this expression it can be seen that the maximum environmental error exists when the temperature reading, and thus the RTD resistance, is maximized. The maximum DAS environmental systematic uncertainty for the system, assuming a 200°F reading) is

$$B_{\text{DAS-env}} = [\pm(0.006/100 \times 135.97\ \Omega + 0.001/100 \times 1\,000\ \Omega)]$$

$$B_{\text{DAS-env}} = \pm 0.0182\ \Omega$$

(f) Applying the sensitivity coefficient previously derived yields the additional systematic uncertainty due to DAS environmental effects as

$$B_{\text{DAS-env}} = (\pm 0.0182\ \Omega) \times (4.675°\text{F}/\Omega) = \pm 0.09°\text{F}$$

B-2.3.1.3 Drift. Post-test calibrations are used to verify the system stability within the accuracy limit of ±0.008% of reading + 0.001% of range for the DAS. Therefore the additional systematic uncertainty due to DAS stability is

$$B_{\text{DAS-stability}} = \pm 0.00°\text{F}$$

B-2.3.1.4 Measurement Resolution. The resolution effect of the DAS is included in the specifications of the system. Therefore, this contributor is included in the base uncertainty and the environmental effects and

$$B_{\text{DAS-Resolution}} = \pm 0.00°\text{F}$$

B-2.3.1.5 Measurement Methodology. Parasitic resistances and parasitic voltages introduced as apart of the measurement loop can result in additional uncertainties. It is assumed that proper installation techniques have been followed, effectively eliminating any contributors due to installation effects.

(a) Parasitic Resistance. Parasitic resistances are introduced into the measurement circuit by lead wires, lead wire imbalances, circuit connections, and multiplexing relays. Using proper installation, calibration, and measurement techniques may minimize effects of parasitic resistances. It has been assumed for this analysis that these techniques have been strictly followed in order to minimize these effects.

The DAS eliminates lead wire resistance effects through the use of the four-wire measurement technique. Reference [9] states "Four-wire or Kelvin connections are generally made to minimize errors created by I-R drops in the cabling or interconnects of a test system." Therefore, lead wire resistance effects are removed via the four-wire measurement technique.

Lead wire imbalances do not contribute error to the measurement due to the use of the four-wire measurement technique, which eliminates parasitic resistances introduced by lead wire imbalances.

Connectors present in the measurement circuit have the potential for introducing parasitic resistances. Calibrating the DAS and RTDs together as a system serves to eliminate any constant parasitic resistances introduced by the connectors. Also, the four-wire measurement technique eliminates the effects of parasitic resistance introduced by circuit connections.

Parasitic resistances are introduced into the measurement circuit by the "contact resistance" inherent in all multiplexing relays. Contact resistance values for two wire armature relays are typically less than 1 Ω. However, the four-wire measurement technique employed by the DAS eliminates contact resistance effects in the measurement circuit.

Therefore, the additional systematic uncertainty introduced by parasitic resistances is

$$B_{\text{DAS-PR}} = \pm 0.00°\text{F}$$

(b) Parasitic Voltages. Parasitic voltages are introduced into the measurement circuit by noise and thermal EMFs. The effects of parasitic voltages may be minimized and/or removed by using proper installation, calibration, and measurement techniques. It has been assumed for this analysis that these procedures have been strictly followed in order to minimize parasitic voltage effects.

The effects of electrostatic and electromagnetic noise are minimized by the use of shielded, twisted pair instrument cable and proper grounding techniques. Also, the DAS is assumed to have a guarded, integrating analog to digital converter, which further reduces external noise effects on measurements. Integration of the input signal is performed at a constant frequency, typically the line frequency, in order to remove all 60 Hz noise from the signal.

Through the use of the four-wire measurement method, system calibrations, and the use of the offset compensated ohms techniques, the additional systematic uncertainty due to noise can be eliminated.

Thermal EMFs are minimized by use of clean copper-to-copper connections and by minimizing temperature gradients in the measurement circuit. The two most common sources of thermal EMFs in the measurement circuit are across circuit connections and multiplexer relays.

Assuming no more than a 1°C temperature differential across any connection and assuming all connections are either clean Cu-Cu or Cu-Pb/Sn, the maximum potential thermal emf across any junction is

$$B_{\text{connection}} = 3\ \mu\text{V}$$

The DAS uses two-wire armature relays in its multiplexers. The thermal electric potential of a two-wire armature relay is < 3 μV, therefore the maximum potential emf across any multiplexer relay is

$$B_{\text{relay}} = 3\ \mu\text{V}$$

Since the magnitude and sign of the thermal EMFs across each connection and relay are dependent upon both the quality of the junction and the temperature differential across the junction, the systematic uncertainty at each junction will be considered independent. The total systematic uncertainty due to parasitic voltages can be estimated as the square root of the sum of the squares of the systematic uncertainty at each junction. For the measurement circuit consisting of two multiplexer relays and 8 Cu-Pb/Sn connections, the total systematic uncertainty due to thermal EMFs is

$$B_{\text{EMF}} = \sqrt{2(B_{\text{relay}})^2 + 8(B_{\text{connection}})^2}$$

This would yield a systematic uncertainty contributor due to thermal EMF of

$$B_{\text{EMF}} = \sqrt{2(3\ \mu\text{V})^2 + 8(3\ \mu\text{V})^2} = 9.5\ \mu\text{V}$$

A voltage error sensitivity coefficient should now be developed to convert these systematic uncertainty contributors from voltage to temperature. Once again using the ASME PTC 19.1 definition of sensitivity as the error propagated to the resulting measurement due to a unit error in the measurement parameter, the voltage error sensitivity coefficient can be found using Ohm's Law.

$$R_{\text{unknown}} = \frac{V_{\text{measured}}}{I_{\text{source}}}$$

The sensitivity of resistance to voltage errors is

$$\theta_{R,\,V} = \frac{\partial R}{\partial V} = \frac{1}{I_{\text{source}}}$$

The source current for the 1 kΩ range is 1 mA, therefore

$$\theta_{R,\,V} = \frac{1}{1\ \text{mA}} = 1\,000\ \frac{\Omega}{\text{V}}$$

The sensitivity of the resulting temperature measurement to a voltage error can now be determined as,

$$\theta_{T,\,V} = \theta_{T,\,R}\left(\frac{°\text{F}}{\Omega}\right) \cdot \theta_{R,\,V}\left(\frac{\Omega}{\text{V}}\right)$$

Using the resistance error sensitivity coefficient calculated earlier yields a voltage error sensitivity coefficient of

$$\theta_{T,\,V} = 4.675\,\frac{°\mathrm{F}}{\Omega} \bullet 1\,000\,\frac{\Omega}{\mathrm{V}} = 4\,675\,\frac{°\mathrm{F}}{\mathrm{V}}$$

Multiplying the parasitic voltage systematic uncertainty by the voltage error sensitivity coefficient will convert this error to units of temperature.

$$B_{\mathrm{EMF}}\,(°\mathrm{F}) = B_{\mathrm{EMF}}\,(\mathrm{V}) \bullet \theta_{T,V}$$

Applying this sensitivity to the DAS environmental systematic uncertainty yields the additional systematic uncertainty due to thermal EMFs as

$$B_{\mathrm{EMF}} = (\pm 9.5\ \mu\mathrm{V}) \bullet (4\,675°\mathrm{F/V})$$

$$B_{\mathrm{EMF}} = 0.04°\mathrm{F}$$

This value is the total systematic uncertainty contributor that can be expected due to parasitic voltages or

$$B_{\text{DAS-PV}} = 0.04°\mathrm{F}$$

(c) Composite Methodology Uncertainty. The composite systematic uncertainty due to the measurement methodology uncertainty contributors, $B_{\text{DAS-Method}}$, is obtained by combining all of the individual DAS methodology systematic uncertainty contributions as the root-sum-square. Therefore, the composite systematic uncertainty due to DAS Measurement Methodology effects becomes:

$$B_{\text{DAS-Method}} = \sqrt{(B_{\text{DAS-PR}})^2 + (B_{\text{DAS-PV}})^2}$$

$$B_{\text{DAS-Method}} = \sqrt{(0.00)^2 + (0.04)^2} = 0.04°\mathrm{F}$$

B-2.3.1.6 Composite Systematic Uncertainty Due to DAS Effects. The composite systematic uncertainty due to DAS effects, $B_{\text{DAS-comp}}$, is obtained by combining all of the individual DAS systematic uncertainty contributions as the root-sum-square. Therefore, the composite systematic uncertainty due to DAS effects becomes:

$$B_{\text{DAS comp}} = \sqrt{\begin{array}{l}(B_{\text{DAS-base}})^2 + (B_{\text{DAS-env}})^2 + (B_{\text{DAS-Drift}})^2 \\ + (B_{\text{DAS-Resolution}})^2 + (B_{\text{Method}})^2\end{array}}$$

$$B_{\text{DAS comp}} = \sqrt{(0.10)^2 + (0.09)^2 + (0.00)^2 + (0.00)^2 + (0.04)^2} = 0.14°\mathrm{F}$$

B-2.3.2 Sensor Systematic Uncertainty Contributors. The following paragraphs analyze the identified systematic uncertainty contributors for the four-wire RTD sensor.

B-2.3.2.1 Four-Wire RTD Sensor Base Systematic Uncertainty. The four-wire RTDs are calibrated to within ±0.15°F. Therefore, the base systematic uncertainty associated with the RTD sensor is

$$B_{\text{RTD\_Base}} = \pm 0.15°\mathrm{F}$$

B-2.3.2.2 Environmental Effects. The heat transfer characteristics between the RTD sensor and its surroundings change from calibration conditions to test conditions, introducing additional error into the temperature measurement. It has been assumed that sufficient installation and insulation practices have been strictly followed in order to remove and/or minimize these errors. Based on this assumption the additional systematic uncertainty due to RTD environmental effects becomes

$$B_{\text{RTD-env}} = \pm 0.00°\mathrm{F}$$

B-2.3.2.3 Drift. Post-test calibrations are used to verify the system stability within the accuracy limit of ±0.15°F. Therefore, the additional systematic uncertainty due to RTD drift becomes

$$B_{\text{RTD-drift}} = \pm 0.00°\mathrm{F}$$

B-2.3.2.4 Resolution. The RTD provides an analog signal into the DAS without any signal conditioning. Therefore the resolution associated with the sensor itself is infinite and contributes no uncertainty to the measurement loop.

$$B_{\text{RTD-Resolution}} = \pm 0.00°\mathrm{F}$$

B-2.3.2.5 Measurement Methodology. Due to the measurement methodology required for a four-wire resistance measurement, there will be an additional error associated with the source current applied to the RTD.

Self-heating in an RTD sensor is due to the continuous power dissipated in the sensor, as well as the heat transfer characteristics between the sensor and its surroundings. The magnitude of the self-heating error is calculated as

$$B_{SH} = \frac{P}{SH}\,(°\mathrm{C})$$

where

B_{SH} = self-heating RTD systematic uncertainty

P = power dissipated in the sensor (milliwatts [mW])

SH = RTD self-heating coefficient (mW/°C)

The power dissipated in the sensor is calculated as

$$P = \frac{I^2 \bullet R}{1000}\,(\mathrm{mW})$$

where

I = measurement current (mA)

R = sensor resistance (Ω)

The maximum power dissipation will occur at the maximum temperature reading of 200°F (135.97 Ω), with 0.14 mW.

The self-heating coefficient for standard RTDs is approximately 12 mW/°C (6.67 mW/°F). Therefore, the additional systematic uncertainty contribution due to RTD self-heating is calculated as

$$B_{\text{RTD-Method}} = \frac{P_{\max}}{6.67 \text{ mW/°F}}$$

$$B_{\text{RTD-Method}} = \pm 0.022\text{°F}$$

B-2.3.2.6 Composite Systematic Uncertainty Due to RTD Sensor Effects. The composite systematic uncertainty due to RTD effects, $B_{\text{RTD-comp}}$, is obtained by combining the individual RTD systematic uncertainty contributors using the root-sum-square method. Therefore, the composite systematic uncertainty due to RTD effects becomes:

$$B_{\text{RTD-comp}} = \sqrt{\begin{aligned}&(B_{\text{RTD-Base}})^2 + (B_{\text{RTD-env}})^2 + (B_{\text{RTD-drift}})^2\\ &+ (B_{\text{RTD-Resolution}})^2 + (B_{\text{RTD-Method}})^2\end{aligned}}$$

$$\begin{aligned}B_{\text{RTD-comp}} &= \sqrt{(0.15)^2 + (0.00)^2 + (0.00)^2 + (0.00)^2 + (0.02)^2}\\ &= 0.15\text{°F}\end{aligned}$$

B-2.3.3 Analytical Uncertainty. The measurements and calculations made in the measurement loop are all accounted for in the calibration methodology. Any lack of fit in the conversion of the resistance values to their engineering units (°F) are accounted for in the calibration methodology by performing the calibration over the expected measurement range using several intermediate points. Therefore, no additional systematic uncertainty will be introduced as a result of any calculations performed on the data and

$$B_{\text{Analytical}} = 0.00\text{°F}$$

B-2.3.4 Total Systematic Uncertainty of Measurement Loop. The total systematic uncertainty of the measurement loop will be a combination of the individual systematic uncertainty contributors. The two cases below illustrate the differences and benefits of a loop calibration vs. non-loop calibration on the overall systematic uncertainty.

B-2.3.4.1 Non-Loop Calibrated System. The total systematic uncertainty of the non-loop calibrated DAS is calculated by considering the calibration accuracy, uncertainty due to system application and analytical uncertainty. The overall systematic uncertainty is calculated as:

$$B_{\text{DAS}} = \sqrt{(B_{\text{RTD comp}})^2 + (B_{\text{DAS comp}})^2 + (B_{\text{Analytical}})}$$

$$B_{\text{DAS}} = \sqrt{(0.15)^2 + (0.14)^2 + (0.00)^2} = 0.21\text{°F}$$

B-2.3.4.2 Loop Calibrated System. For systems that are loop calibrated, the base uncertainty of the RTD and DAS are combined into a new base uncertainty that encompasses the entire measurement loop. In this case, for systems loop calibrated to an accuracy of 0.15°F, the composite systematic uncertainty due to DAS effects is recalculated omitting the base uncertainty since this will be included in the base uncertainty for the RTD and will account for the effects of the DAS as well. The resulting overall system uncertainty will be

$$B_{\text{DAS}} = \sqrt{(B_{\text{RTD comp}})^2 + (B_{\text{DAS comp}})^2 + (B_{\text{Analytical}})^2}$$

$$B_{\text{DAS}} = \sqrt{(0.15)^2 + (0.10)^2 + (0.00)^2} = 0.18\text{°F}$$

B-3 UNCERTAINTY OF DC VOLTAGE MEASUREMENT

The following subsections describe the uncertainty calculations for the DC voltage measurements.

B-3.1 System Configuration/Specifications

(a) The following data acquisition system configuration will be examined:

(1) DC voltage inputs (1 to 5 V DC) into a multiplexing data logger with a signal conditioning and A/D conversion and subsequent conversion to engineering units.

(b) The data logger accuracy for the voltage measurement is as follows:

(1) DC voltage: ±(0.005% of reading + 0.0005% of range) for 10 V DC range

(c) The temperature coefficients for the voltage measurement is as follows:

(1) DC voltage: ±(0.001% of reading + 0.0001% of range)/°C

B-3.2 Assumptions

(a) The voltage signals have a total uncertainty of 0.10% of reading. This uncertainty includes all appropriate uncertainty contributors for the sensor providing the voltage signal.

(b) All instruments are installed using good handling practices and correct calibration and measurement techniques are followed.

(c) Circuit connections are made with clean copper-to-copper or copper to lead/tin junctions, and the maximum temperature differential across any connection in the measurement circuit is limited to no more than 1°C.

(d) Thermal equilibrium is obtained for all measurements by exposing the entire system to the same environment and allowing suitable instrument warm-up periods.

(e) Methodology systematic uncertainty due to sensor location or installation technique with respect to the measured parameter, spatial effects, and random uncertainties will not be considered in this calculation. Such

uncertainties require further evaluation using actual test data or site-specific information.

(f) The system is operated at ambient conditions that are ±10°C (18°F) from the calibration conditions.

(g) The system is pre- and post-test calibrated to verify the stability of the system.

(h) Measurements are made under steady-state conditions. Therefore, transient effects will not be considered in this analysis.

B-3.3 Analysis

The following paragraphs identify and analyze the individual uncertainty contributors identified for the overall systematic uncertainty of the measurement loop.

B-3.3.1 DAS Systematic Uncertainty Contributors. The following paragraphs analyze the identified systematic uncertainty contributors for the DAS.

B-3.3.1.1 Base Systematic Uncertainty. The DAS is calibrated to ±(0.005% of reading + 0.0005% of range) accuracy. The largest error as a percent of the reading will occur at the lowest expected reading of 1 V DC. Therefore, the base uncertainty associated with the DAS is

$$B_{\text{Base, DAS}} = \frac{(0.005\% \cdot 1\text{ V} + 0.001\% \cdot 10\text{ V}}{1\text{ V}} \cdot 100 = \pm 0.015\%$$

B-3.3.1.2 Environmental Effects. Operation of the DAS in environmental conditions that differ from those in which it was calibrated can potentially introduce additional uncertainty. Manufacturer's specifications often provide temperature coefficients, which may be used to derate the performance of the instrument based on the expected operating temperature range.

The DAS environmental systematic uncertainty contributor may be calculated from the equation

$$B_{\text{DAS-env}} = TC \cdot \Delta T$$

where

TC = temperature coefficient used to derate the accuracy specifications, given by the manufacturer for the proper resistance range

ΔT = the difference between the ambient temperature range during calibration and the ambient temperature range during operation, evaluated for the worst-case difference

For this example, DAS has a temperature coefficient of

$$TC = [\pm 0.001\% \text{ of reading} + 0.0001\% \text{ of range}]/°C$$

For this analysis, a temperature difference of 10°C is assumed.

Substituting the values of the temperature coefficient and temperature differential of 7°C into the equation for the DAS environmental systematic uncertainty yields

$$B_{\text{DAS-env}} = [\pm(0.001\% \text{ of reading} + 0.0001\% \text{ of range})/°\text{C}] \times [10°\text{C}]$$

$$B_{\text{DAS-env}} = [\pm(0.01\% \text{ of reading} + 0.001\% \text{ of range})]$$

From this expression it can be seen that the maximum environmental error as a percent of the measured voltage exists when the reading is minimized. The maximum DAS environmental systematic uncertainty for the system, (assuming a 1 V DC reading) as a percent of reading is

$$B_{\text{DAS-env}} = \pm\frac{0.006\% \cdot 1\text{ V} + 0.001\% \cdot 10\text{ V}}{1\text{ V}} = 0.016\%$$

B-3.3.1.3 Drift. Post-test calibrations are used to verify the system stability within the accuracy limit of ±0.005% of reading + 0.0005% of range for the DAS. Therefore, the additional systematic uncertainty due to DAS stability is

$$B_{\text{DAS-stability}} = \pm 0.00\%$$

B-3.3.1.4 Measurement Resolution. The resolution effect of the DAS is included in the specifications in Section 2. Therefore, this contributor is included in the base uncertainty and the environmental effects and

$$B_{\text{DAS-Resolution}} = \pm 0.00\%$$

B-3.3.1.5 Measurement Methodology. Parasitic resistances and parasitic voltages introduced as a part of the measurement loop can result in additional uncertainties. It is assumed that proper installation techniques have been followed, effectively eliminating any contributors due to installation effects.

(a) Parasitic Resistance. Parasitic resistances are introduced into the measurement circuit by lead wires, lead wire imbalances, circuit connections, and multiplexing relays. Using proper installation, calibration, and measurement techniques may minimize effects of parasitic resistances. It has been assumed for this analysis that these techniques have been strictly followed in order to minimize these effects.

Connectors present in the measurement circuit have the potential for introducing parasitic resistances. Calibrating the DAS and sensor together as a system serves to eliminate any constant parasitic resistances introduced by the connectors.

Parasitic resistances are introduced into the measurement circuit by the "contact resistance" inherent in all multiplexing relays. Contact resistance values for two wire armature relays are typically less than 1 Ω.

Zeroing the sensor after installation or forcing a known output from the sensor and adjusting the offset coefficient used for the system accordingly can effectively eliminate any of the above effects. This is effective if the voltage signal is linear with respect to the engineering units. Otherwise, the voltage offset provided by the parasitic resistances must be accounted for as an additional systematic uncertainty contributor. For this example, a linear offset is assumed. Therefore, the additional systematic uncertainty introduced by parasitic resistances is

$$B_{\text{DAS-PR}} = \pm 0.00\%$$

(b) Parasitic Voltages. Parasitic voltages are introduced into the measurement circuit by noise and thermal EMFs. The effects of parasitic voltages may be minimized and/or removed by using proper installation, calibration, and measurement techniques. It has been assumed for this analysis that these procedures have been strictly followed in order to minimize parasitic voltage effects.

The effects of electrostatic and electromagnetic noise are minimized by the use of shielded, twisted pair instrument cable and proper grounding techniques. Also, the DAS is assumed to have a guarded, integrating analog to digital converter, which further reduces external noise effects on measurements. Integration of the input signal is performed at a constant frequency, typically the line frequency, in order to remove all 60 Hz noise from the signal.

Thermal EMFs are minimized by use of clean copper to copper connections and by minimizing temperature gradients in the measurement circuit. The two most common sources of thermal EMFs in the measurement circuit are across circuit connections and multiplexer relays.

Assuming no more than a 1°C temperature differential across any connection and assuming all connections are either clean Cu-Cu or Cu-Pb/Sn, the maximum potential thermal emf across any junction is

$$B_{\text{connection}} = 3\ \mu\text{V}$$

The DAS uses two wire armature relays in its multiplexers. The thermal electric potential of a two wire armature relay is <3 μV, therefore the maximum potential emf across any multiplexer relay is

$$B_{\text{relay}} = 3\ \mu\text{V}$$

Since the magnitude and sign of the thermal EMFs across each connection and relay are dependent upon both the quality of the junction and the temperature differential across the junction, the systematic uncertainty contributor at each junction will be considered independent. The total systematic uncertainty due to parasitic voltages can be estimated as the square root of the sum of the squares of the systematic uncertainty at each junction. For the measurement circuit consisting of one multiplexer relay and four Cu-Pb/Sn connections, the total systematic uncertainty due to thermal EMFs is

$$B_{\text{EMF}} = \sqrt{(B_{\text{relay}})^2 + 4(B_{\text{connection}})^2}$$

This would yield a systematic uncertainty due to thermal EMFs of

$$B_{\text{EMF}} = \sqrt{(3\ \mu\text{V})^2 + 4(3\ \mu\text{V})^2} = 6.71\ \mu\text{V}$$

The maximum uncertainty in the measurement due to the thermal EMF as a percent of reading will be at the minimum reading of 1 V.

$$B_{\text{EMF}} = \frac{\pm 6.71\ \mu\text{V}}{1\ \text{V}}\, 100\% = 0.0007\%$$

(c) Composite Methodology Uncertainty. The composite systematic uncertainty due to the measurement methodology contributors, $B_{\text{DAS-Method}}$, is obtained by combining all of the individual DAS methodology systematic uncertainty contributions as the root-sum-square. Therefore, the composite systematic uncertainty due to DAS measurement methodology effects becomes:

$$B_{\text{DAS-Method}} = \sqrt{(B_{\text{DAS-PR}})^2 + (B_{\text{EMF}})^2}$$

$$B_{\text{DAS-Method}} = \sqrt{(0.00\%)^2 + (0.0007\%)^2} = 0.0007\%$$

B-3.3.1.6 Composite Systematic Uncertainty Due to DAS Effects. The composite systematic uncertainty due to DAS effects, $B_{\text{DAS-comp}}$, is obtained by combining all of the individual DAS systematic uncertainty contributors as the root-sum-square. Therefore, the composite systematic uncertainty due to DAS effects becomes:

$$B_{\text{DAS comp}} = \sqrt{(B_{\text{DAS-env}})^2 + (B_{\text{DAS-Drift}})^2 + (B_{\text{DAS-Resolution}})^2 + (B_{\text{Method}})^2}$$

$$B_{\text{DAS comp}} = \sqrt{(0.016)^2 + (0.00)^2 + (0.00)^2 + (0.0007)^2} = 0.016\%$$

B-3.3.2 Sensor Systematic Uncertainty Contributors. The following paragraphs analyze the identified systematic uncertainty contributors for the DC voltage sensor.

B-3.3.2.1 DC Voltage Base Systematic Uncertainty. The uncertainty for the voltage signal is ±0.10% of reading. Therefore, the base uncertainty associated with the voltage sensor is

$$B_{\text{Base, DC v}} = \pm 0.10\%$$

B-3.3.2.2 Environmental Effects. It is assumed that sufficient installation practices have been strictly followed in order to remove and/or minimize any errors due to installation effects. This includes installing the sensor in the appropriate location and orientation to remove any associated contributors. Based on this assumption, the additional systematic uncertainty due to DC voltage sensor environmental effects becomes

$$B_{\text{DC v-env}} = \pm 0.00\%$$

B-3.3.2.3 Drift. Post-test calibrations are used to verify the system stability within the accuracy limit of ±0.10% of reading. Therefore, the additional systematic uncertainty due to drift becomes

$$B_{\text{DC v-drift}} = \pm 0.00\%$$

B-3.3.2.4 Resolution. The sensor provides an analog signal into the DAS without any signal conditioning. Therefore the resolution associated with the sensor itself is infinite and contributes no uncertainty to the measurement loop.

$$B_{\text{DC v-Resolution}} = \pm 0.00\%$$

B-3.3.2.5 Measurement Methodology. There are no additional uncertainty contributors for the sensor due to the measurement methodology. It is assumed that the instrument is installed and operated using proper care and according to the manufacturer's guidance. Therefore,

$$B_{\text{DC v-Method}} = 0.00\%$$

B-3.3.2.6 Composite Systematic Uncertainty Due to DC Voltage Sensor Effects. The composite systematic uncertainty due to sensor effects, $B_{\text{DC v-comp}}$, is obtained by combining the individual sensor systematic uncertainty contributors using the root-sum-square method. Since there were no additional contributors identified, the resulting composite systematic uncertainty due to the sensor effects is

$$B_{\text{DC v-comp}} = 0.00\%$$

B-3.3.3 Analytical Uncertainty. The measurements made in the measurement loop are all accounted for in the calibration methodology. Any lack of fit in the conversion of the voltage values to their engineering units are accounted for in the calibration methodology by performing the calibration over the expected measurement range using several intermediate points. Therefore, no additional uncertainty will be introduced as a result of any calculations performed on the data and

$$B_{\text{Analytical}} = 0.00\%$$

B-3.3.4 Total Systematic Uncertainty of Measurement Loop. The total measurement uncertainty of the measurement loop is calculated by considering the calibration accuracy, uncertainty due to system application and analytical uncertainty. The overall system uncertainty is calculated as:

$$B_{\text{DAS}} = \sqrt{(B_{\text{base, DAS}})^2 + (B_{\text{base, RTD}})^2 + (B_{\text{RTD comp}})^2 + (B_{\text{DAS comp}})^2 + (B_{\text{Analytical}})}$$

$$B_{\text{DAS}} = \sqrt{(0.0.015)^2 + (0.10)^2 + (0.00)^2 + (0.016)^2 + (0.00)^2} = 0.10\%$$

B-4 UNCERTAINTY OF DIGITAL SIGNAL INPUT

The following subsections describe the uncertainty calculations for the digital signal inputs.

B-4.1 System Configuration/Specifications

The following data acquisition system configuration will be examined:

(a) digital signal inputs into a multiplexing data logger with no signal conditioning or A/D conversion. The signals are read directly in engineering units.

B-4.2 Assumptions

(a) All instruments are installed using good handling practices and correct calibration and measurement techniques are followed.

(b) Methodology systematic uncertainty due to sensor location or installation technique with respect to the measured parameter, spatial effects, and random uncertainties will not be considered in this calculation. Such uncertainties require further evaluation using actual test data or site-specific information.

(c) The system is pre- and post-test calibrated to verify the stability of the system.

(d) Measurements are made under steady-state conditions. Therefore transient effects will not be considered in this analysis.

B-4.3 Analysis

The following paragraphs identify and analyze the individual uncertainty contributors identified for the overall systematic uncertainty of the measurement loop.

B-4.3.1 DAS Systematic Uncertainty Contributors. No signal conditioning or manipulation is performed on the signal input. Therefore, there will be no uncertainty in the signal due to the DAS. Because no signal conditioning or manipulation occurs within the DAS, there will be no effects due to changes in the environment, drift or resolution. The only factor that can influence the digital signal will be effects due to measurement methodology effects as discussed in para. B-4.3.1.1.

B-4.3.1.1 Measurement Methodology. Digital signals can be influenced by a variety of factors including external signal noise and wiring methodologies. These effects are minimized by using standard industry practices for installing lines and cables carrying the digital signal and ensuring that the communications protocols are appropriate for the environment. For example, the recommended cable length for signals sent via RS232 communications is no longer than 35 ft. Routing signals through cables improperly run or through longer lengths can result in degradation in signal strength or quality, interrupting the data stream. Proper pre-test equipment checks will help ensure that all digital signals are working properly. Therefore,

$$B_{\text{DAS, Method}} = 0.00\%$$

B-4.3.1.2 Composite Systematic Uncertainty Due to DAS Effects. Since no uncertainty contributors have been identified for this example that contribute any additional systematic uncertainty to the measurement loop, the composite uncertainty due to DAS effects is

$$B_{\text{DAS, comp}} = 0.00\%$$

B-4.3.2 Sensor Systematic Uncertainty Contributors. The following subsections analyze the identified systematic uncertainty contributors for the digital signal input.

B-4.3.2.1 Digital Signal Base Uncertainty. The source for the digital signal is calibrated to ±0.10% of reading. Any signal conditioning provided by the device is assumed to be included in the calibration methodology. Therefore, the base uncertainty associated with the digital input sensor is

$$B_{\text{Base, digital}} = \pm 0.10\%$$

B-4.3.2.2 Environmental Effects. It is assumed that sufficient installation practices have been strictly followed in order to remove and/or minimize any errors due to installation of the sensor and its output. Based on this assumption the additional systematic uncertainty due to digital sensor environmental effects becomes

$$B_{\text{digital-env}} = \pm 0.00\%$$

B-4.3.2.3 Drift. Post-test calibrations are used to verify the system stability within the accuracy limit of ±0.10% of reading. Therefore, the additional systematic uncertainty due to drift becomes

$$B_{\text{digital-drift}} = \pm 0.00\%$$

B-4.3.2.4 Resolution. The digital signal base uncertainty is assumed to include any effects from the resolution of the A/D conversion. Therefore,

$$B_{\text{digital-Resolution}} = \pm 0.00\%$$

B-4.3.2.5 Measurement Methodology. There are no additional uncertainty contributors for the sensor due to the measurement methodology. It is assumed that the instrument is installed and operated using proper care and according to the manufacturer's guidance. Therefore,

$$B_{\text{digital-Method}} = 0.00\%$$

B-4.3.2.6 Composite Systematic Uncertainty Due to Digital Sensor Effects. The composite systematic uncertainty due to sensor effects, $B_{\text{digital-comp}}$, is obtained by combining the individual sensor systematic uncertainty contributions using the root-sum-square method. Since there were no additional contributors identified, the resulting composite systematic uncertainty due to the sensor effects is

$$B_{\text{digital-comp}} = 0.00\%$$

B-4.3.3 Analytical Uncertainty. For this example, the digital signals are provided in terms of engineering units requiring no post acquisition conversion. Therefore,

$$B_{\text{Analytical}} = 0.00\%$$

B-4.3.4 Total Systematic Uncertainty of Measurement Loop. The total measurement uncertainty of the measurement loop is calculated by considering the systematic uncertainty contributors from the DAS, sensor input, and analytical uncertainty. For this example, no uncertainty contributors other than the base uncertainty of the digital sensor have been identified. Therefore, the total systematic uncertainty of the measurement loop is

$$B_{\text{Digital}} = 0.10\%$$

B-5 CONCLUSIONS

The analysis presented above shows three common types of measurements made using standard installation and measurement practices. The following conclusions can be drawn.

B-5.1 Four-Wire RTD Measurements

From the analysis in Section 2, it can be seen that some contributors are more significant than others. In particular, it should be noticed that the only significant contributors to the overall uncertainty were the calibration uncertainty, the calibration method (loop calibration vs. non-loop calibration), and the environmental effect on the data acquisition system. The difference as to whether the individual contributors are significant will depend on the desired parameter measurement uncertainty. The more stringent the requirements, the more detail the uncertainty analysis will require. For example, if an uncertainty of 0.5°F is specified for temperature measurement, then much of the analysis in Section 2 above can be shown to result in negligible uncertainty with respect to the target uncertainty. Once the base uncertainty and any major contributors are determined to result in an uncertainty significantly less than the target uncertainty, then the target uncertainty of 0.5°F could be used as the parameter uncertainty without a detailed analysis of the remaining contributors. If, however, a tighter uncertainty is required, then more detail is required. For example, if the target uncertainty for the four-wire RTD system is 0.2°F, then the loop calibrated systematic uncertainty or a lower operating ambient temperature would be required in order to meet the acceptance criterion. Additionally, the temperature measurement uncertainty can be reevaluated at various temperatures to allow for uncertainty values representative of varying test conditions to be determined. Regardless of the approach used, the process should be the same in that all uncertainty contributors should be identified and then either justified as negligible or evaluated.

B-5.2 DC Voltage Measurements

From the analysis in Section 3, it can be seen that, in this instance, the uncertainty in the measurement loop is insignificant compared to the uncertainty of the sensor signal and can essentially be ignored. Because the base systematic uncertainty of the DAS is an order of magnitude less than the base systematic uncertainty of the sensor, it is likely that any additional contributors will also be on a similar order of magnitude. If, however, the uncertainty of the input signal was lower or the base systematic uncertainty of the DAS were higher, then the contributors from the DAS would become significant in the overall uncertainty calculation.

B-5.3 Digital Inputs

From the analysis in Section 4, it can be seen that the digital signal device requires the least effort to analyze. This is because the DAS functions only to read the data from the device and store the read value(s) with no manipulation. Since no data manipulation or signal conditioning occurs, there are no valid uncertainty contributors provided the instrumentation is installed properly and the communications are functionally checked for any signal degradation.

B-5.4 Summary

The impact of the varying uncertainty contributors varies significantly with the measurement type and the quality of the DAS being used. Installation, usage and calibration practices can also play a significant role in the overall uncertainty of a system. The practice of post-test calibration, for example eliminates the need for examining the effects of instrument drift provided the instrument passes the post-test calibration check. Pretest instrument diagnostics also help eliminate any contributions due to the installation effects on the system. As shown above, digital signals are the least influenced by outside factors when properly used, however it is not always practical or cost effective to provide a digital interface for every sensor input. In addition, the acceptance criteria for uncertainty may not require the lower uncertainties typically associated with digital systems.

Selection of a DAS for use in testing should take into account the uncertainty requirements of the test as well as usability of the system (e.g., ease of use, installation requirements, cost, etc.). Selection of a DAS along with the measurement strategy should occur as a part of the test design so that the final test strategy optimizes the test effort with respect to test uncertainty, instrumentation requirements, cost, and staffing requirements. Intermediate and advanced systems may have the capability for real-time test data analysis or performing diagnostic calculations such as stability determinations or heat balances, reducing the effort required for the test conduct and/or subsequent analysis of test data. Stringent uncertainty requirements will require either more accurate components and better defined measurement strategies, a more detailed uncertainty analysis, or both. As discussed in subsection 6-1, all uncertainty contributors should be identified and either justified as being negligible or evaluated and included in the overall uncertainty. As noted in para. 6-1.1, a ratio of 3.3 to 1 for a single contributor can be shown to have a negligible effect on the resulting uncertainty. Several contributors whose values are of a similar magnitude, however, may not result in a negligible contribution when considered together. Therefore, the omission of any identified uncertainty contributor must be made with care.

NONMANDATORY APPENDIX C
FLOATING-POINT DATA REPRESENTATION (IEEE 754-1985)

Many data acquisition devices have the capability to acquire data directly as a floating-point number. Since the data in its raw form is likely to be in binary format, it may be necessary to convert it to a readable floating-point value. The following is a description of the floating-point representation according to the IEEE 754 standard.

The value consists of three components: the sign bit, the exponent, and the mantissa. The following shows how the three components are arranged within a 32-bit binary number.

S EEEEEEEE MMMMMMMMMMMMMMMMMMMMMMM

E = exponent
M = mantissa
S = sign bit (0 for positive, 1 for negative)

The floating-point value, N is calculated in eq. (C-1). Note that the exponent is first adjusted by subtracting −127 to allow for negative exponents, and the mantissa is adjusted by appending a "1." as a prefix to integer represented by the 23-bit binary number.

$$N = (-1)^{S} \times 2^{(E-127)} \times 1.M \tag{C-1}$$

Example:
0 10000010 01010000000000000000000

E = 130
M = 3125
S = 0 (positive)

$$N = (-1)^{0} \times 2^{(130-127)} \times 1.3125 = 10.5$$

Although this is the standard as prescribed by IEEE, some hardware and software platforms may use slight variations of the above floating-point representation.

NONMANDATORY APPENDIX D
SAMPLE DATA ACQUISITION SYSTEM OUTPUT EXAMPLE

Table D-1 illustrates some of the data management requirements and recommendations of Section 7. Although the proper formatting of data output seems trivial, it is actually quite essential to conducting quality tests and providing adequate traceability for future use of the test data.

Table D-1 Sample Data

Start	12/13/2002 11:15				
End	12/13/2002 11:45				
	01PRESS2	01SE55550	01TEMP14	C01TEMP14	01TEMP14_CORR [Note (1)]
Data Time Stamp	Exhaust Temperature, °F	Turbine Speed, RPM	Ambient Temperature, °F [Note (4)]	Ambient Temperature Calibration Correction, °F	Corrected Ambient Temperature [Note (2)], °F [Note (3)]
13-Dec-02 11:15:00	1,093.54	3,602.35	59.68	−0.211	59.47
13-Dec-02 11:15:30	1,093.57	3,601.56	59.66	−0.211	59.45
13-Dec-02 11:16:00	1,093.61	3,599.87	59.64	−0.211	59.43
13-Dec-02 11:16:30	1,093.64	3,600.80	59.65	−0.211	59.44
13-Dec-02 11:17:00	1,093.68	3,600.54	59.68	−0.211	59.47
13-Dec-02 11:17:30	1,093.71	3,600.71	59.67	−0.211	59.46
13-Dec-02 11:18:00	1,093.76	3,601.04	59.71	−0.211	59.50
13-Dec-02 11:18:30	1,093.83	3,599.40	59.75	−0.211	59.54
13-Dec-02 11:19:00	1,093.89	3,599.80	59.91	−0.212	59.70
13-Dec-02 11:19:30	1,093.96	3,599.44	59.99	−0.213	59.78
13-Dec-02 11:20:00	1,094.02	3,597.75	59.96	−0.213	59.74
13-Dec-02 11:20:30	1,094.08	3,597.53	59.93	−0.213	59.71
13-Dec-02 11:21:00	1,094.42	3,599.67	59.91	−0.212	59.70
13-Dec-02 11:21:30	1,094.93	3,600.68	59.91	−0.212	59.70
13-Dec-02 11:22:00	1,094.93	3,600.99	59.90	−0.212	59.69
13-Dec-02 11:22:30	1,094.93	3,601.53	59.86	−0.212	59.65
13-Dec-02 11:23:00	1,094.93	3,601.40	59.96	−0.213	59.75
13-Dec-02 11:23:30	1,094.94	3,601.27	60.06	−0.213	59.85
13-Dec-02 11:24:00	1,094.94	3,601.14	60.16	−0.214	59.95
13-Dec-02 11:24:30	1,094.94	3,601.02	60.26	−0.215	60.05
13-Dec-02 11:25:00	1,094.95	3,600.89	60.37	−0.215	60.15
13-Dec-02 11:25:30	1,094.95	3,600.66	60.47	−0.216	60.25
13-Dec-02 11:26:00	1,094.92	3,599.99	60.47	−0.216	60.26
13-Dec-02 11:26:30	1,094.85	3,599.12	60.43	−0.216	60.22
13-Dec-02 11:27:00	1,094.79	3,598.61	60.43	−0.216	60.21
13-Dec-02 11:27:30	1,094.72	3,599.48	60.37	−0.215	60.15

NOTES:
(1) Measurement tag name or ID.
(2) Measurement or tag description.
(3) Measurement engineering units.
(4) Raw, uncorrected measurements.

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