

# Mechanical and Thermal Energy Storage Systems

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## Performance Test Codes

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# 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 Code. 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 Code.

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 before starting the test, and preferably before signing the contract, the parties to a commercial test agree 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

ASME PTC 53, Mechanical and Thermal Energy Storage Systems, is a Draft Standard for Trial Use applicable to mechanical and thermal energy storage system(s) (ESS). When the full Code is issued, it will define uniform test procedures and quantifiable test methods for assessing, determining, and reporting the performance of mechanical or thermal ESS across varying technology platforms. ASME PTC 53 is intended to have broad applicability; however, the Code is not intended to overlap the scope of similar codes published by other agencies such as the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) and the Institute of Electrical and Electronics Engineers (IEEE). ASME PTC 53 will cover mechanical and thermal technologies including compressed air, flywheels, thermal storage ranging from molten salts to cryogenic liquids, and pumped hydromechanical energy.

(a) The PTC 53 Committee is issuing as a Draft Standard for Trial Use the first three Sections of the Code to allow current technology developers, engineers, and consumers to consider consistent strategies, methods, and systems for performance testing.

(1) [Section 1](#) describes the scope and object of the Code.

(2) [Section 2](#) describes definitions and terms used in the Code.

(3) [Section 3](#) describes guiding principles for application of the Code.

(b) Sections and Appendices on various unit configurations, data collection and handling requirements, performance parameters, uncertainty analysis, test reports, and more definitive test boundaries for representative ESS applications are currently in development and will be added to the final Code. The following Sections will be added, per the guidance found in ASME PTC 1-2015:

(1) Section 4, Instruments and Methods of Measurement

(2) Section 5, Computation of Results

(3) Section 6, Report of Results

(4) Section 7, Test Uncertainty

The PTC 53 Committee intends to accept comments on the first three Sections of the Code while preparing the remaining Sections.

**Submitting Comments and Proposing Revisions.** Comments and proposals for revision should be directed to the Secretary, PTC 53 Committee using the following form: <http://go.asme.org/PTC53CommentForm>. Any proposals for revision 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.

The comment form contains instructions on how to submit comments.

**Attending Committee Meetings.** The PTC Standards Committee regularly holds meetings and/or telephone conferences that are open to the public. Persons wishing to attend any meeting and/or telephone conference should contact the Secretary of the PTC Standards Committee. Future Committee meeting dates and locations can be found on the Committee Page at <http://go.asme.org/PTCcommittee>.

# ASME PTC COMMITTEE

## Performance Test Codes

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

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# Section 1

## Object and Scope

### 1-1 OBJECT

The objective of this Draft Standard, hereafter referred to as the “Code,” is to establish uniform test methods and procedures for conducting performance tests of mechanical or thermal energy storage system(s) (ESS). An ESS is a system that consumes energy to increase the internal energy of the storage media and releases the stored energy, producing useful power or heat. This Code provides standard test procedures for ESS with the goal to provide the highest level of accuracy consistent with current engineering practice.

This Code provides procedures for measuring the following parameters:

- (a) the quantity of energy input
- (b) the rate of energy input (power)
- (c) the quantity of nonuseful energy flows in/out of the system during input, steady-state storage, and discharge
- (d) the quantity of useful energy output
- (e) the rate of useful energy output (power)

The Code provides quantifiable methods to assess the performance of mechanical or thermal energy storage systems for various technology platforms and applications.

When tests are conducted in accordance with a code, the test results themselves, without adjustment for uncertainty, yield the best available indication of actual performance of the equipment tested within the operational parameters defined in this Performance Test Code (PTC). This Code does not specify means to compare those results to contractual guarantees. Therefore, it is recommended that parties to a commercial test agree on the method to be used for comparing results to commercial guarantees before starting the test.<sup>1</sup> It is beyond the scope of this Code to determine or interpret how such comparisons are made.

This Code is not to be used in troubleshooting equipment. However, this Code can be used to quantify the magnitude of performance anomalies of equipment that is suspected to be performing poorly or to confirm the need for maintenance, if simpler means are not adequate. This Code can be used as a source or reference for simpler routine or special equipment test procedures.

### 1-2 SCOPE

#### 1-2.1 Types of Systems to Which This Code May Apply

This Code applies to mechanical or thermal ESS including, but not limited to, compressed air, flywheel, molten salt, and pumped hydromechanical ESS and sensible, latent, cryogenic, thermochemical, ice-based, or phase-change-material thermal ESS.

ASME PTC 53 applies to the measurement of the performance of an ESS at the specified conditions, with all equipment associated with the system functioning in accordance with those conditions.

An ESS may use any of various media, including, but not limited to, the following:

- (a) thermal energy storage media, such as phase-change media (e.g., liquefied air or water-ice) or sensible heating media (e.g., molten salt or thermal fluids and oils)
- (b) compression media, such as compressed air or springs
- (c) gravitational media, such as pumped hydromechanical energy or railcars on inclines
- (d) chemical media, such as hydrogen or ammonia reactions
- (e) kinetic media, such as flywheels
- (f) electrolytic media, such as flow batteries

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<sup>1</sup> Manufacturers typically provide correction curves or multiplication factors to adjust the performance guarantees for off-design conditions typically encountered during a test.

This Code provides methods to measure energy and material flows to and from an ESS that are relevant to assessment of ESS performance. For example, some ESS may use energy inputs from multiple external sources. Some ESS may also produce by-products, such as water, carbon dioxide, or industrial gases, that may have economic value or disposal costs of interest to users of this Code.

### **1-2.2 Types of Systems to Which This Code Does Not Apply**

Electrical battery storage devices (lead-acid, lithium ion, etc.) have been specifically excluded from this Code since the test procedures for that technology have been defined in test codes promulgated by others.

### **1-3 UNCERTAINTY**

This Code requires an uncertainty analysis in accordance with ASME PTC 19.1. The pretest uncertainty analysis is used to develop unit-specific test procedures that result in meeting an agreed-upon target uncertainty. Typical values of test uncertainties, various unit configurations, and performance parameters are presented in [Section 3](#).

Test uncertainty is an estimate of the limit of error of a test result. It is the interval about a test result that contains the true value with a given probability, or level of confidence. Test uncertainty is based on calculations using statistics, instrumentation information, calculation procedure, and actual test data. Code tests are suitable for use whenever performance must be determined with minimum uncertainty. Code tests are meant specifically for equipment operating in an industrial setting.

### **1-4 REFERENCES**

The following is a list of publications referenced in this Code:

ASME PTC 1, General Instructions

ASME PTC 2, Definitions and Values

ASME PTC 3.1, Diesel and Burner Fuels

ASME PTC 3.2, Solid Fuels

ASME PTC 3.3, Gaseous Fuels

ASME PTC 19.1, Test Uncertainty

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([www.asme.org](http://www.asme.org))

## Section 2

# Definitions and Descriptions of Terms

### 2-1 DEFINITIONS

*charge energy*: the amount of primary energy crossing the test boundary during the charge interval.

*charge interval*: the time duration during which the charging process operates.

*charge loss rate*: the change of the state of charge during a standby interval, expressed as kilowatt-hours per hour.

*charge power*: the rate at which charge energy crosses the test boundary; the charge energy divided by the charge interval.

*charge power rating*: a charge power designated in a test plan (such as maximum, minimum, nominal, or guaranteed) that may be derived from contracts, specifications, nameplates, guarantees, or other sources.

*charge process*: the means by which primary energy is transformed into increased internal energy of the storage medium.

*charge start-up interval*: the time duration of transition from the standby state to the charge power rating.

*discharge depth*: a fraction or percentage equal to 1 minus the minimum state of charge at which the ESS can operate, which may be qualified as maximum, rated, normal, or guaranteed, and/or be referenced to the discharge power rating.

*discharge energy*: the amount of primary energy crossing the test boundary during a discharge interval.

*discharge interval*: the time duration during which the discharge process operates.

*discharge power*: the rate at which discharge energy crosses the test boundary; the discharge energy divided by the discharge interval.

*discharge power rating*: a discharge power indicated in a test plan (maximum, minimum, nominal, guaranteed, etc.), which may be derived from contracts, specifications, nameplates, guarantees, or other sources.

*discharge process*: the means by which internal energy of the storage medium is decreased and transformed into primary energy.

*discharge start-up interval*: the time duration of the transition from the standby state to the discharge power rating.

*energy loss*: the amount of energy leaving the test boundary from the storage container, which decreases the internal energy of the storage medium.

*energy storage system (ESS)*: a system that consumes primary energy to increase the internal energy of a storage medium and releases the stored energy at a later time as primary energy.

*exhaust energy*: the amount of nonprimary energy leaving the test boundary of the ESS during the charge interval or discharge interval.

*fuel energy*: the amount of energy crossing the test boundary during a storage cycle in the form of combustible mass, i.e., the fuel rate multiplied by the higher heating value.

*fuel heat rate*: the fuel energy divided by the discharge energy during a storage cycle, expressed as British thermal units per kilowatt-hour (kilojoules per kilowatt-hour).

*fuel rate*: for solid and liquid fuels, the mass of fuel fired per unit of output. For gaseous fuels, it is defined as cubic feet of gas at 59°F and 14.696 psia (cubic meters at 15°C and 101.325 kPa) per unit of output. Fuel rates should be qualified by reference to the unit of output.<sup>1</sup>

*higher heating value*: heat released from the rapid oxidation of fuel. Heating value of fuels is determined in accordance with the following Codes:

ASME PTC 3.1, Diesel and Burner Fuels

ASME PTC 3.2, Solid Fuels

ASME PTC 3.3, Gaseous Fuels

<sup>1</sup> Taken from ASME PTC 2-2001 (R2014), Definitions and Values.

Each Code will specify using either the higher or lower heating value, typically expressed as British thermal units per pound mass (kilojoules per kilogram).

Water vapor is one of the products of combustion for all fuels that contain hydrogen. The higher heating value of a fuel depends on whether this water vapor is allowed to remain in the vapor state or is condensed to liquid. In a bomb calorimeter, the products of combustion are cooled to the initial temperature and all of the water vapor formed during combustion is condensed to liquid. This gives the higher, or gross, heating value of the fuel with the heat of vaporization included in the reported value.<sup>1</sup>

*incidental material*: the amount of mass crossing the test boundary into the storage container during the standby state, which may increase the internal energy of the storage medium.

*internal energy*: a state variable; its change from one state to another is independent of the process that produces the change. Internal energy changes, rather than absolute values, are important. Internal energy may be set to any convenient base. For steam, this base has been set at the triple point, 32°F and 0.0891 psia (273.15 K and 611.2 Pa). The symbol for internal energy is  $u$ , and it is expressed as British thermal units per pound mass (joules per kilogram).<sup>1</sup>

*material loss*: the amount of mass leaving the test boundary from the storage container, which decreases the internal energy of the storage medium.

*overall efficiency*: the discharge energy divided by the sum of charge energy, fuel energy, secondary energy, and standby energy during a storage cycle, expressed as a percentage.

*primary energy*: the principal form in which energy is delivered to and from the ESS.

*primary energy rate*: the charge energy divided by the discharge energy during a storage cycle, expressed as kilowatt-hours per kilowatt-hour.

*primary material*: the principal form in which mass is delivered to and from the ESS.

*ramp rate*: the rate of change of charge power or discharge power of an ESS.

*rated discharge energy*: the discharge energy delivered from the ESS designated in a test plan (such as maximum, minimum, nominal, or guaranteed), which may be derived from contracts, specifications, nameplates, guarantees, or other sources.

*secondary energy*: the amount of nonfuel energy and/or nonprimary energy entering the ESS during a storage cycle.

*secondary energy rate*: the secondary energy divided by the discharge energy during a storage cycle, expressed as British thermal units per kilowatt-hour (kilojoules per kilowatt-hour).

*standby energy*: the amount of primary energy or fuel energy crossing the test boundary during the standby state. Standby energy may increase or maintain the internal energy of the storage medium or may be parasitic.

*standby interval*: a time duration during which the ESS is in the standby state.

*standby power*: the rate at which standby energy crosses the test boundary; the standby energy divided by the standby interval.

*standby state*: a condition in which neither the charging process nor the discharging process occurs.

*state of charge*: the fraction of rated discharge energy present in the ESS.

*storage container*: a vessel, tank, reservoir, cavern, or other prescribed volume that holds primary material within the ESS.

*storage cycle*: a sequence comprising the charge process, a standby state, and the discharge process in which the state of charge is the same at the beginning and end of the sequence.

*storage medium*: the mechanical, chemical, or thermal material within the energy storage system whose internal energy is changed.

## Section 3 Guiding Principles

### 3-1 INTRODUCTION

This Section provides guidance on performance testing of mechanical or thermal energy storage system(s) (ESS) and outlines the steps required to plan, conduct, and evaluate a Code test of ESS performance. The subsections discuss the following:

- (a) test plan ([subsection 3-2](#))
- (b) test preparations ([subsection 3-3](#))
- (c) conduct of test ([subsection 3-4](#))
- (d) calculation and reporting of results ([subsection 3-5](#))

This Code includes procedures for testing the ESS to determine various types of test goals. It also provides specific instructions for multiple-party tests conducted to satisfy or verify guaranteed performance specified in commercial agreements.

#### 3-1.1 Test Goals

The object of the test shall be agreed to by all parties and shall be defined in writing before the test(s) commence. Tests may be designed to satisfy different goals, such as

- (a) to ascertain contractual performance for a newly installed ESS
- (b) to perform acceptance testing
- (c) to determine absolute performance
- (d) to determine comparative performance
- (e) to determine performance at specific operating condition(s) or with certain fixed parameters

#### 3-1.2 General Precaution

Reasonable precautions should be taken when preparing to conduct a Code test. Indisputable records shall be kept to identify and distinguish the equipment to be tested and the exact method of testing selected. Descriptions, drawings, or photographs may all be used to give a permanent, explicit record. Instrument location shall be predetermined, agreed to by the parties to the test, and described in detail in test records. Redundant calibrated instruments should be provided for instruments susceptible to in-service failure or breakage.

#### 3-1.3 Agreements and Compliance With Code Requirements

This Code is suitable for use whenever performance must be determined with minimum uncertainty. Strict adherence to the requirements specified in this Code is critical to achieving that objective.

#### 3-1.4 Acceptance Tests

This Code may be incorporated by reference into contracts to serve as a means to verify commercial guarantees for ESS such as storage capacity, energy input, and energy output. If this Code is used for guarantee acceptance testing or for any other tests where there are multiple parties represented, those parties shall mutually agree on the exact method of testing and the methods of measurement, as well as any deviations from the Code requirements.

**3-1.4.1 Prior Agreements.** Prior to any test, there shall be agreement on the exact method of testing and the methods of measurement. The parties to the test shall agree on all material issues not explicitly prescribed by this Code, as identified in [para. 3-2.3](#) and throughout the Code, including

- (a) location and timing of the test
- (b) confidentiality of test results
- (c) number of copies of test results
- (d) organization of personnel, including designation of the engineer in responsible charge of the test

- (e) intent of the contract or specification if ambiguities or omissions appear evident
- (f) pretest inspections
- (g) modifications to the test plan based on preliminary testing

**3-1.4.2 Data Records and Test Log.** For all acceptance and other official tests, a complete set of data and a complete copy of the test log shall become the property of each of the parties to the test. As the only evidence of actual test conditions, the original log; data sheets, files, and disks; recorder charts; tapes; etc., shall permit clear and legible reproduction. Copying by hand is not permitted. The completed data records shall include the date and time of day the observations were recorded. The observations shall be the actual readings without application of any instrument corrections. The test log should constitute a complete record of events including details that at the time may seem trivial or irrelevant. Erasures, destruction, or deletion of any data record, page of the test log, or recorded observation is not permitted. If any corrections are made, the alteration shall be entered so that the original entry remains legible and an explanation for the change is included. For manual data collection, the test observations shall be entered on carefully prepared forms that constitute original data sheets authenticated by the observers' signatures. For automatic data collection, printed output or electronic files shall be authenticated by the test coordinator and other representatives of the parties to the test. When no paper copy is generated, the parties to the test shall agree in advance to the method used for authenticating, reproducing, and distributing the data. The electronic data files shall be copied onto tape, disk, or other suitable storage media and distributed to each party to the test. The data files shall be in a format that is easily accessible to all. Data residing on a machine should not remain there unless a permanent backup copy is made.

**3-1.4.3 Analysis and Interpretation.** During the conduct of a test, or during the subsequent analysis or interpretation of the observed data, an obvious inconsistency may be found. If so, reasonable effort should be made to adjust or eliminate the inconsistency. Failing this, test runs should be repeated.

### 3-1.5 Test Boundary

The test boundary identifies the energy streams that must be measured to calculate corrected results. The test boundary is an accounting concept used to define the streams that must be measured to determine performance. All input and output energy streams required for test calculations shall be determined with reference to the point at which they cross the boundary. Energy streams within the boundary need not be determined unless they verify base operating conditions, facilitate determination of the state of charge, or relate functionally to conditions outside the boundary.

The methods and procedures of this Code have been developed to provide flexibility in defining the test boundary for a test. The test boundary is to be defined for the specific test objective.

For this Code to apply, the test boundary must encompass a discrete ESS. This means that all energy streams that cross the boundary shall be accounted for.

For a particular test, the specific test boundary shall be established by the parties to the test. Some or all of the typical streams required for common ESS are shown in [Figure 3-1.5-1](#).

In the figure, the solid lines indicate the streams crossing the test boundary for which some or all of the mechanical energy, electrical energy, heat, chemical energy, mass flow rate, thermodynamic conditions, and chemical analysis shall be determined to calculate the results of an overall ESS performance test.

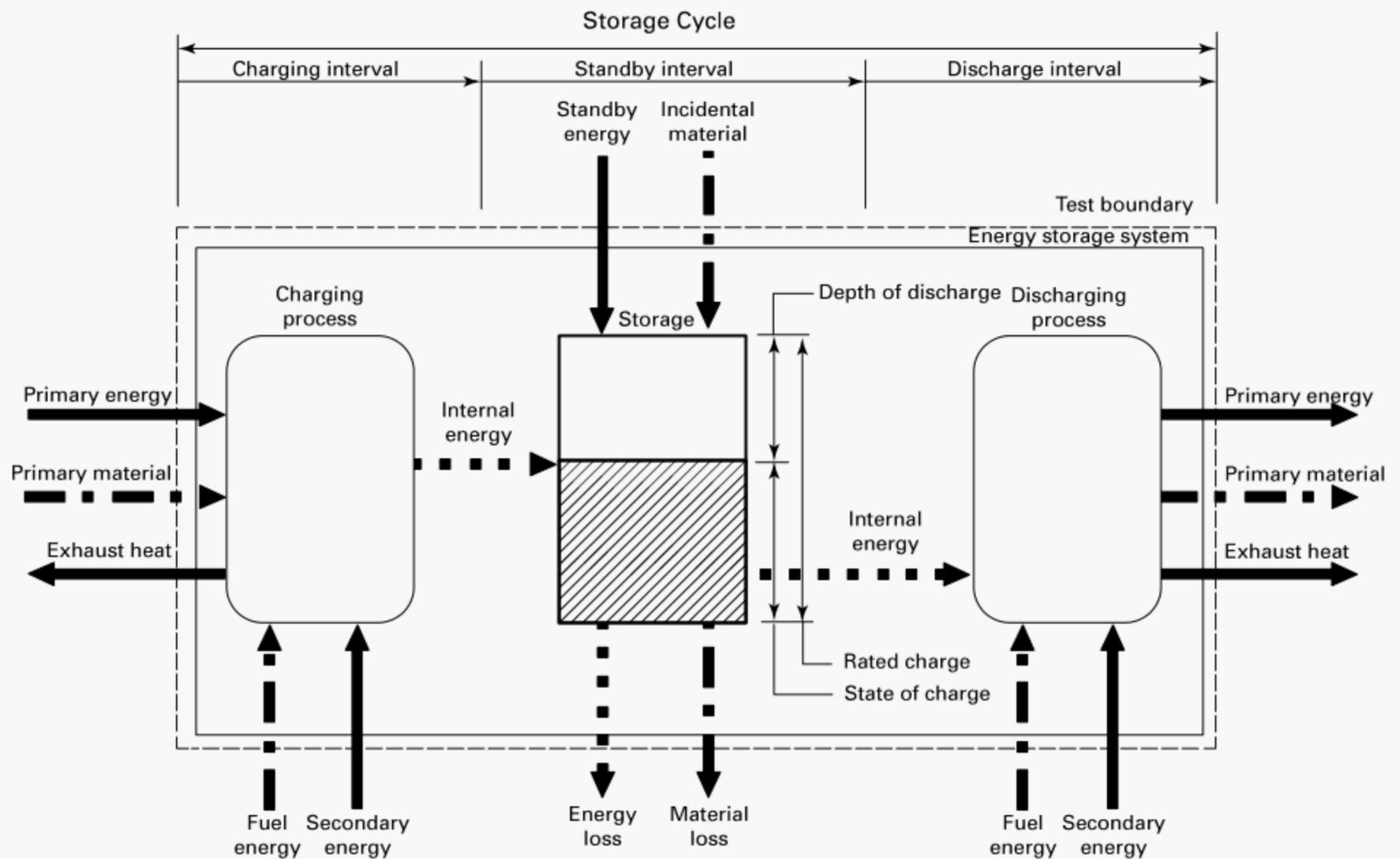
Determination of emissions is outside the scope of this Code.

### 3-1.6 Required Measurements

Some flexibility is required by this Code in defining the test boundary, since it is somewhat dependent on a particular ESS design. This Code does not exclude the use of the ESS instrumentation and distributed control system (DCS) for recording primary measurements; however, such use requires extra care. Factory calibration of instrumentation generally is not to the standard required by this Code for performance testing. Additionally, the DCS is not designed to be used as a Code-level data acquisition system. If the DCS is to be used, the test team must understand the compression (number of significant figures recorded) and dead band settings within the DCS or data history, the uncertainty of analog-to-digital conversions, and any algorithms that impact the readings and their effect on uncertainty within the DCS.

**3-1.6.1 Primary Energy Input.** Measure or calculate energy flows at the point where they cross the test boundary. The test boundary would typically be where energy enters the ESS; however, the actual measurement may be taken upstream or downstream of that point if a better measuring location is available and the process conditions at the metering point are equivalent to, or can be accurately corrected to, the conditions at the test boundary.

Figure 3-1.5-1 Generic Test Boundary



**3-1.6.2 Secondary Energy Inputs.** Secondary energy inputs to the ESS may include, but are not limited to, process energy return, makeup, low-energy external heat recovery, and auxiliary power. Measurements to determine the process conditions and/or energy flows are required for correction to the base reference conditions.

**3-1.6.3 Ambient Conditions.** The pressure, temperature, and humidity, as applicable, shall be determined for the air used in ESS components. The measurements of these properties shall be made at the plane representative of the air properties where the air enters each ESS component. The measurement of ambient air properties at a single location or multiple locations upstream of the plant is not an acceptable alternative.

**3-1.6.4 Primary Energy Output.** The primary energy output from an ESS is the output for the ESS's specified primary use. The criteria for selection of the specific measurement points are based on a determination of the lowest achievable uncertainty.

**3-1.6.5 Secondary Energy Outputs.** Secondary energy outputs are other ESS outputs, including losses. Secondary energy outputs shall be determined to calculate the results.

### 3-1.7 Criteria for Selection of Measurement Locations

Measurement locations are selected to provide the lowest level of measurement uncertainty. The preferred location is at the test boundary, but only if that is the best location for determining required parameters.

### 3-1.8 Specific Required Measurements

The specific measurements required for a test depend on the particular ESS design and the test boundary required to meet the specific test intent.

### 3-1.9 Application of Corrections

The calculation of results for any ESS described by this Code requires adjusting the test-determined values of energy input and power by the application of additive and multiplicative correction factors. The general forms of these equations are as follows:

$$P_{\text{discharge,corr}} = (P_{\text{discharge,meas}} + \text{additive } P \text{ corrections}) \times (\text{multiplicative } P \text{ corrections})$$

$$\text{HR}_{\text{fuel,corr}} = \frac{E_{\text{fuel,meas}} + \text{additive } E_{\text{fuel}} \text{ corrections}}{E_{\text{discharge,meas}} + \text{additive } E_{\text{discharge}} \text{ corrections}} \times (\text{multiplicative HR corrections})$$

$$\eta_{\text{corr}} = \frac{E_{\text{discharge,meas}} + \text{additive } E \text{ corrections}}{E_{\text{charge,meas}} + E_{\text{fuel,meas}} + E_{\text{sec,meas}} + E_{\text{stby,meas}} + \sum E \text{ additive corrections}} \times (\text{multiplicative } \eta \text{ corrections})$$

where

additive  $E_{\text{discharge}}$  corrections = correction factors to  $E_{\text{discharge,meas}}$  that are additive in nature

additive  $E_{\text{fuel}}$  corrections = correction factors to  $E_{\text{fuel,meas}}$  that are additive in nature

additive  $P$  corrections = correction factors to  $P_{\text{discharge,meas}}$  that are additive in nature

$E_{\text{charge,meas}}$  = measured ESS charge energy

$E_{\text{discharge,meas}}$  = measured ESS discharge energy

$E_{\text{fuel,meas}}$  = measured ESS fuel energy

$E_{\text{sec,meas}}$  = measured ESS secondary energy

$E_{\text{stby,meas}}$  = measured ESS standby energy

$\text{HR}_{\text{fuel,corr}}$  = corrected fuel heat rate

multiplicative HR corrections = correction factors to  $\text{HR}_{\text{fuel,corr}}$  that are multiplicative in nature

multiplicative  $P$  corrections = correction factors to  $P_{\text{discharge,meas}}$  that are multiplicative in nature

multiplicative  $\eta$  corrections = correction factors to  $\eta$  that are multiplicative in nature

$P_{\text{discharge,corr}}$  = corrected ESS discharge power

$P_{\text{discharge,meas}}$  = measured ESS discharge power

$\eta$  = overall efficiency

$\eta_{\text{corr}}$  = corrected overall efficiency

The format of the general equations identifies and represents the various corrections to measured performance and mathematically decouples them so that they can be applied separately. The correction factors are also identified as being necessary due to operational effects for which corrections are allowable, such as those caused by changes in ESS process flows and those that are necessary due to uncontrollable external effects.

While these correction factors are intended to account for all variations from base reference conditions, it is possible that ESS performance could be affected by processes or conditions not foreseen at the time this Code was written. In this case, additional correction factors, either additive or multiplicative, would be required.

All correction factors must result in no correction if all test conditions are equal to the base reference conditions. Test correction curves should reflect the final control settings.

### 3-1.10 Design, Construction, and Start-up Considerations

During the design phase of the ESS, consideration should be given to accurately conducting acceptance testing for overall performance of the specific type of ESS.

Consideration should also be given to the requirements of instrumentation accuracy, calibration, and recalibration documentation requirements, and the location of permanent plant instrumentation to be used for testing. Adequate provisions for installation of temporary instrumentation where plant instrumentation is not adequate to meet the requirements of this Code shall also be considered during the design stages. For example, all voltage transformers (VT) and current transformers (CT) used for power measurement should be calibrated.

If the electrical, mechanical, or thermal hosts are unable to accept stored energy output from the ESS, then other provisions shall be made to maintain the test values within appropriate permissible deviations from design.

## 3-2 TEST PLAN

A detailed test plan shall be prepared prior to conducting a Code test to document all issues affecting the conduct of the test and to provide detailed procedures for performing the test. The test plan should include the schedule of test activities, designation and description of responsibilities of the test team, test procedures, and report of results.

For a commercial test, the purchase contract can specify the time limit, following the first dependable commercial operation, within which a field acceptance test should be undertaken. Failing this, an acceptance test should be undertaken within the period stated in this Code but not more than 6 months from the time the equipment is first put into operation, except with written agreement to the contrary. Deterioration from use of the equipment during prior operation, which may adversely affect the results, should be corrected by the purchaser before acceptance tests are conducted, or agreement should be reached for adjusting the test results to compensate for such deterioration. The parties to a commercial test should recognize the impracticality of exact prediction of equipment availability for test purposes and should seek a mutually satisfactory adjustment of any unforeseen situation. An official test for other purposes may be conducted at any time.

### 3-2.1 Schedule of Test Activities

A test schedule should be prepared that includes the sequence of events and anticipated time of test, notification of the parties to the test, test plan preparations, test preparation and conduct, and preparation of the report of results.

### 3-2.2 Test Team

The test plan shall identify the test team organization who will be responsible for the planning and preparation, conduct, analysis, and reporting of the test in accordance with this Code. The test team should include test personnel needed for data acquisition, sampling, and analysis, as well as operations and other groups needed to support the test preparations and implementation, such as supplier representatives, customer(s), witnessing party(ies), and outside laboratory and other services.

A test coordinator shall be designated with the responsibility for the execution of the test in accordance with the test requirements. The test coordinator is responsible for establishing a communication plan for all test personnel and all test parties. The test coordinator shall also ensure that complete written records of all test activities are prepared and maintained. The test coordinator arranges the setting of required operating conditions with the plant operations staff.

When the manufacturer or supplier is a party to the test, they should have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust equipment or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the equipment for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions. Any actions taken shall be documented and immediately reported to all parties to the test.

### 3-2.3 Test Procedures

The test plan should include test procedures that provide details for the conduct of the test. The following are included in the test procedures:

- (a) object of test
- (b) method of operation
- (c) data to be recorded and method of recording and archiving data
- (d) test acceptance criteria for test completion
- (e) base reference conditions
- (f) defined test boundary identifying inputs, outputs, and measurement locations
- (g) complete pretest uncertainty analysis, with systematic uncertainties established for each measurement and an estimate of random uncertainties
- (h) specific type, location, and calibration requirements for all instrumentation and measurement systems and frequency of data acquisition
- (i) sample collection, handling, and analysis method and frequency for ESS process constituents such as fuels, working fluids, and waste streams
- (j) method of ESS laboratories to be used for analyses of ESS process constituents
- (k) required operating disposition or accounting for all internal mechanical energy, thermal energy, and auxiliary power consumers having a material effect on test results
- (l) required levels of equipment cleanliness and inspection procedures
- (m) procedures to account for performance degradation, if applicable

- (n) equipment lineup requirements
- (o) preliminary testing requirements
- (p) pretest stabilization criteria
- (q) required steadiness criteria and methods of maintaining operating conditions within these limits
- (r) allowable variations from base reference conditions and methods of setting and maintaining operating conditions within these limits
- (s) number of test runs and duration of each run
- (t) test start and stop requirements
- (u) data acceptance and rejection criteria
- (v) allowable range of energy input conditions, including constituents and heating value
- (w) correction curves with curve-fitting algorithms, tabular data, or a thermal model
- (x) sample calculations or detailed procedures specifying test-run data reduction and calculation and correction of test results to base reference conditions
- (y) the method for combining test runs to calculate the final test results
- (z) requirements for data storage, document retention, and test report distribution
- (aa) test report format, contents, inclusions, and index

### 3-3 TEST PREPARATIONS

All parties to the test shall be given timely notification, as defined by prior agreement, to allow them the necessary time to respond and to prepare personnel, equipment, or documentation. Updated information should be provided as it becomes known.

A test log shall be maintained during the test to record any occurrences affecting the test, the time of the occurrence, and the observed resultant effect. This log becomes part of the permanent record of the test.

The safety of personnel involved in the test should be considered; for example, the following should be provided:

- (a) safe access to test point locations
- (b) availability of suitable utilities
- (c) safe work areas for personnel

In addition, care of the instrumentation involved in the test should be considered; there may be potential for calibration shifting or damage to instrumentation due to extreme ambient conditions such as temperature or vibration.

Documentation shall be developed or be made available for calculated or adjusted data to provide independent verification of algorithms, constants, scaling, calibration corrections, offsets, base points, and conversions.

#### 3-3.1 Preparation

For acceptance tests, the manufacturer or supplier shall have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. For other official tests, the manufacturer or supplier may, by request of the ESS owner, have reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. The manufacturer, however, is not thereby empowered to alter or adjust equipment or conditions in such a way that regulations, contract, safety, or other stipulations are altered or voided. The manufacturer may not make adjustments to the equipment for test purposes that may prevent immediate, continuous, and reliable operation at all capacities or outputs under all specified operating conditions. Any actions taken shall be documented and immediately reported to all parties to the test.

The remainder of this subsection describes preparations relating to various aspects of testing.

#### 3-3.2 Test Apparatus

Instrumentation used for data collection shall be at least as accurate as instrumentation identified in the pretest uncertainty analysis. This instrumentation can be either permanent plant instrumentation or temporary test instrumentation.

Multiple instruments should be used as needed to reduce overall test uncertainty. The frequency of data collection is dependent on the particular measurement and the duration of the test.

Equipment and instruments shall be examined as necessary to ensure validity of test and operating procedures and suitability of instruments. Calibrated redundant instruments should be provided for instruments that are susceptible to in-service failure or breakage. Redundant instruments should also be considered for the measurement of key parameters that have a large effect on test results or the test uncertainty. Calibration or adequate checks of all instruments must be carried out, and those records and calibration reports shall be made available.

### 3-3.3 Location and Identification of Instruments

Instruments shall be located/positioned to minimize the effect of ambient conditions, e.g., temperature or temperature variations, on uncertainty. Care shall be used in routing lead wires to the data collection equipment to prevent electrical noise in the signal. Manual instruments shall be located so that they can be read with precision and convenience by the observer. All instruments shall be marked uniquely and unmistakably for identification. Calibration tables, charts, or mathematical relationships shall be readily available to all parties to the test. Observers recording data shall be instructed on the desired degree of precision of readings.

### 3-3.4 Frequency and Timing of Observations

The timing of instrument observations shall be determined by an analysis of the time lag of both the instrument and the process so that a correct and meaningful mean value and departure from allowable operating conditions may be determined. Sufficient observations shall be recorded to prove that steady-state conditions existed during the test when this is a requirement. A sufficient number of observations shall be taken to reduce the random component of uncertainty to an acceptable level. To the extent practical, at least 30 readings should be collected to minimize the random error impact on the post-test uncertainty analysis. The use of automated data acquisition systems is recommended to facilitate acquiring sufficient data.

### 3-3.5 Test Conditions

Since an ASME PTC 53 test is not intended to provide detailed information on individual components, this Code does not provide corrections for the effect of any equipment that is not in a clean and functional state. Prior to conducting a test, the cleanliness, condition, and age of the equipment should be determined by inspection of the equipment or review of the operational records, or both. Cleaning should be completed prior to the test, and equipment cleanliness should be agreed upon by the parties to the test.

The ESS should be checked to ensure that equipment and subsystems are installed and operating in accordance with their design parameters and that the plant is ready to test.

## 3-4 CONDUCT OF TEST

This subsection provides guidelines on the actual conduct of the performance test and addresses the following areas:

- (a) starting and stopping tests and test runs ([para. 3-4.7](#))
- (b) methods of operation prior to and during tests ([para. 3-4.8](#))
- (c) adjustments prior to and during tests ([para. 3-4.1](#))
- (d) duration and number of tests and number of readings ([para. 3-4.12](#))
- (e) constancy of test conditions ([para. 3-4.13](#))

### 3-4.1 Adjustments

Once testing has started, adjustments to the equipment that can influence the results of the test should require repetition of any test runs conducted prior to the adjustments. For the purpose of a test, no adjustments should be permissible that are inappropriate for reliable and continuous operation following a test under any and all of the specified outputs and operating conditions.

### 3-4.2 Data Collection

Data shall be taken by automatic data-collecting equipment or by a sufficient number of competent observers. Automatic data-logging and advanced instrument systems shall be calibrated to the required accuracy. No observer shall be required to take so many readings that lack of time may result in insufficient care and precision. Consideration shall be given to specifying duplicate instrumentation and taking simultaneous readings for certain test points to attain the specified accuracy of the test.

### 3-4.3 Operating Philosophy

The tests should be conducted as closely as possible to the specified operating conditions to reduce and minimize the magnitude and number of corrections for deviations from the specified conditions.

### 3-4.4 Permissible Deviations

The equipment tested should be operated to ensure that its performance is bounded by the permissible fluctuations and permissible deviations specified.

### 3-4.5 Preliminary Testing

Preliminary test runs, with records, serve to determine if equipment is in suitable condition to test, to check instruments and methods of measurement, to check adequacy of organization and procedures, and to train personnel. All parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried through to the calculation of results as an overall check of procedure, layout, and organization. If a preliminary test run complies with all the necessary requirements of the ESS test plan, test procedures, and this Code, the test may be used as an official test run within the meaning of this Code. Reasons for a preliminary run include the following:

- (a) to determine whether ESS equipment is in suitable condition for conduct of the test
- (b) to make adjustments, the needs of which were not evident during the preparation of the test
- (c) to check the operation of all instruments, controls, and data acquisition systems
- (d) to ensure that the estimated uncertainty as determined by the pretest analysis is reasonable by checking the complete system
- (e) to ensure the facility's operation can be maintained in a steady-state performance
- (f) to ensure process boundary inputs and outputs, other than those identified in the test requirements, are not constrained
- (g) to familiarize test personnel with their assignments
- (h) to retrieve enough data to fine-tune the control system if necessary

### 3-4.6 Inconsistent Measurements

If any measurement influencing the result of a test is inconsistent with some other similar measurement, although either or both of them may have been made strictly in accordance with the rules of this Code, the cause of the inconsistency shall be identified and eliminated.

### 3-4.7 Starting and Stopping Tests and Test Runs

Acceptance tests shall be conducted as promptly as possible following initial equipment operation and preliminary test runs. Other official tests may be conducted as necessary. The equipment should be operated for sufficient time to demonstrate that intended test conditions, e.g., steady state, have been established. Agreement on procedures and time should be reached before commencing the test.

**3-4.7.1 Starting Criteria.** Prior to starting each performance test, the following conditions shall be satisfied:

(a) *Configuration.* Operation configuration and disposition for testing have been reached in accordance with the agreed-upon test requirements, including

- (1) equipment operation and method of control
- (2) ESS configuration, including required process inputs and outputs
- (3) equipment lineup/cycle isolation
- (4) ESS operation within the bounds of the performance correction curves, algorithms, or programs
- (5) equipment operation within allowable limits
- (6) for a series of test runs, completion of internal adjustments required for repeatability

(b) *Stabilization.* Prior to the start of a test, the ESS shall be operated for a sufficient period of time at test conditions to demonstrate and verify stability. Some parameters measured during an ESS test will not remain constant during the test. Stability, in the context of ESS tests, shall be construed to allow ESS conditions that are expected to vary over time to do so in consistent, predictable ways.

(c) *Data Collection.* The data acquisition system(s) are functioning, and test personnel are in place and ready to collect samples or record data.

**3-4.7.2 Stopping Criteria.** Tests are normally stopped when the test coordinator is satisfied that requirements for a complete test run have been satisfied. The test coordinator should verify that methods of operation during a test, specified in [para. 3-4.9](#), have been satisfied. The test coordinator may extend or terminate the test if the requirements are not met.

Data logging should be checked to ensure completeness and quality. After all test runs are completed, equipment operating only for the purposes of the test should be secured, and operation control should be returned to normal dispatch function, if appropriate.

### 3-4.8 Methods of Operation Prior to and During Tests

All equipment necessary for normal and sustained operation at the test conditions shall be operated during the test or accounted for in the corrections. Intermittent operation of equipment within the test boundary should be accounted for in a manner agreeable to all parties.

### 3-4.9 Operating Mode

The operating mode of the ESS during the test shall be consistent with the goal of the test and form the basis of the correction methodology. The corrections used in the general performance equation and the development of correction curves will be affected by the operating mode of the plant. If a specified corrected or measured load is desired, the ESS control system should be configured to maintain the load during the test. If a specified disposition is required, the control system should maintain the disposition and not make changes to the parameters that should be fixed, such as valve position.

The ESS equipment should be operated in a manner consistent with the basis of design or guarantee, or in a manner that will reduce the overall test uncertainty and will permit correction from test operating conditions to base reference conditions.

Process energy must be controlled in the most stable manner possible. This may require operation in manual mode or venting to the atmosphere if the host is unable to satisfy stability or quantity criteria.

### 3-4.10 Equipment Operation

Equipment required for normal ESS operation shall be operated as defined by the respective equipment suppliers' instructions (to support the overall objectives of the test). Equipment that is necessary for ESS operation or that would normally be required for the ESS to operate at base reference conditions shall be operating or accounted for in determining auxiliary power loads.

Any changes in equipment operation that affect test results by more than 0.25% shall invalidate a test run, or may be quantified and included in test result calculations. A switchover to redundant equipment, such as a standby pump, is permissible.

### 3-4.11 Proximity to Design Conditions

It is desirable to operate the plant during the test as closely as possible to the base reference performance conditions, and within the allowable design range of the ESS and its equipment so as to limit the magnitude of corrections to test parameters.

### 3-4.12 Duration of Runs, Number of Test Runs, and Number of Readings

**3-4.12.1 Duration of Runs.** The duration of a test run shall be of sufficient length that the data reflects the average efficiency and/or performance of the ESS. This includes consideration for deviations in the measurable parameters due to controls, energy inputs, energy outputs, and typical ESS operating characteristics. Depending on the personnel available and the method of data acquisition, it may be necessary to increase the duration of a test to obtain a sufficient number of samples of the measured parameters to attain the required test uncertainty.

**3-4.12.2 Number of Test Runs.** A run is a complete set of observations with the unit at stable operating conditions. A test is a single run or the average of a series of runs.

While multiple runs are not required, the advantages of multiple runs should be recognized. Conducting more than one run

(a) provides a valid method of rejecting bad test runs.

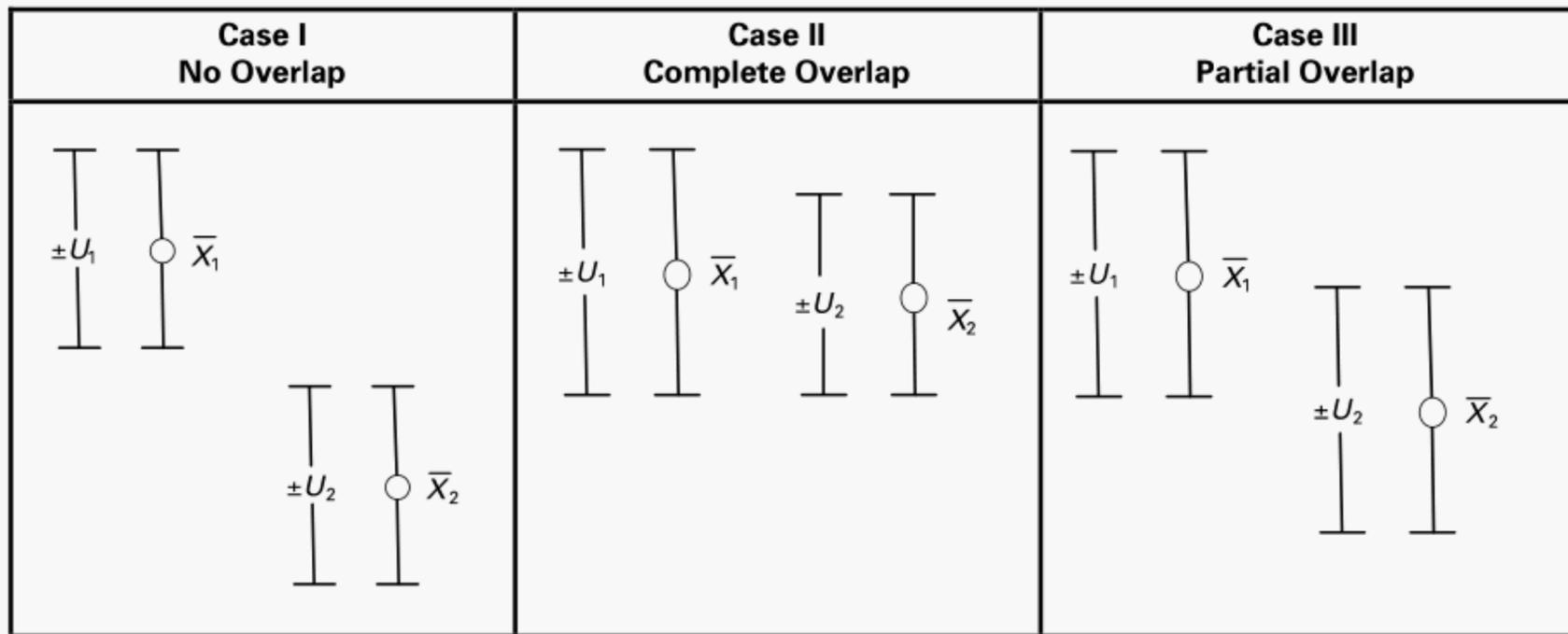
(b) establishes the validity of the results.

(c) verifies the repeatability of the results. Results may not be repeatable due to variations in either test methodology (test variations) or the actual performance of the equipment being tested (process variations).

After completion of the first test run that meets the criteria for an acceptable test run (which may be a preliminary test run), the data should be consolidated and preliminary results calculated and examined to ensure that the results are reasonable.

**3-4.12.3 Evaluation of Test Runs.** When comparing results from two test runs ( $X_1$  and  $X_2$ ) and their uncertainty intervals, the test team should consider the three cases illustrated in [Figure 3-4.12.3-1](#).

Figure 3-4.12.3-1 Three Post-Test Cases



(a) Case I: A problem clearly exists when there is no overlap between uncertainty intervals. In this case, the uncertainty intervals may have been grossly underestimated, an error may exist in the measurements, or the true value may not be constant. Investigation to identify bad readings, overlooked or underestimated systematic uncertainty, etc., is necessary to resolve this discrepancy.

(b) Case II: When the uncertainty intervals completely overlap, one can be confident that there has been a proper accounting of all major uncertainty components. The smaller uncertainty interval,  $X_2 \pm U_2$ , is wholly contained in the interval  $X_1 \pm U_1$ .

(c) Case III: This case, where a partial overlap of the uncertainty exists, is the most difficult to analyze. For both test run results and both uncertainty intervals to be correct, the true value lies in the region where the uncertainty intervals overlap. Consequently, the larger the overlap, the more confidence there is in the validity of the measurements and the estimate of the uncertainty intervals. As the difference between the two measurements increases, the overlap region shrinks.

Should a run or set of runs fall under Case I or Case III, the results from all of the runs should be reviewed in an attempt to explain the reason for excessive variation. If the reason for the variation cannot be determined, then either increase the uncertainty band to encompass the runs to make them repeatable or conduct more runs so that the precision component of uncertainty may be calculated directly from the test results.

The results of multiple runs shall be averaged to determine the mean result. The uncertainty of results is calculated in accordance with ASME PTC 19.1.

**3-4.12.4 Number of Readings.** Sufficient readings shall be taken within the test duration to yield total uncertainty consistent with a pretest uncertainty analysis. Ideally, at least 30 sets of data should be recorded for all nonintegrated measurements of primary parameters and variables. There are no specific requirements for the number of integrated readings or for measurements of secondary parameters and variables for each test run.

### 3-4.13 Constancy of Test Conditions

The state of charge of the ESS shall be the same at the start and end of the performance test.

## 3-5 CALCULATION AND REPORTING OF RESULTS

The data taken during the test should be reviewed and rejected in part or in whole if they are not in compliance with the requirements for the constancy of test conditions. See [para. 3-4.6](#).

Each Code test shall include pretest and post-test uncertainty analyses, and the results of these analyses shall fall within Code requirements for the type of plant being tested.

### 3-5.1 Causes for Rejection of Readings

Upon completion of the test or during the test itself, the test data shall be reviewed to determine if data from certain time periods should be rejected prior to the calculation of test results. Refer to ASME PTC 19.1 for data rejection criteria. A test log shall be kept. Data collected during any plant upset that causes a violation of the requirements of specified test procedures shall be rejected. Data collected a minimum of 10 min following the recovery of these criteria shall also be rejected to allow for restabilization.

Should serious inconsistencies that affect the results be detected during a test run or during the calculation of the results, the run shall be invalidated completely; however, if the affected part of the run is at the beginning or end of the run, the run may be invalidated in part. A run that has been invalidated shall be repeated, if necessary, to attain the test objectives. During the test, should any control system set points be modified that effect stability of operation beyond Code-allowable limits as defined in the specified test procedures, test data shall be considered for rejection from the calculation of test results. The data rejected shall be that collected during the period starting immediately prior to the change and ending no less than 10 min following the recovery of the criteria found in the specified test procedures.

An outlier analysis of spurious data should also be performed in accordance with ASME PTC 19.1 on all primary measurements after the test has ended. This analysis will highlight any other time periods that should be rejected prior to calculating the test results.

### 3-5.2 Uncertainty

Procedures relating to test uncertainty are based on concepts and methods described in ASME PTC 19.1. ASME PTC 19.1 specifies procedures for evaluating measurement uncertainties from both random and systematic errors and the effects of these errors on the uncertainty of a test result.

#### 3-5.2.1 Pretest and Post-Test Uncertainty Analyses

(a) *Pretest.* A pretest uncertainty analysis shall be performed so that the test can be designed to meet Code requirements. Estimates of systematic and random errors for each proposed test measurement should be used to help determine the number and quality of test instruments required for compliance with Code or contract specifications.

The pretest uncertainty analysis shall include an analysis of random uncertainties to establish permissible fluctuations of key parameters in order to attain allowable uncertainties. In addition, a pretest uncertainty analysis can be used to determine the correction factors that are significant to the corrected test. For simplicity, this Code allows elimination of those corrections that do not change the test results by 0.05%. Also, pretest uncertainty analysis should be used to determine the level of accuracy required for each measurement to maintain overall Code standards for the test.

(b) *Post-Test.* A post-test uncertainty analysis shall also be performed as part of a Code test. The post-test uncertainty analysis will reveal the actual quality of the test to determine whether the allowable test uncertainty has been realized.

### 3-5.3 Data Distribution and Test Report

Copies of all data shall be distributed by the test coordinator to those requiring it at the conclusion of the test. A test report shall be written and distributed by the test coordinator. A preliminary report incorporating calculations and results may be required before the final test report is submitted.

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