ASME PTC 53-2022

Mechanical and Thermal Energy Storage Systems

Performance Test Codes

AN AMERICAN NATIONAL STANDARD

The American Society of Mechanical Engineers

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NOTICE

All ASME Performance Test Codes (PTCs) shall adhere to the requirements of ASME PTC 1, General Instructions. It is expected that the Code user is fully cognizant of the requirements of ASME PTC 1 and has read them before applying ASME PTCs.

ASME PTCs provide unbiased test methods for both the equipment supplier and the users of the equipment or systems. The Codes are developed by balanced committees representing all concerned interests and specify procedures, instrumentation, equipment-operating requirements, calculation methods, and uncertainty analysis. Parties to the test can reference an ASME PTC confident that it represents the highest level of accuracy consistent with the best engineering knowledge and standard practice available, taking into account test costs and the value of information obtained from testing. Precision and reliability of test results shall also underlie all considerations in the development of an ASME PTC, consistent with economic considerations as judged appropriate by each technical committee under the jurisdiction of the ASME Board on Standardization and Testing.

When tests are run in accordance with a Code, the test results, without adjustment for uncertainty, yield the best available indication of the actual performance of the tested equipment. Parties to the test shall ensure that the test is objective and transparent. All parties to the test shall be aware of the goals of the test, technical limitations, challenges, and compromises that shall be considered when designing, executing, and reporting a test under the ASME PTC guidelines.

ASME PTCs do not specify means to compare test results to contractual guarantees. Therefore, the parties to a commercial test should 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 ASME PTC to determine or interpret how such comparisons shall be made.

FOREWORD

ASME PTC 53, Mechanical and Thermal Energy Storage Systems, defines uniform test procedures and quantifiable test methods for assessing and reporting the performance of mechanical or thermal energy storage systems (ESSs) across various technology platforms. ASME PTC 53 is intended to have broad applicability; however, this Code is not intended to overlap the scope of similar codes published by other organizations 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 covers mechanical and thermal technologies including compressed air, flywheels, thermal storage ranging from molten salts to cryogenic liquids, and pumped hydromechanical energy.

The ASME PTC 53 Committee issued ASME PTC 53 as a Draft Standard for Trial Use in 2018 to allow technology developers, engineers, and consumers to consider consistent strategies, methods, and systems for performance testing. ASME PTC 53-2022 builds on the Draft Standard, adding Sections on instrumentation and measurement, computation and reporting of results, and uncertainty. ASME PTC 53-2022 is a complete PTC for industry use.

ASME PTC 53-2022 was approved by the American National Standards Institute as an American National Standard on September 15, 2022.

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Performance Test Codes

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General. ASME codes and standards are developed and maintained by committees with the intent to represent the consensus of concerned interests. Users of ASME codes and standards may correspond with the committees to propose revisions or cases, report errata, or request interpretations. Correspondence for this Code should be sent to the staff secretary noted on the committee's web page, accessible at https://go.asme.org/PTCcommittee.

Revisions and Errata. The committee processes revisions to this Code on a periodic basis to incorporate changes that appear necessary or desirable as demonstrated by the experience gained from the application of the Code. Approved revisions will be published in the next edition of the Code.

In addition, the committee may post errata on the committee web page. Errata become effective on the date posted. Users can register on the committee web page to receive e-mail notifications of posted errata.

This Code is always open for comment, and the committee welcomes proposals for revisions. 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 background information and supporting documentation.

Cases

(a) The most common applications for cases are

(1) to permit early implementation of a revision based on an urgent need

(2) to provide alternative requirements

(3) to allow users to gain experience with alternative or potential additional requirements prior to incorporation directly into the Code

(4) to permit the use of a new material or process

(b) Users are cautioned that not all jurisdictions or owners automatically accept cases. Cases are not to be considered as approving, recommending, certifying, or endorsing any proprietary or specific design, or as limiting in any way the freedom of manufacturers, constructors, or owners to choose any method of design or any form of construction that conforms to the Code.

(c) A proposed case shall be written as a question and reply in the same format as existing cases. The proposal shall also include the following information:

(1) a statement of need and background information

(2) the urgency of the case (e.g., the case concerns a project that is underway or imminent)

(3) the Code and the paragraph, figure, or table number(s)

(4) the edition(s) of the Code to which the proposed case applies

(d) A case is effective for use when the public review process has been completed and it is approved by the cognizant supervisory board. Approved cases are posted on the committee web page.

Interpretations. Upon request, the committee will issue an interpretation of any requirement of this Code. An interpretation can be issued only in response to a request submitted through the online Interpretation Submittal Form at https://go.asme.org/InterpretationRequest. Upon submitting the form, the inquirer will receive an automatic e-mail confirming receipt.

ASME does not act as a consultant for specific engineering problems or for the general application or understanding of the Code requirements. If, based on the information submitted, it is the opinion of the committee that the inquirer should seek assistance, the request will be returned with the recommendation that such assistance be obtained. Inquirers can track the status of their requests at https://go.asme.org/Interpretations.

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.

Interpretations are published in the ASME Interpretations Database at https://go.asme.org/Interpretations as they are issued.

Committee Meetings. The PTC Standards Committee regularly holds meetings that are open to the public. Persons wishing to attend any meeting should contact the secretary of the committee. Information on future committee meetings can be found on the committee web page at https://go.asme.org/PTCcommittee.

Section 1
Object and Scope

1-1 OBJECT

The object of this Code is to establish uniform test methods and procedures for conducting performance tests of mechanical or thermal energy storage systems (ESSs). An ESS is a system that consumes energy to increase the internal energy of the storage media and releases that stored energy to produce useful power or heat. The standard test procedures for ESSs established by this Code 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 non-useful energy flows in and 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)

This Code provides quantifiable methods to assess the performance of mechanical or thermal ESSs in 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 a Performance Test Code (PTC). This Code does not specify means to compare results to contractual guarantees. Therefore, parties to a commercial test should agree on the method for comparing results to commercial guarantees before starting the test.[1] It is beyond the scope of this Code to determine or interpret how such comparisons are made.

This Code shall not be used to troubleshoot equipment. However, this Code can be used to quantify the magnitude of performance anomalies of equipment suspected of 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 simple 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 ESSs in which mechanical or thermal means are used to affect the storage and release of energy from suitable mechanical, thermal, or fluid media.

This Code 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

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 ESSs may use energy inputs from multiple external sources. Some ESSs 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] Manufacturers typically provide correction curves or multiplication factors to adjust the performance guarantees for off-design conditions typically encountered during a test.

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

Cellular electrical battery storage devices (lead-acid, lithium ion, etc.) are specifically excluded from this Code. Test codes promulgated by other professional organizations have defined test procedures for that technology.

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 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 MFC 11. Measurement of Fluid Flow by Means of Coriolis Mass Flowmeters. The American Society of Mechanical Engineers.
ASME PTC 1. General Instructions. The American Society of Mechanical Engineers.
ASME PTC 2-2001 (R2014). Definitions and Values. The American Society of Mechanical Engineers.
ASME PTC 4. Fired Steam Generators. The American Society of Mechanical Engineers.
ASME PTC 12.4. Moisture Separator Reheaters. The American Society of Mechanical Engineers.
ASME PTC 19.1. Test Uncertainty. The American Society of Mechanical Engineers.
ASME PTC 19.3. Temperature Measurement. The American Society of Mechanical Engineers.
ASME PTC 19.5. Flow Measurement. The American Society of Mechanical Engineers.
ASME PTC 19.6. Electrical Power Measurements. The American Society of Mechanical Engineers.
ASME PTC 19.22. Data Acquisition Systems. The American Society of Mechanical Engineers.
ASME PTC 46-2015. Overall Plant Performance. The American Society of Mechanical Engineers.
ASTM D240-19. Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter. ASTM International.
ASTM D1945. Standard Test Method for Analysis of Natural Gas by Gas Chromatography. ASTM International.
ASTM D3588-98. Standard Practice for Calculating Heat Value, Compressibility Factor, and Relative Density of Gaseous Fuels. ASTM International.
ASTM D4809. Standard Test Method for Heat of Combustion of Liquid Hydrocarbon Fuels by Bomb Calorimeter (Precision Method). ASTM International.
ASTM E1137. Standard Specification for Industrial Platinum Resistance Thermometers. ASTM International.
IEEE 120. Master Test Guide for Electrical Measurements in Power Circuits. Institute of Electrical and Electronics Engineers.
IEEE C57.13. IEEE Standard Requirements for Instrument Transformers. Institute of Electrical and Electronics Engineers.
NIST Technical Note 1265. Guidelines for Realizing the International Temperature Scale of 1990 (ITS-90). National Institute of Standards and Technology.

Section 2
Definitions and Descriptions of Terms

2-1 DEFINITIONS

charge energy: the primary energy that crosses the test boundary during a charge interval.

charge interval: the time duration during which the charging process takes place.

charge loss rate: a measure of the change of the state of charge during a standby interval. This change in power is expressed in kilowatt-hours per hour.

charge power: the rate at which charge energy crosses the test boundary, determined by the charge energy divided by the charge interval.

charge power rating: the charge power indicated in a test plan (e.g., maximum, minimum, nominal, or guaranteed), which 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 ratio of the minimum state of charge at which the energy storage system can operate to the maximum state of charge. Discharge depth may be qualified as maximum, rated, normal, or guaranteed; it may be referenced to the discharge power rating.

discharge energy: the primary energy that crosses the test boundary during a discharge interval.

discharge interval: the time duration during which the discharge process occurs.

discharge power: the rate at which discharge energy crosses the test boundary, determined by the discharge energy divided by the discharge interval.

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

discharge process: the means by which the 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 that leaves the test boundary from the storage container, thus decreasing 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 later releases that stored energy as primary energy.

exhaust energy: the nonprimary energy that leaves the test boundary of the energy storage system during the charge interval or discharge interval.

fuel energy: the energy that crosses the test boundary as combustible mass during a storage cycle, determined by 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.[1]

[1] Adapted from ASME PTC 2-2001 (R2014).

higher heating value: heat released from the rapid oxidation of fuel. Heating value of fuels is determined in accordance with ASTM D240-19 and ASTM D3588-98. Each Code specifies using either the higher or the 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.[1]

incidental material: the mass that crosses 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; the change from one state to another 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).[1]

material loss: the mass that leaves the storage container but does not pass through the discharge process. Material loss decreases the internal energy of the storage container.

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 energy storage system.

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 energy storage system.

ramp rate: the rate of change of charge power or discharge power of an energy storage system.

rated discharge energy: the discharge energy delivered from the energy storage system indicated in a test plan (e.g., maximum, minimum, nominal, or guaranteed), which may be derived from contracts, specifications, nameplates, guarantees, or other sources.

secondary energy: the nonfuel energy and/or nonprimary energy that enters the energy storage system 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 primary energy or fuel energy that crosses the test boundary during the standby state. Standby energy may increase or maintain the internal energy of the storage medium, or it may be parasitic.

standby interval: the time duration during which the energy storage system is in the standby state.

standby power: the rate at which standby energy crosses the test boundary, determined by 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 energy storage system.

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

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 the end of the sequence.

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

stored energy rate: the total energy that enters or leaves the storage container divided by the discharge energy during a storage cycle, expressed as British thermal units per kilowatt-hour (kilojoules per kilowatt-hour).

total energy: the sum of internal, potential, and kinetic energy within the storage medium.

2-2 SYMBOLS AND SUBSCRIPTS

Symbols used in this Code are listed in Table 2-2-1. Subscripts used in this Code are listed in Table 2-2-2.

Table 2-2-1
Symbols and Abbreviations Used in ASME PTC 53

Symbol or Abbreviation	Definition	Intensive or Extensive [Note (1)]
B	Standby energy	...
c_p	Specific heat at constant pressure	Intensive
dp	Differential pressure (integral calculus)	...
E	Rate of energy flow to or from storage container	...
e	Cell half-potential	...
F	Faraday's constant	...
f	Frictional dissipation	...
FHR	Fuel heat rate	...
G	Gibbs free energy	Extensive
g	Gravitational acceleration	...
g_c	Force-to-mass conversion factor	...
h	Specific enthalpy	Intensive
HHV	Higher heat value of fuel	...
I_m	Moment of inertia	...
J	Mechanical equivalent of heat	...
K	Constant of proportionality relating mass flow of electrolyte to electric current	...
Kin$E$	Kinetic energy component of total energy	...
LHV	Lower heat value of fuel	...
M	Total mass of storage medium within storage container	...
$\dot{m}$	Mass flow rate of storage medium to or from storage container	...
n	Molar flow	...
P	Power, rate of primary energy flow	...
p	Pressure of storage medium within storage container	...
PER	Primary energy rate	...
Pot$E$	Potential energy component of total energy	...
Q	Rate of fuel heat input	...
S	Total entropy	Extensive
s	Fluid velocity	...
SER	Stored energy rate	...
T	Temperature	...
t	Time	...
U	Internal energy component of total energy	Extensive
V	Total volume of storage container	Extensive
v	Specific volume	Intensive
W	Work	...
X	Secondary energy	...
XER	Secondary energy rate	...
Y	Primary energy	...
z	Elevation	...
α	Multiplicative correction factor for power output during discharge	...
β	Multiplicative correction factor for fuel heat input during discharge	...
Δ	Additive correction factor for fuel heat input during discharge	...
Δh	Change in enthalpy	...
Δp	Change in pressure	...
ΔT	Change in temperature	...
Δt	Interval duration	...
ΔU	Change in internal energy over a time interval	Extensive
Δu	Change in internal energy over a time interval	Intensive

Table 2-2-1
Symbols and Abbreviations Used in ASME PTC 53 (Cont'd)

Symbol or Abbreviation	Definition	Intensive or Extensive [Note (1)]
ε	Multiplicative correction factor for primary energy input during discharge	...
ζ	Multiplicative correction factor for standby power	...
η	Efficiency	...
θ	Additive correction factor for standby power	
κ	Additive correction factor to correct to base reference composition of the storage medium	...
λ	Multiplicative correction factor to correct to base reference composition of the storage medium	...
μ	Multiplicative correction factor for mass flow rate from storage during discharge	...
ξ	Additive correction factor for secondary energy	...
π	Multiplicative correction factor to mass flow rate into storage during charge	...
σ	Additive correction factor for power input during charge	...
τ	Multiplicative correction factor for power input during charge	...
ϕ	Additive correction factor for primary energy input during discharge	...
ψ	Multiplicative correction factor for secondary energy	...
Ω	Rotational speed	...
ω	Additive correction factor for power output during discharge	...

NOTE: (1) Thermodynamic properties may be extensive or intensive. Extensive properties pertain to an entire storage system or component; intensive properties are per unit of mass.

Table 2-2-2
Subscripts Used in ASME PTC 53

Subscript	Description
avail	Pertains to the mass available in storage
C	Pertains to the charge interval or the charging process
corr	Measured or calculated result corrected to base reference conditions
cycle	Pertains to a cycle of charge interval, standby interval, or discharge interval
D	Pertains to the discharge interval or the discharging process
end	Pertains to the end of a measurement interval
i, *j*	Indices for summation and multiplication
meas	Measured or determined result before correction to base reference conditions
rated	Pertains to vendor specification
roundtrip	Pertains to the combination of charging and discharging intervals or the combination of charging and discharging processes
SB	Standby
start	Pertains to the start of a measurement interval
total	Sum of all preceding values; for energy, sum of internal energy, kinetic energy, and potential energy

Section 3
Guiding Principles

3-1 INTRODUCTION

This Section provides guidance on performance testing of mechanical or thermal ESSs 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 commences. Tests may be designed to satisfy goals such as

(a) ascertaining contractual performance for a newly installed ESS
(b) performing acceptance testing
(c) determining absolute performance
(d) determining comparative performance
(e) determining performance at specific operating conditions 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 made that identify and distinguish the equipment to be tested and the exact method of testing selected. Descriptions, drawings, or photographs may all be used to create 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 verification of commercial guarantees for the ESS, i.e., storage capacity, energy input, and energy output. If this Code is used for 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. Before 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
(h) computational formulations and methods
(i) definition and application of correction factors

3-1.4.2 Data Records and Test Log. A complete set of data and a complete copy of the test log for all acceptance and other official tests 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 on or 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 is used to define the energy streams that must be measured to determine performance and calculate corrected results. 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 shall be defined by the parties to the test 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 ESSs are shown in Figure 3-1.5-1. In the figure, the solid lines indicate the streams crossing the test boundary. Some or all of the mechanical energy, electrical energy, heat, chemical energy, mass flow rate, thermodynamic conditions, and chemical composition of these streams shall be determined to calculate the results of an overall ESS performance test.

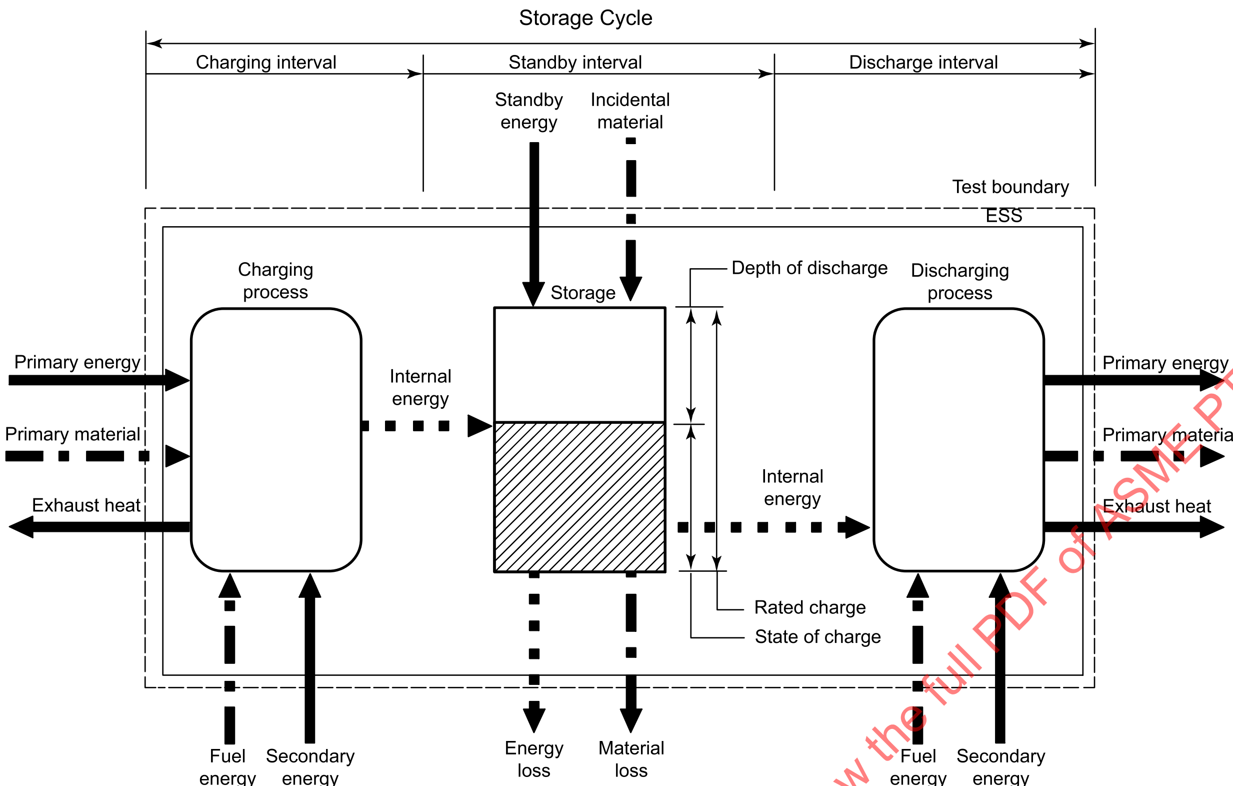
Determination of emissions is outside the scope of this Code.

3-1.6 Required Measurements

Some flexibility is required by this Code in defining the test boundary and measurement methods, since they are somewhat dependent on the design of the ESS. 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 ESS instrumentation is generally 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 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. Primary energy input to the ESS is measured or calculated at the point where the energy flows cross the test boundary. The test boundary is typically 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 or energy flows or both 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 selecting 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 and used to calculate the test 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 design of the ESS 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:

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

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

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

where

additive $E_{\text{discharge}}$ corrections = correction factors to $E_{\text{discharge,meas}}$ that are additive in nature
additive E_{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 $\text{P}_{\text{discharge,meas}}$ that are multiplicative in nature
multiplicative η corrections = correction factors to η that are multiplicative in nature
$P_{\text{discharge, corr}}$ = corrected ESS discharge power
$P_{\text{discharge, meas}}$ = measured ESS discharge power
η = overall efficiency
η_{corr} = corrected overall efficiency

Symbols and subscripts are defined in Tables 2-2-1 and 2-2-2.

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 necessary due to either operational effects for which corrections are allowable, such as those caused by changes in ESS process flows, or 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 that case, additional correction factors, either additive or multiplicative, would be required.

If all test conditions are equal to the base reference conditions, then all correction factors must result in no correction. 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

(a) conducting accurate acceptance testing for overall performance of the specific type of ESS.
(b) the requirements of instrumentation accuracy, calibration, and recalibration.
(c) documentation requirements.
(d) the location of permanent plant instrumentation used for testing.

(e) adequate provisions for the installation of temporary instrumentation where plant instrumentation is not sufficient to meet the requirements of this Code. For example, all voltage transformers and current transformers used for power measurement should be verified to perform per their design specifications, and their transmitters 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 before 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 of responsible parties, description of responsibilities of the test team, test procedures, and report of results.

For a commercial test, the purchase contract should 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 an 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 include 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 that 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, e.g., supplier representatives, customers, witnessing parties, and outside laboratory and other services.

The parties to the performance test shall designate a test coordinator responsible 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 a 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, the 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 or adjustments made by the manufacturer 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. Test procedures should include the following:

(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 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 the necessary time, as defined by prior agreement, 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 effect. This log becomes part of the permanent record of the test.

Safety is obviously of primary concern when performing work with any energy system. However, it is beyond the scope of a PTC to thoroughly address safety issues. 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

Care should also be taken of the instrumentation involved in the test as there may be calibration shifts or damage to the instrumentation due to extreme ambient conditions such as temperature or vibration. Documentation shall be developed or 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 a reasonable opportunity to examine the equipment, correct defects, and render the equipment suitable to test. For other official tests, the manufacturer or supplier may, at the request of the ESS owner, 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, the 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 by the manufacturer shall be documented and immediately reported to all parties to the test.

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 may be used as needed to reduce overall test uncertainty. The frequency of data collection is dependent on the specific 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 included in the test report and made available to all interested parties to the test.

3-3.3 Location and Identification of Instruments

Instruments shall be 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 the observers can read them with precision and convenience. 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 posttest 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. Before 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 before 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 is organized as follows:

(a) adjustments before and during tests, para. 3-4.1
(b) methods of operation before and during tests, para. 3-4.8
(c) starting and stopping tests and test runs, para. 3-4.7
(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 require repetition of any test runs conducted before the adjustments. No adjustments are permissible that are inappropriate for reliable and continuous operation following a test under specified outputs and operating conditions.

3-4.2 Data Collection

Data shall be taken by automatic data-collecting equipment or by the number of observers specified in the test plan. 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, determine if equipment is in suitable condition to test, check instruments and methods of measurement, check adequacy of organization and procedures, and train personnel. All parties to the test may conduct reasonable preliminary test runs as necessary. Observations during preliminary test runs should be carried out 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, it 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 adjust to needs that 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 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 starting the test.

3-4.7.1 Starting Criteria. Before the start of 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. Before the start of a test, the ESS shall be operated for sufficient 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 or systems 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 Before 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

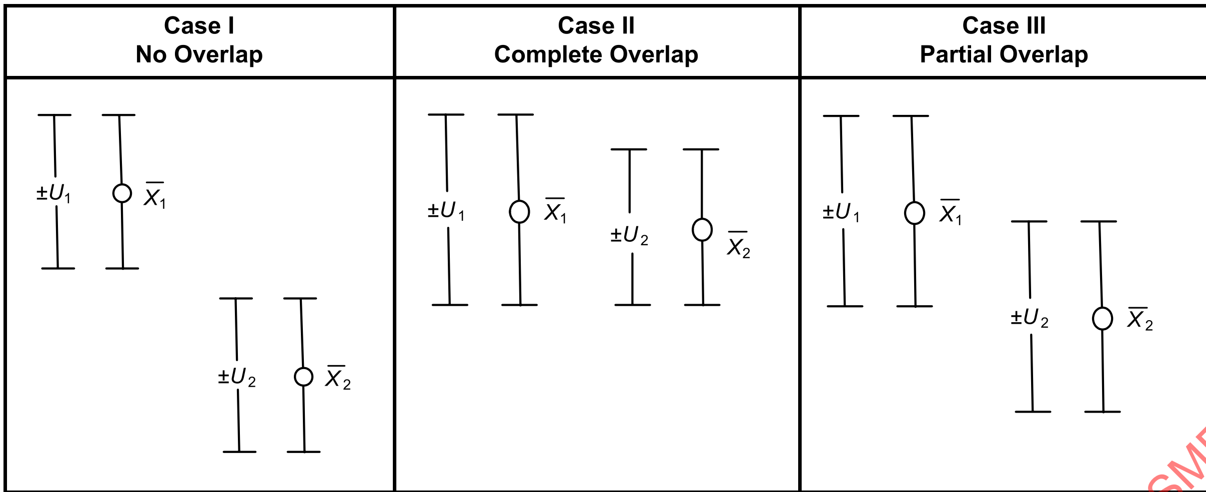
During the test, the plant should be operated as closely as possible to the base reference performance conditions and within the allowable design range of the ESS and its equipment to limit the magnitude of corrections to test parameters.

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 duration 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 sufficient 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.

Figure 3-4.12.3-1
Three Posttest Cases



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.

(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 is necessary to resolve this discrepancy by identifying bad readings, overlooked or underestimated systematic uncertainty, etc.

(b) Case II. When the uncertainty intervals completely overlap, the test team 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 contained within 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 must lie 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 test team should review results from all runs to explain the reason for excessive variation. If the reason for the variation cannot be determined, the test team should 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 test team shall average results of multiple runs 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 a cycle 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 posttest 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

During the test or upon completion, the test data shall be reviewed to determine if data from certain time periods should be rejected before the calculation of test results. See 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. Test data shall be rejected from the calculation of test results if any control system set points are modified during the test in a way that affects stability of operation beyond Code-allowable limits, as defined in the specified test procedures. Data collected immediately before the change until no less than 10 min following the recovery of the criteria specified in the test procedures shall be rejected.

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 before calculation of the test results.

3-5.2 Uncertainty

3-5.2.1 Procedures. 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. The maximum allowable test uncertainty shall be agreed to by the parties to a test before the performance of the test.

3-5.2.2 Pretest and Posttest 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 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) Posttest. A posttest uncertainty analysis shall also be performed as part of a Code test. The posttest 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

At the conclusion of the test, the test coordinator shall distribute copies of all data to those who require it. The test coordinator shall also write and distribute a test report. A preliminary report incorporating calculations and results may be required before the final test report is submitted.

Section 4
Instruments and Methods of Measurement

4-1 INTRODUCTION

This Section presents the mandatory provisions for instrumentation used in an ASME PTC 53 test. Many of the provisions herein have been taken from ASME PTC 46-2015. This Section uses the philosophy of ASME Performance Test Codes (see ASME PTC 1) to determine the minimum reasonably achievable uncertainty.

The ASME Instruments and Apparatus Supplements (the ASME PTC 19 series) outline the governing requirements of instrumentation for all ASME performance testing. Users of this Code must be familiar with the ASME PTC 19 series codes applicable to the instrumentation specified and explained in this Section. For convenience, this Section reviews the portions of the ASME PTC 19 codes that directly apply to the requirements of this Code.

Subsections 4-6 through 4-9 cover the primary measurement parameters of energy, power, pressure, flow, and temperature that are significant for an ASME PTC 53 test; the ASME PTC 19 series is the basis for other applicable parameters that depend on the configuration of the ESS. If, due to advances in the state of the art, the instrumentation requirements become more rigorous or the ASME PTC 19 series is revised or updated, the more rigorous requirements shall supersede those set forth in this Code. As they become available, new devices and methods may be used in lieu of any instrumentation recommended in this Code, provided they meet the allowable accuracy and uncertainty specified herein.

4-2 INSTRUMENT ACCURACY

The instrumentation used to measure a parameter will have different required type, accuracy, redundancy, and handling depending on how the measured parameter is used and how it affects the performance result. This Code requires high-accuracy instrumentation to measure the primary parameters required to calculate performance per Section 5. This Code does not require high-accuracy instrumentation to measure any secondary parameters that are included in the test plan (see subsection 3-2). The instruments that measure secondary parameters may be permanently installed plant instrumentation.

This Code requires verification of instrumentation output before the test period. This verification can be by calibration or by comparison against two or more independent measurements of the parameters referenced to the same location. The instruments should also have redundant or other independent instruments that can verify the integrity during the test period.

4-3 INSTRUMENT CALIBRATION

4-3.1 Laboratory and Field Calibration

Laboratory-grade calibrations shall be performed for all instruments used to measure primary parameters for testing under this Code. These calibrations shall be in strict compliance with established policies, requirements, and objectives of a laboratory's quality assurance program. Steps must be taken to ensure proper space, lighting, and environmental conditions such as temperature, humidity, ventilation, and low noise and vibration levels. Valid certificates of calibration for each instrument shall be available during the performance test. Field calibration is allowed for instruments used to measure secondary parameters. To clarify, primary parameters are those that are either directly or indirectly used for the calculation of performance parameters as covered in Section 5. Any other parameters shall be considered secondary.

The necessary calibration status shall be maintained during transportation and while on-site. The response of the reference standards to environmental changes or other relevant parameters shall be established and documented. Field calibration measurement and test equipment shall be calibrated by approved sources traceable to the National Institute of Standards and Technology (NIST) or another recognized international standard organization or to a recognized natural physical (intrinsic) constant through unbroken comparisons having defined uncertainties. Achievable uncertainties from field calibration are expected to be larger than those from laboratory calibrations due to possible adverse effects caused by the environment at the place of calibration or transportation of the calibration equipment. Field calibration can be used as a check of laboratory-calibrated instruments that are suspected to have drifted or that do not have redundancy.

Instruments used to measure primary parameters should be calibrated in a manner replicating test conditions. As it is often not practical or possible to perform calibrations under replicated environmental conditions, additional elemental error sources must be identified and estimated. Error source considerations shall be given to all process and ambient conditions, including temperature, pressure, humidity, electromagnetic interference, and radiation, that may affect the measurement system.

The instruments measuring primary parameters should be laboratory calibrated at a minimum of 2 points more than the order of the calibration curve fit; this applies if the calibration data is applied to the measured data or if the instrument is of the quality that the deviation between the laboratory calibration and the instrument reading is negligible in terms of affecting the test result. Flow metering that requires calibration should have a 20-point calibration. Instrument transformers do not require calibration at 2 points more than the order of the calibration curve fit and shall be calibrated in accordance with para. 4-6.3.

Each instrument should also be calibrated such that the measuring point is approached in an increasing and decreasing manner. This calibration minimizes any possibility of hysteresis effects. Some instruments are built with a mechanism to alter the range once the instrument is installed. In this case, the instrument shall be calibrated at each range used during the test period. Some devices cannot practically be calibrated over the entire operating range. For example, flow-measuring devices are often calibrated at flows lower than the operating range and the calibration data is extrapolated.

The instruments measuring secondary parameters should undergo field verifications and, if calibrated, need only be calibrated at one point in the expected operating range.

4-3.2 Quality Assurance Program

The quality assurance program should be designed to ensure that the instruments are calibrated as required and that properly trained technicians calibrate the equipment in the correct manner. A facility that performs a calibration shall have in place a quality assurance program that documents the following information:

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

The parties to the test should be allowed access to the calibration facility for auditing. The quality assurance program should also be made available during such a visit.

4-4 INSTRUMENT VERIFICATION

Verification is a way to check that the deviations between the values indicated by a measuring instrument and the corresponding known values are consistently smaller than the limits of the permissible error defined in a standard, regulation, or specification particular to the management of the measuring device. The result of the verification leads to a decision either to restore to service or to perform adjustments, repair, downgrade, or declare obsolete.

Verification techniques include field calibrations, nondestructive inspections, intercomparison of redundant instruments, check of transmitter zeros, and energy stream accounting practices. Nondestructive inspections include, but are not limited to, atmospheric pressure observations on absolute pressure transmitters, field checks including visual inspection, and no-load readings on power meters. Intercomparisons include, but are not limited to, water or electronic bath checks on temperature measurement devices and reconciliations on redundant instruments. Energy stream accounting practices include, but are not limited to, mass, heat, and energy balance computations. The applicable field verification requirements shall be judged based on the unique requirements of each setup. As appropriate, manufacturers' recommendations and the ASME PTC 19 series should be referenced for further field verification techniques.

4-4.1 Calibration Drift

Calibration drift can result from instrument malfunction, transportation, installation, or removal of the test instrumentation. When field verification indicates the drift is less than the instrument accuracy, the drift is considered acceptable, and the pretest calibration is used as the basis for determining the test results. Should the calibration drift combined with the reference standard accuracy, as the square root of the sum of the squares, exceed the required accuracy of the instrument, it is unacceptable. The following are some recommended field verification practices that lead to the application of good engineering judgment on drift:

(a) When instrumentation is transported to the test site between the calibration and the test period, a single-point check before and after the test period can isolate when the drift may have occurred. For example, verify the zero-pressure point on the vented pressure transmitters, the zero-load point on the wattmeters, or the ice point on the temperature instrument.

(b) In locations where redundant instrumentation is used, calibration drift should be analyzed to determine which calibration data (initial or recalibration) produces better agreement between redundant instruments.

Where experience in the use of a particular model or type of instrument has shown that calibration drift can be unacceptable, and no other device is available, redundancy is recommended. When practical, redundant instruments should be used to measure all primary parameters. Exceptions are redundant flow elements and redundant electrical metering devices, because of the large increase in costs. One benefit of redundant instruments is a reduction in the random component of uncertainty. Another is the ability to monitor instrument integrity and detect instrument-related problems through comparison techniques. Other independent instruments in separate locations can also monitor instrument integrity. For example, enthalpies in a constant-enthalpy process can be used to compare pressure and temperature at one point in a steam line to the pressure and temperature of another location in the line.

4-4.2 Loop Calibration

All instruments used to measure primary parameters should be loop calibrated. Loop calibration involves the calibration of the instrument through the signal-conditioning equipment. This may be accomplished by calibrating instrumentation using the test signal-conditioning equipment either in a laboratory or on-site during test setup before the instrument is connected to process. Alternatively, the signal-conditioning device may be calibrated separately from the instrument by applying a known signal to each channel using a precision signal generator.

If loop calibration is not performed, an uncertainty analysis in accordance with ASME PTC 19.1 and ASME PTC 19.22 shall be performed to ensure that the combined uncertainty of the measurement system meets the uncertainty requirements of this Code.

4-5 REFERENCE STANDARDS

Reference standards shall be routinely calibrated in a manner that provides traceability to NIST or another recognized international standard organization or to defined natural physical (intrinsic) constants and has accuracy, stability, range, and resolution for the intended use. They shall be maintained for proper calibration, handling, and usage in strict compliance with a calibration laboratory quality program. When it is necessary to use reference standards for field calibrations, adequate measures shall be taken to ensure that the necessary calibration status is maintained during transportation and while on-site. The integrity of reference standards shall be verified by proficiency testing or interlaboratory comparisons. All reference standards should be calibrated at the frequency specified by the manufacturer unless the user has data to support extension of the calibration period. Supporting data is historical calibration data that demonstrate a calibration drift less than the accuracy of the reference standard for the desired calibration period.

The collective uncertainty of reference standards shall be known, and the collective uncertainty of the reference standards selected for use in the calibration should contribute less than 25% to the overall calibration uncertainty. The overall calibration uncertainty of the calibrated instrument shall be determined at a 95% confidence level. A reference standard with a lower uncertainty may be used if the uncertainty of the reference standard combined with the random uncertainty of the instrument being calibrated is less than the accuracy requirement of the instrument. For example, for some kinds of flow metering, the 25% rule cannot be met. However, curve fitting from calibration is achievable from a 20-point calibration in a lab with an uncertainty of better than 0.2%.

In general, all instrumentation used to measure primary parameters shall be calibrated against reference standards traceable to NIST or another recognized international standard organization or to recognized natural physical (intrinsic) constants with values assigned or accepted by NIST. Instrumentation used to measure secondary parameters does not need to be calibrated against a reference standard. These instruments may be calibrated against a calibrated instrument.

4-6 ENERGY AND POWER MEASUREMENT

Energy in the forms of electric power, gaseous or liquid fuel, or thermal fluids may act as inputs or outputs in an ESS.

4-6.1 Consistent Gaseous or Liquid Fuel Heat Energy Measurement

Consistent liquid or gaseous fuels are those with heating values that vary less than 1.0% over the course of a performance test. For this Code test, the heat input from consistent fuels shall be determined by direct measurement of fuel flow and the online-chromatograph-determined heating value. However, where online measurement of heating value is not possible and where the parties to the test agree, heating value can be measured by sampling the stream periodically (minimum 4 samples per hour) and analyzing each sample individually for heating value. For applications where the ESS charge or discharge process, or both, is less than 1 hr, online measurement shall be done. Online measurement of heat value shall also be done where fuels with frequent variation in heat value (nonconsistent fuels) are expected. The analysis of gas, either by online chromatography or from sample analysis in a laboratory in accordance with ASTM D1945, determines the amount and kind of gas constituents from which heating value is calculated. Liquid fuel heating value may be determined by a calorimeter in accordance with ASTM D4809. Flow and temperature measurements are covered in subsections 4-8 and 4-9, respectively.

The flow instrument shall record time-integrated flow, in kilograms, as well as instantaneous flow, in kilograms per hour, with a time stamp at a minimum interval of 1 s. The temperature instrument shall record the temperature, in Kelvin, at a minimum interval of 5 s.

4-6.2 Thermal Fluid Energy Measurement

Thermal fluid is a liquid phase heat transfer medium. Thermal oil, glycol, molten salt, and water are common heat transfer media. An ESS configuration can have heat input and/or output through a thermal fluid medium across its control boundary. No phase change is considered in the thermal fluid during its heat transfer cycle for the purpose of this Code.

The heat input or output or both shall be determined by direct measurement of the thermal fluid flow and its temperature. The heat input or output or both shall be determined by multiplying the flow with the heat capacity and temperature of the fluid at the control boundary of the ESS. The variability of the heat capacity shall be acquired from the thermal fluid supplier for engineered thermal fluids. Variability curves or tables shall be acquired for conditions that substantially affect the heat capacity value, such as pressure and temperature.

The flow instrument shall record time-integrated flow and instantaneous flow, in kilograms per hour, with a time stamp at a minimum interval of 1 s. The temperature instrument shall record the temperature, in Kelvin, at a minimum interval of 5 s.

4-6.3 Electrical Energy and Power Measurement

Electrical energy and power measurement includes the measurement of polyphase (three-phase) alternating current real (active) and reactive power. Typically, the polyphase measurement will be the net or overall primary electrical input or output from the ESS boundary or a secondary electrical input or output.

Guidance for the measurements of electrical power is provided in ASME PTC 19.6. See IEEE 120 for measurement requirements not included in ASME PTC 19.6 or this Section or for any additionally required instruction.

Primary parameters shall be measured with 0.1% or better accuracy class power metering, 0.3% or better accuracy class (metering type) current transformers, and 0.3% or better accuracy class (metering type) voltage transformers. For absolute values of electrical power, power measurements should be made using a Class A type of measurement as described in ASME PTC 19.6. An ASME PTC 19.6 Class B measurement can be used for relative values of electrical power measurements, i.e., the ratio or difference in ESS charging and discharging electrical power rates using the same current and voltage instrument transformers.

Secondary parameters can be measured with any type of power measurement device. The use of calibrated transformers will lower overall test uncertainty; however, use of calibrated transformers is not a Code requirement. As a good practice, secondary parameters should be measured with 0.5% accuracy class power metering.

Power factor may be calculated from measurements of active and reactive power as described in ASME PTC 19.6 or measured directly using three-phase power factor transducers when balanced load and frequency conditions prevail. Power factor calculations or direct measurements shall have a systematic uncertainty equal to or less than 0.01 of the indicated power factor.

The energy meters should have the capability to display, record, and provide a soft- or hard-copy output of the instantaneous value of active power (in kilowatts), reactive power [in kilovolt-amperes reactive (kVAR)], and power factor with a time stamp of 0.5 s or better and the time-integrated value of active energy (in kilowatt-hours), reactive energy [in kilovolt-amperes reactive hours (kVARh)], and total electrical energy (in kilovolt-amperes).

The following five types of electrical-metering equipment may be used to measure electrical energy:

(a) Wattmeters measure instantaneous active power.
(b) Watt-hour meters measure active energy.
(c) VAR meters measure instantaneous reactive power.
(d) VAR-hour meters measure reactive energy.
(e) Power factor meters measure power factor.

Single- or polyphase metering equipment may be used. However, if polyphase metering equipment is used, the output from each phase must be available or the meter must be calibrated for three-phase measurements.

The warm-up time of electrical-metering equipment shall be in accordance with the manufacturer's recommendations to ensure instrument specifications are met. Electrical-metering equipment with various measurement range settings should be selected to minimize the reading error while encompassing the test conditions. The systematic uncertainty associated with digital power analyzers using some form of digitizing technique to convert an analog signal to digital form shall consider influence quantities including, but not limited to, environmental effects such as ambient temperature, magnetic fields, electric fields, humidity, power factor, crest factor, digital-to-analog output accuracy, timer accuracy (integration time), and long-term stability.

The leads to the instruments shall be arranged so that inductance or any other similar cause will not influence the readings. Inductance may be minimized by using twisted and shielded pairs for instrument leads. The whole arrangement of instruments should be checked for stray fields. Additionally, the lead wires shall have insulation resistance appropriate for their ratings.

To minimize the voltage drop in the voltage circuit, wire gage shall be chosen considering the length of the wiring, the load on the voltage transformer circuit, and the resistance of the safety fuses. For an accurate absolute value of power measurement, the errors due to wiring resistance (including fuses) shall always be accounted for by either voltage-drop measurement or calculation. For a relative value of measured power difference or ratio, measurements of voltage drop and correction for instrument transformer calibrations and burdens are not necessary if the same instrument transformers are used for each instrument.

Extreme care must be exercised in the transportation of calibrated portable instruments. The instruments should be located in an area as free of stray electrostatic and magnetic fields as possible. Where integrating meters are used, a suitable timing device shall be provided to accurately determine the real power during the test period.

To reduce the effect of instrumental loss on measurement accuracy, power-metering equipment should be selected that uses a separate source of power and has high-impedance voltage inputs (i.e., 2.4 MΩ) and low-impedance current inputs (i.e., 6 mΩ).

Wattmeters and watt-hour meters, collectively referred to as power meters, shall be calibrated by applying power through the test power meter and a wattmeter or watt-hour meter standard simultaneously. This comparison should be conducted at a minimum of five power levels across the expected power range. The difference between the test and the standard instruments for each power level should be calculated and applied to the power measurement data from the test. For test points between the calibration power levels, a curve-fit or linear interpolation should be used. The selected power levels should be approached in an increasing and decreasing manner. The calibration data at each power level should be averaged to minimize any hysteresis effect. Should polyphase metering equipment be used, the output of each phase must be available, or the meter must be calibrated with all three phases simultaneously.

When calibrating watt-hour meters, the output from the wattmeter standard should be measured with frequency high enough to reduce the random error during calibration so that the total uncertainty of the calibration process meets the required level. The average output can be multiplied by the calibration time interval to compare against the watt-hour meter output.

Wattmeters should be calibrated at the electrical line frequency of the equipment under test, i.e., a meter calibrated at 60 Hz should not be used on 50 Hz equipment and vice versa. Wattmeter standards should have power flow through them before calibration. The standard should be checked for zero reading each day before calibration.

To calibrate a VAR meter or VAR-hour meter, either a VAR standard or a wattmeter standard and an accurate phase-angle measuring device shall be used. The device used to supply power through the standard and test instruments must have the capability of shifting phase to create several different stable power factors. These different power factors create reactive power over the calibration range of the instrument.

If a VAR meter standard is used, the above procedure for calibration of wattmeters should be used. If a wattmeter standard and phase-angle meter is used, simultaneous measurements from the standard, phase-angle meter, and test instrument should be taken. The VAR level shall be calculated from the average watts and the average phase angle. VAR meters should be calibrated at the electrical line frequency of the equipment under test, i.e., a meter calibrated at 60 Hz should not be used on 50 Hz equipment and vice versa. VAR meters are particularly sensitive to frequency and should be used within 0.5 Hz of the calibration frequency.

When calibrating VAR-hour meters, the output from the VAR meter standard or wattmeter/phase-angle meter combination should be measured with frequency high enough to reduce the random error during calibration so the total uncertainty of the calibration process meets the required level. The average output can be multiplied by the calibration time interval to compare against the VAR-hour meter output. If polyphase metering equipment is used, the output of each phase must be available, or the meter must be calibrated with all three phases simultaneously.

Instrument transformers, including voltage and current transformers, are used to reduce the voltages and currents to values that can be conveniently measured, typically to 120 V and 5 A, respectively, and to insulate the metering instruments from the high potential that may exist on the circuit under test. Use and application of instrument transformers is described in ASME PTC 19.6. Additional details pertaining to instrument transformer practice are described in detail in IEEE C57.13.

Voltage transformers shall be calibrated for turns ratio and phase angle and operated within their rated burden range. The method of calibration should permit the determination of the turns ratio and phase angle to an uncertainty of ±0.1% and ±0.9 mrad (3 min), respectively. The calibration shall consist of ratio and phase-angle tests from 90% to 110% of rated primary voltage at rated frequency with zero burden and with the maximum standard burden for which the transformer is rated at its best accuracy class.

Current transformers shall be calibrated for turns ratio and phase angle at zero external burden (0 VA) and at least one burden that exceeds the maximum expected during the test at 10% and 100% of rated primary current. Accuracy test results may be used from factory type (design) tests in the determination of turns ratio and phase-angle correction factors. ASME PTC 19.6 should be consulted to determine the associated equations in providing an analytical determination of the transformer ratio correction factor (RCFc).

4-7 PRESSURE MEASUREMENT

4-7.1 Introduction

This subsection presents requirements and guidance for the measurement of pressure. Electronic pressure measurement equipment should be used for primary measurements to minimize systematic and random error. Electronic pressure measurement equipment provides inherent compensation procedures for sensitivity, zero balance, thermal effect on sensitivity, and thermal effect on zero. Other devices that meet the uncertainty requirements of this subsection may be used. Factors affecting the uncertainty of the pressure measurement include, but are not limited to, ambient temperature, resolution, repeatability, linearity, hysteresis, vibration, power supply, stability, mounting position, radio frequency interference (RFI), static pressure, water leg, warm-up time, data acquisition, spatial variation, and primary element quality.

The piping between the process and the secondary element must accurately transfer the pressure to obtain accurate measurements. Possible sources of error include pressure transfer, leaks, friction loss, trapped fluid (i.e., gas in a liquid line or liquid in a gas line), density variations within legs (i.e., water legs), and density variations between legs (differential pressure only).

All signal cables should have a grounded shield and twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from devices that produce electromotive force (EMF) such as motors, generators, electrical conduit, cable trays, and electrical service panels.

Before calibration, the pressure transmitter range may be altered to better match the process. However, the sensitivity to ambient temperature fluctuation may increase as the range is altered.

Additional calibration points will increase accuracy but are not required. During calibration, the measuring point should be approached from an increasing and decreasing manner to minimize hysteresis effects.

Some pressure transmitters allow the user to change the range once the transmitter is installed. The transmitters must be calibrated at each range used during the test period.

Where appropriate for steam and water processes, the readings from all static pressure transmitters and any differential pressure transmitters with taps at different elevations (such as on vertical flow elements) shall be adjusted to account for elevation head in water legs. This adjustment shall be applied at the transmitter either automatically by the control system or data acquisition system or manually by the user after the raw data is collected. Care must be taken to ensure this adjustment is applied properly, particularly at low static pressures, and that it is applied only once.

4-7.2 Required Uncertainty

The required uncertainty depends on the type of parameters and variables being measured per the measurement classification and instrumentation categorization.

Class 1 primary parameters and variables shall be determined with a 0.1% accuracy class pressure transmitter or equivalent that has an instrument systematic uncertainty of ±0.3% or better of calibrated span. Barometric pressure shall be measured with a pressure transmitter that has an instrument systematic uncertainty of ±0.1% or better of calibrated span.

Class 2 primary parameters and variables shall be determined with a 0.25% accuracy class pressure transmitter or equivalent that has an instrument systematic uncertainty of ±0.50% or better of calibrated span.

Secondary parameters and variables can be measured with any type of pressure transmitter or equivalent device.

4-7.3 Recommended Pressure Measurement Devices

Pressure transmitters are the recommended pressure measurement devices. The three types of pressure transmitters are absolute pressure transmitters, gage pressure transmitters, and differential pressure transmitters; the selection of type of transmitter is based on application considerations.

4-7.3.1 Absolute Pressure Transmitters

(a) Application. Absolute pressure transmitters measure pressure referenced to absolute zero pressure. Absolute pressure transmitters should be used on all measurement locations with a pressure equal to or less than atmospheric. Absolute pressure transmitters may also be used to measure pressures above atmospheric pressure.

(b) Calibration. Absolute pressure transmitters can be calibrated using one of the following methods:

(1) The first calibration method involves connecting the test instrument to a device that develops an accurate vacuum at desired levels. Such a device can be a deadweight gage in a bell jar referenced to zero pressure or a divider piston mechanism with the low side referenced to zero pressure.

(2) The second calibration method uses a suction-and-bleed control mechanism to develop and hold a constant vacuum in a chamber to which the test instrument and the calibration standard are both connected. The chamber must be maintained at constant vacuum during the calibration of the instrument.

(3) Other methods and devices can be used to calibrate absolute pressure transmitters provided that the same level of care is taken.

4-7.3.2 Gage Pressure Transmitters

(a) Application. Gage pressure transmitters measure pressure referenced to atmospheric pressure. The test site atmospheric pressure must be subtracted from the absolute pressure to obtain gage pressure:

$$p_g = p_{\text{abs}} - p_{\text{atm}} \tag{4-7-1}$$

where

p_{abs} = absolute pressure
p_{atm} = atmospheric pressure
p_g = gage pressure

This test site atmospheric pressure should be measured by an absolute pressure transmitter. Gage pressure transmitters may be used only on measurement locations with pressures higher than atmospheric. Gage pressure transmitters are preferred over absolute pressure transmitters in measurement locations above atmospheric pressure because they are easier to calibrate.

(b) Calibration. Gage pressure transmitters can be calibrated by an accurate deadweight gage. The pressure generated by the deadweight gage must be corrected for local gravity, air buoyancy, piston surface tension, piston area deflection, actual mass of weights, actual piston area, and working medium temperature. If these corrections are not made, the pressure generated by the deadweight gage may be inaccurate. The actual piston area and mass of weights are determined each time the deadweight gage is calibrated. Other devices can be used to calibrate gage pressure transmitters provided that the same level of care is taken.

4-7.3.3 Differential Pressure Transmitters

(a) Application. Differential pressure transmitters are used where flow is determined by a differential pressure meter, or where pressure drops in a duct or pipe must be determined and it is practical to route the pressure tubing.

(b) Calibration. Differential pressure transmitters used to determine Class 1 primary parameters and variables must be calibrated at line static pressure unless available information detailing the effect of line static pressure on instrument accuracy demonstrates compliance with the uncertainty requirements of para. 4-7.3. Calibrations at line static pressure are performed by applying the actual expected process pressure to the instrument as it is being calibrated. Calibrations at line static pressure can be accomplished by one of the following three methods:

(1) two highly accurate deadweight gages
(2) a deadweight gage and divider combination
(3) one deadweight gage and one differential pressure standard

Differential pressure transmitters used to determine either Class 2 primary parameters and variables or secondary parameters and variables do not require calibration at line static pressure. These differential pressure transmitters can be calibrated using one accurate deadweight gage connected to the “high” side of the instrument.

If line static pressure calibration is not used, the span must be corrected for high-line static pressure shift unless the instrument is internally compensated for the effect. Once the instrument is installed in the field, the differential pressure from the source should be equalized and a zero value read. This zero bias must be subtracted from the test-measured differential pressure. Other devices can be used to calibrate differential pressure transmitters provided that the same level of care is taken.

4-7.4 Absolute Pressure Measurements

4-7.4.1 Introduction. Absolute pressure measurements are the total pressure measured at a point and may be expressed as the sum of the atmospheric and gage pressures at that point. Absolute pressure is defined by the pressure in a vacuum, where the atmospheric pressure is zero. Absolute pressure transmitters should be used for these measurements. Typical absolute pressure measurements in an ASME PTC 53 test may include barometric pressure and condenser pressure.

For vacuum pressure measurements, differential pressure transmitters may be used with the "low" side of the transmitter connected to the source. This effectively results in a negative gage that is subtracted from atmospheric pressure to obtain an absolute value. This method may be used but is not recommended for Class 1 primary parameters and variables since these measurements are typically small and the difference of two larger numbers may result in error.

4-7.4.2 Installation. Absolute pressure transmitters used for absolute pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting requirements should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing large enough to avoid friction effects and prevent blockage.

(f) Keep corrosive or high temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 0.61 m (2 ft) horizontally from the source before the downward slope begins. This horizontal length allows condensation to form completely so the downward slope will be completely full of liquid.

The water leg is the condensed liquid in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head must be subtracted from the pressure measurement. The static head is calculated by multiplying the sensing line vertical height by gravity and the density of the liquid in the sensing line.

All vacuum measurement sensing lines should slope continuously upwards from the source to the instrument. A purge system should be used that isolates the purge gas while measuring the process. A continuous purge system may be used; however, it must be regulated to have no influence on the reading. Before the test period, readings from all purged instrumentation should be taken successively with the purge on and with the purge off to prove that the purge air has no influence.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check must be conducted. For vacuum measurements, the leak check is performed by isolating first the purge system and then the source. If the sensing line has no leaks, the instrument reading will not change. For nonvacuum measurements, the leak check is performed using a leak detection fluid on the impulse tubing fittings.

Barometric pressure devices should be installed in the same general area and at the same general elevation that is most representative of the test boundary and minimizes test uncertainty.

4-7.5 Gage Pressure Measurements

4-7.5.1 Introduction. Gage pressure measurements are pressure measurements that are at or above atmospheric pressure. These measurements may be made with gage or absolute pressure transmitters. Gage pressure transmitters are recommended since they are easier to calibrate and to check in situ. Typical gage pressure measurements in an ASME PTC 46 test may include gas fuel pressure and process return pressure. Caution must be used with low-pressure measurements because they may enter the vacuum region at part load operation.

4-7.5.2 Installation. Gage pressure transmitters used for gage pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that in which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting requirements should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Use impulse tubing large enough to avoid friction effects and prevent blockage.

(f) Keep corrosive or high temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 0.61 m (2 ft) horizontally from the source before the downward slope begins. This horizontal length allows condensation to form completely so the downward slope will be completely full of liquid.

The water leg is the condensed liquid or water in the sensing line. This liquid causes a static pressure head to develop in the sensing line. This static head must be subtracted from the pressure measurement. The static head is calculated by multiplying the sensing line vertical height by gravity and the density of the liquid in the sensing line.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing line upstream of the instrument. The instrument sensing line should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing line of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Once transmitters are connected to the process, a leak check must be conducted. The leak check is performed using a leak detection fluid on the impulse tubing fittings.

4-7.6 Differential Pressure Measurements

4-7.6.1 Introduction. Differential pressure measurements are used to determine the difference in static pressure between pressure taps in a primary element. Differential pressure transmitters should be used for these measurements. Typical differential pressure measurements in an ASME PTC 46 test may include the differential pressure of gas fuel or process return through a flow element or pressure loss in a pipe or duct. The differential pressure transmitter measures the pressure difference or pressure drop used to calculate the fluid flow.

4-7.6.2 Installation. Differential pressure transmitters used for pressure measurements shall be installed in a stable location to minimize the effects associated with ambient temperature, vibration, mechanical shock, corrosive materials, and RFI. Transmitters should be installed in the same orientation as they were calibrated. If the transmitter is mounted in a position other than that at which it was calibrated, the zero point may shift by an amount equal to the liquid head caused by the different mounting position. Impulse tubing and mounting requirements should be installed in accordance with the manufacturer's specifications. In general, the following guidelines should be used to determine transmitter location and placement of impulse tubing:

(a) Keep the impulse tubing as short as possible.

(b) Slope the impulse tubing at least 8 cm/m (1 in./ft) upward from the transmitter toward the process connection for liquid service.

(c) Slope the impulse tubing at least 8 cm/m (1 in./ft) downward from the transmitter toward the process connection for gas service.

(d) Avoid high points in liquid lines and low points in gas lines.

(e) Ensure both impulse legs are at the same temperature.

(f) When using a sealing fluid, fill both impulse legs to the same level.

(g) Use impulse tubing large enough to avoid friction effects and prevent blockage.

(h) Keep corrosive or high temperature process fluid out of direct contact with the sensor module and flanges.

In steam service, the sensing line should extend at least 0.61 m (2 ft) horizontally from the source before the downward slope begins. This horizontal length allows condensation to form completely so the downward slope will be completely full of liquid.

Each pressure transmitter should be installed with an isolation valve at the end of the sensing lines upstream of the instrument. The instrument sensing lines should be vented to clear water or steam (in steam service) before the instrument is installed. This will clear the sensing lines of sediment or debris. After the instrument is installed, allow sufficient time for liquid to form in the sensing line so the reading will be correct.

Differential pressure transmitters should be installed using a five-way manifold, as shown in Figure 4-7.6.2-1. This is recommended rather than a three-way manifold because the five-way manifold eliminates the possibility of leakage past the equalizing valve. The vent valve acts as a telltale for leakage detection past the equalizing valves.

Once transmitters are connected to process, a leak check must be conducted. For gaseous fluids, a leak check is performed using a leak detection fluid on the impulse tubing fittings.

When a differential pressure meter is installed on a flow element located in a vertical steam or water line, the measurement must be corrected for the difference in sensing line height and fluid head change unless the upper sensing line is installed against a steam or water line inside the insulation down to where the lower sensing line protrudes from the insulation.

For upward flow

$$\Delta p_{\text{true}} = \Delta p_{\text{meas}} + n(p_{\text{amb}} - p_{\text{pipe}}) \times (g/g_c) \times \Delta z \tag{4-7-2}$$

For downward flow

$$\Delta p_{\text{true}} = \Delta p_{\text{meas}} - n(p_{\text{amb}} - p_{\text{pipe}}) \times (g/g_c) \times \Delta z \tag{4-7-3}$$

where

p_{amb} = ambient pressure
p_{pipe} = pressure inside the pipe
Δp_{meas} = change in measured pressure
Δp_{true} = change in true pressure
Δz = change in height

4-8 FLOW MEASUREMENT

4-8.1 Introduction

This subsection presents requirements and guidance for the measurement of flow. The recommended classes of meters are differential pressure meters (orifice, nozzle, and venturi), mass flowmeters (Coriolis flowmeters), and ultrasonic and mechanical meters (turbine meters and positive displacement meters). Table 4-8.1-1 defines the recommended, acceptable, and not recommended flowmeters for different applications. This Code does not limit the use of other flow measurement devices that are not currently available or reliable; if such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

In accordance with ASME PTC 19.5, the flow must be either steady or changing very slowly as a function of time. Pulsations of flow must be small compared with the total flow rate. The frequency of data collection must adequately cover several periods of unsteady flow. Fluctuations in the flow shall be suppressed before the beginning of a test by very careful adjustment of flow and level controls or by introducing a combination of conductance (e.g. pump recirculation) and resistance (e.g., throttling the pump discharge) in the line between the pulsation sources and the flow-measuring device. Hydraulic damping devices such as restrictors on instruments do not eliminate errors due to pulsations and therefore shall not be permitted.

Two-phase flow measurement is beyond the scope of ASME PTC 19.5. ASME PTC 12.4 describes methods for the measurement of two-phase flow when it is desirable to measure the flow rate of a two-phase mixture.

Figure 4-7.6.2-1
Five-Way Manifold

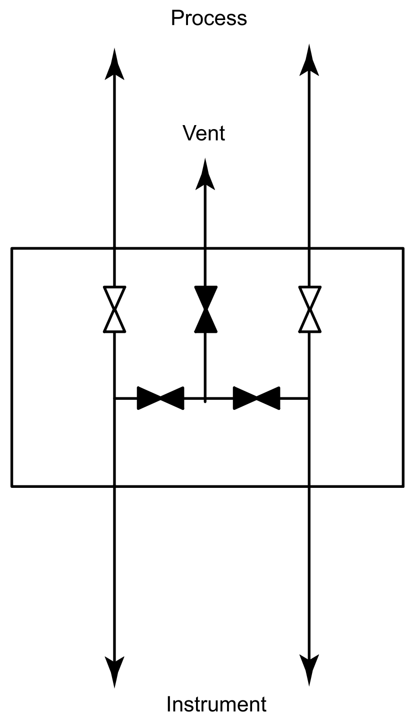


Table 4-8.1-1
Recommended Flowmeters for Various Fluids

Fluid	Type of Flowmeter					
	Orifice	Nozzle or Venturi	Coriolis	Ultrasonic	Turbine	Positive Displacement
Fuel gas	R	N	R	A	A	N
Liquid fuel	A	N	R	N	A	R
Thermal fluid	A	N	R	N	A	R
Steam	R	R	N	N	N	N
Water	R	R	R	A	A	A

GENERAL NOTE: A = acceptable; N = not recommended; and R = recommended.

All signal cables should have a grounded shield and twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from EMF-producing devices such as motors, generators, electrical conduit, cable trays, and electrical service panels.

Mass flow rate, as shown by computer printout or flow computer, is not acceptable without showing intermediate results and the data used for the calculations. In the case of a differential pressure class meter, intermediate results include the discharge coefficient, the corrected diameter for thermal expansion, and the expansion factor. Raw data include temperature and static and differential pressures.

In the case of a mechanical meter, intermediate results include the meter constant or constants used in the calculation, and how the constants are determined from the calibration curve of the meter. Data include frequency, temperature, and pressure.

Fuel analysis and the intermediate results used in the calculation of the fluid density are required for any flow measurement devices.

4-8.2 Required Uncertainty

Primary parameters shall be determined with flow measurement devices that have a systematic uncertainty of no more than ±0.5% of mass flow rate. Secondary parameters shall be measured with flow measurement devices/methods that will result in a relative uncertainty contribution to the result of no more than ±0.2%.

4-8.3 Flow Measurement Devices

Differential pressure meters (orifice, nozzle, and venturi), Coriolis flowmeters, ultrasonic flowmeters, and mechanical meters (turbine and positive displacement) are the recommended flow measurement devices. Uncertainty and application considerations should be used in the selection of the most appropriate flow measurement device.

When a flow measurement device is laboratory calibrated, the entire primary device must be calibrated. This shall include the primary element, upstream and downstream metering runs, and flow conditioners. A positive, mechanical alignment method shall be in place to replicate the precise position of the meter run or primary element when it was calibrated. The flow section must remain free of dirt and moisture for shipping and storage. Whenever possible, the flow section should be shipped as one piece, and not disassembled for shipping or installation.

4-8.3.1 Differential Pressure Meters. Differential pressure meters used in the measurement of primary parameters shall be laboratory calibrated. If flow straighteners or other flow-conditioning devices are used in the test, they shall be included in the meter piping run when the calibration is performed. Qualified hydraulic laboratories commonly calibrate within an uncertainty of 0.2%. Thus, with inherent curve-fitting inaccuracies, uncertainties of less than 0.3% in the discharge coefficients of laboratory-calibrated meters can be achieved. The procedure for fitting a curve through laboratory calibration data is provided in detail in ASME PTC 19.5 for each differential pressure meter. The procedures for extrapolation of a calibration to a higher Reynolds number than available in the laboratory are given for each meter in ASME PTC 19.5. Differential pressure meters used in the measurement of primary parameters may use the empirical formulations for the discharge coefficient for differential pressure class meters if the uncertainty requirements are met and the meter is designed, manufactured, installed, and operated in strict accordance with ASME PTC 19.5.

For a differential pressure meter to be used for primary parameter measurement, it shall be manufactured, calibrated, installed, and operated in accordance with ASME PTC 19.5. The calculation of the flow must be done in accordance with that Code. The documentation of factory measurements, manufacturing requirements, dimensional specifications of the installation including upstream and downstream disturbances, and the start-up procedures must be examined to validate compliance with the requirements of ASME PTC 19.5.

Primary parameters shall be measured with a minimum of two sets of differential pressure taps, each with independent differential pressure measurement devices. The two sets of pressure taps should be separated by 90 deg or 180 deg. For the throat tap nozzle, the meter should be manufactured with four sets of differential pressure taps, and two sets of taps should be individually measured. Further, the flow calculation should be done separately for each pressure tap pair and averaged. The results shall be investigated if they differ from each tap set calculation by more than the flow measurement uncertainty.

In cases where the metering run is installed downstream of a bend or tee, the pairs of single taps should be installed so that their axes are perpendicular to the plane of the bend or tee. Differential pressure meters should be assembled, calibrated, and left intact for the duration of the test. Once manufactured and calibrated, the flowmeter assembly should not be disassembled at the primary element flanges. If it is necessary to disassemble the section for inspection or other purposes before the test, provisions for the accurate realignment and reassembly (e.g., pins) must be built into the section to replicate the precise position of the flow element when it was manufactured and calibrated. If proper reassembly is not assured by the recommended methods, then the flow element shall be treated as uncalibrated in the uncertainty analysis.

In addition, gaskets or seal rings (if used) shall be inserted in such a way that they do not protrude at any point inside the pipe or across the pressure tap or slot.

The total measurement uncertainty of the flow contains components consisting of the uncertainty in the determination of fluid density, flow element (bore) and pipe diameter, pressure, temperature, and differential pressure measurement. See ASME PTC 19.5 for the methodology in the determination of the systematic uncertainty.

4-8.3.2 Orifice Meters. Orifice meters may be used for low-pressure steam and for fuel gas and liquids in pipes greater than 5 cm (2 in.). In accordance with ASME PTC 19.5, the three types of available tap geometries are flange taps, D and D/2 taps, and corner taps. This Code recommends that only flange or corner taps be used for primary measurements with orifice meters. The procedure for curve fitting, including extrapolation, and evaluating the curve for the coefficient of discharge shall be conducted in compliance with ASME PTC 19.5.

4-8.3.3 Nozzle Meters. Nozzle meters may be used for steam flows and for water flow in pipes at least 10 cm (4 in.). In accordance with ASME PTC 19.5, the three types of ASME-recommended primary elements are low beta ratio nozzles, high beta ratio nozzles, and throat tap nozzles. Other nozzles may be used if an equivalent level of care is taken in their fabrication and installation and if they are calibrated in a laboratory with the same care and precision as required by ASME PTC 19.5.

At least 20 calibration points should be run over the widest range of Reynolds numbers possible that applies to the performance test. The procedure for determining whether the calibration curve parallels the theoretical curve shall be conducted in accordance with ASME PTC 19.5. The procedures for curve fitting, including extrapolation if necessary, and evaluating the curve for the coefficient of discharge shall be conducted in compliance with ASME PTC 19.5.

4-8.3.4 Venturi Meters. Venturi meters may be used for steam flows and for water flow in pipes at least 10 cm (4 in.). In accordance with ASME PTC 19.5, the ASME (classical Herschel) venturi is the recommended type of primary element. Other venturis may be used if an equivalent level of care is taken in their fabrication and installation and if they are calibrated in a laboratory with the same care and precision as required by ASME PTC 19.5.

According to ASME PTC 19.5, ASME venturi meters commonly maintain the same physics of flow as throat tap nozzles due to similar design considerations. As such, and similar to nozzle meters, at least 20 calibration points should be run over the widest range of Reynolds numbers possible that applies to the performance test. The procedures for curve fitting, including extrapolation, and evaluating the curve for the coefficient of discharge shall be conducted in compliance with ASME PTC 19.5.

4-8.3.5 Coriolis Flowmeters. Coriolis flowmeters may be used for gas fuel flows and liquid flows within the line pressure and temperature specification and characterization of the flowmeter. Coriolis flowmeters measure mass flow directly. Due to the meters' insensitivity to velocity profile distortion and swirl, no straight-run or flow-conditioning requirements are typically necessary. To minimize measurement uncertainty, the zero reading of the Coriolis meter must be verified at the test line temperature before the start of the performance test. ASME MFC 11 provides additional details on Coriolis flowmeters.

Coriolis flowmeters are generally calibrated with water, but other fluids may be used because the constants are valid for other fluids. The calibration points shall be taken at flow rates that surround the range of flow rates expected during the test. The effect of operating pressure and temperature on the flowmeter during the test must be applied to correct for the influence of operating conditions different from calibration conditions. The Coriolis flowmeter must be characterized for the line pressure and line temperature. The constants within the meter's processing during lab calibrations shall be identical to those present in the meter when it is put into operation and during performance testing. Such constants compensate for physical, electrical, and sensor characteristics. In addition, it should be confirmed that the calibration factors determined during lab calibration are also applied correctly in the meter's processor.

4-8.3.6 Ultrasonic Meters. Ultrasonic flowmeters can be used for gas fuel flow measurements and water flow measurements. These meters measure velocity of the flowing fluid by which volumetric flow can be calculated by known physical dimensions of the metering section. ASME PTC 19.5, Section 10, describes ultrasonic flowmeters in more detail. Due to the sensitivity of the velocity profile on its measurement, a flow conditioner shall be used in addition to adequate upstream and downstream straight-run lengths. To ensure proper application, manufacturers often provide ultrasonic flowmeters complete with flow conditioner and spool pieces of necessary straight-run length.

The laboratory calibration of ultrasonic flowmeters shall be conducted in a complete assembled spool piece configuration. When used for natural gas flow measurement, the laboratory calibration is typically conducted with natural gas at flow rates that surround the range of flow experienced during base load operation of the gas turbine. The constants and algorithms within the meter's processing during laboratory calibrations shall be identical to those present in the meter when it is put into operation and during performance testing. Such constants and algorithms compensate for physical, electrical, and sensor characteristics. In addition, it should be confirmed that the calibration factors determined during laboratory calibration are applied correctly in the meter's processor.

4-8.3.7 Mechanical Meters. This subsection presents the application and calibration requirements for the use of turbine and positive displacement meters. Turbine meters are commonly classified as inference meters as they measure certain properties of the fluid stream and "infer" a volumetric flow. Positive displacement meters are commonly classified as direct meters as they measure volumetric flow directly by continuously separating (isolating) a flow stream into discrete volumetric segments and counting them. Mechanical meters require periodic maintenance, testing, and recalibration as the calibration shifts over time due to wear, damage, or contamination.

All mechanical meters used in the measurement of primary parameters shall be laboratory calibrated. These calibrations shall be performed on each meter using the fluid, operating conditions, and piping arrangements as nearly identical to the test conditions as practical. If flow straighteners or other flow-conditioning devices are used in the test, they shall be included in the meter piping run when the calibration is performed.

4-8.3.7.1 Turbine Meters. Turbine meters are recommended for applications with liquid flow rates in pipes less than 8 cm (3 in.). The two basic turbine meter designs are electromagnetic and mechanical.

The electromagnetic-style meter has moving parts, including the rotor and bearings. The rotor velocity is monitored by counting pulses generated as the rotor passes through a magnetic flux field created by a pickup coil located in the measurement module. A meter factor, or K-factor, is determined for the meter in a flow calibration laboratory by counting the pulses for a known volume of flow and is normally expressed as pulses per actual cubic feet (acf). This K-factor is unique to the meter and defines its accuracy.

The mechanical-style meter uses a mechanical gear train to determine the rotor's relationship to volume flow. The gear train is commonly comprised of a series of worm gears, drive gears, and intermediate gear assemblies that translates the rotor movement to a mechanical counter. In the mechanical-style meter, a proof curve is established in a flow calibration laboratory and a combination of change gears is installed to shift the proof curve to 100%.

Turbine meter performance is commonly defined by rangeability, linearity, and repeatability.

(a) Rangeability is a measure of the stability of the output under a given set of flow conditions. It is the ratio of the maximum meter capacity to the minimum capacity for a set of operating conditions during which the meter maintains its specified accuracy.

(b) Linearity is the total deviation in the meter's indication over a stated flow range; it is commonly expressed by meter manufacturers to be within ±0.5% over limited flow ranges. High-accuracy meters have typical linearities of ±0.15% for liquids and ±0.25% for gases, usually specified over a 10:1 dynamic range below maximum rated flow.

(c) Repeatability is the ability of the meter to indicate the same reading each time the same conditions exist; it is normally expressed as ±0.1% of reading for liquids and ±0.25% for gases. Accuracy must be expressed as a composite statement of repeatability and linearity over a stated range of flow rates.

Dual-rotor turbine meters with self-checking and self-diagnostic capabilities are recommended to aid measurement accuracy to detect and adjust for mechanical wear, fluid friction, and upstream swirl. Additionally, dual-rotor meter electronics and flow algorithms detect and make partial adjustments for severe jetting and pulsation. ASME PTC 19.5 should be consulted for guidance for flow disturbances that may affect meter performance and standardized tests to assess the effects of such disturbances.

In accordance with ASME PTC 19.5, an individual calibration shall be performed on each turbine meter at conditions as close as possible to the test conditions under which the meter is to operate. This shall include using the fluid, operating conditions (temperature and pressure), and piping arrangements as nearly identical to the test conditions as is practical with calibration data points that are taken at flow rates that surround the range of expected test flows. The orientation of the turbine meter will influence the nature of the load on the rotor bearings and thus the performance of the meter at low flow rates. For optimum accuracy, the turbine meter should be installed in the same orientation in which it was calibrated. The turbine meter calibration report must be examined to confirm the uncertainty as calibrated in the calibration medium.

As the effect of viscosity on the turbine meter calibration K-factor is unique, turbine meters measuring liquid fuel flow rate shall be calibrated at two kinematic viscosity points surrounding the test fluid viscosity. Each kinematic viscosity point shall have three different calibration temperatures that encompass the liquid fuel temperature expected during the test. A universal viscosity curve (UVC) should be developed to establish the sensitivity of the meter's K-factor to a function of the ratio of the output frequency to the kinematic viscosity. The UVC reflects the combined effects of velocity, density, and absolute viscosity acting on the meter. The latter two effects are combined into a single parameter by using kinematic viscosity.

4-8.3.7.2 Positive Displacement Meters. This Code recommends positive displacement meters for liquid fuel flows for all size pipes, but in particular for pipes less than 8 cm (3 in.). There are many designs of positive displacement meters including wobble plate, rotating piston, rotating vanes, and gear or impeller types. All these designs measure volumetric flow directly by continuously separating (isolating) a flow stream into discrete volumetric segments and counting them. As such, they are often called "volumeters." Because each count represents a discrete volume of fluid, positive displacement meters are ideally suited for automatic batching and accounting. Unlike differential pressure class meters and turbine meters, positive displacement meters are relatively insensitive to piping installations and otherwise poor flow conditions. Use of positive displacement meters is recommended without temperature compensation. The effects of temperature on fluid density can be accounted for by calculating the mass flow based on the specific gravity at the flowing temperature.

Fuel analyses should be completed on samples taken during testing. The lower and higher heating value of the fuel and the specific gravity of the fuel should be determined from these fuel analyses. The specific gravity should be evaluated at three temperatures covering the range of temperatures measured during testing. The specific gravity at flowing temperatures should then be determined by interpolating between the measured values to the correct temperature.

Positive displacement meters should be calibrated in the same fluid at the same temperature and flow rate as is expected in their intended performance test environment or service. If the calibration laboratory does not have the identical fluid, the next best procedure is to calibrate the meter in a similar fluid over the same range of viscosity-pressure drop factor expected in service. This recommendation implies duplicating the absolute viscosity of the two fluids.

4-9 TEMPERATURE MEASUREMENT

4-9.1 Introduction

This subsection presents requirements and guidance for the measurement of temperature. Recommended temperature measurement devices and the calibration and application of temperature measurement devices are discussed. Electronic temperature measurement equipment should be used for primary measurements to minimize systematic and random error. Factors affecting the uncertainty of the temperature include, but are not limited to, stability, environment, self-heating, parasitic resistance, parasitic voltages, resolution, repeatability, hysteresis, vibration, warm-up time, immersion or conduction, radiation, dynamics, spatial variation, and data acquisition.

Since temperature measurement technology changes over time, this Code does not limit the use of other temperature measurement devices not currently available or not currently reliable. If such a device becomes available and is shown to be of the required uncertainty and reliability, it may be used.

All signal cables should have a grounded shield or twisted pairs to drain any induced currents from nearby electrical equipment. All signal cables should be installed away from devices that produce electromagnetic fields, e.g., motors, generators, electrical conduit, cable trays, and electrical service panels.

4-9.2 Required Uncertainty

The required uncertainty depends on the type of parameters and variables being measured. Class 1 primary parameters and variables shall be determined with temperature measurement devices that have an instrument systematic uncertainty of no more than ±0.28°C (±0.50°F) for temperatures less than 93°C (200°F) and no more than ±0.56°C (±1.0°F) for temperatures more than 93°C (200°F).

Class 2 primary parameters and variables shall be determined with temperature measurement devices that have an instrument systematic uncertainty of no more than ±1.7°C (±3.0°F).

Secondary parameters and variables should be determined with temperature measurement devices that have an instrument systematic uncertainty of no more than ±3.9°C (±7.0°F).

These uncertainty limits are exclusive of any effects of temperature spatial gradient uncertainty effects, which are considered systematic.

4-9.3 Recommended Temperature Measurement Devices

The recommended temperature measurement devices are thermocouples, resistance temperature detectors (RTD), and thermistors. Economics, application, and uncertainty factors should be considered in the selection of the most appropriate temperature measurement device. The thermistor is best characterized for its sensitivity, the thermocouple is the most versatile, and the RTD is the most stable.

4-9.3.1 Thermocouples. Thermocouples may be used to measure the temperature of any fluid above 93°C (200°F). The maximum temperature is dependent on the type of thermocouple and sheath material used. Thermocouples should not be used for measurements below 93°C (200°F). Thermocouples used to measure primary parameters must have continuous leads from the measuring junction to the connection on the reference junction. These high-accuracy thermocouples must have a reference junction at 0°C (32°F) or an ambient reference junction that is well insulated and calibrated.

The elements of a thermocouple must be electrically isolated from each other, from ground, and from conductors on which they may be mounted, except at the measuring junction. When a thermocouple is mounted along a conductor, such as a pipe or metal structure, special care should be taken to ensure good electrical insulation between the thermocouple wires and the conductor to prevent stray currents in the conductor from entering the thermocouple circuit and vitiating the readings. Stray currents may further be reduced with the use of guarded integrating analog-to-digital (A/D) techniques. Further, to reduce the possibility of magnetically induced noise, the thermocouple wires should be constructed in a twisted uniform manner.

Thermocouples are susceptible to drift after cycling. Cycling is the act of exposing the thermocouple to process temperature and then removing it to ambient conditions. The number of times a thermocouple is cycled should be kept to a minimum. Thermocouples can be used effectively in high-vibration areas such as main or high-pressure inlets to a steam turbine. High-vibration measurement locations may not be conducive to other measurement devices. This Code recommends that the highest electromagnetic field per degree be used in all applications. NIST has recommended temperature ranges for each specific type of thermocouple.

The temperature of the reference junction shall be measured accurately using either software or hardware compensation techniques. The accuracy with which the temperature of the measuring junction is measured can be no greater than the accuracy with which the temperature of the reference junction is known. The reference junction temperature shall be held at the ice point or at the stable temperature of an isothermal reference. When thermocouple reference junctions are immersed in an ice bath (i.e., a mixture of melting shaved ice and water), the bulb of a precision thermometer shall be immersed at the same level as the reference junctions and in contact with them. Any deviation from the ice point shall be promptly corrected. Each reference junction shall be electrically insulated. When the isothermal-cold junction reference method is used, it shall employ an accurate temperature measurement of the reference sink. When electronically controlled reference junctions are used, they shall have the ability to control the reference temperature to within ±0.03°C (±0.05°F). Particular attention must be paid to the terminals of any reference junction since errors can be introduced by temperature variation, material properties, or wire mismatching. By calibration, the overall reference system shall be verified to have an uncertainty of less than ±0.1°C (±0.2°F). Isothermal thermocouple reference blocks furnished as part of digital systems may be used in accordance with this Code provided the accuracy is equivalent to the electronic reference junction. Commercial data acquisition systems use a measured reference junction, and the accuracy of this measurement is incorporated into the manufacturer's specification for the device. The uncertainty of the reference junction shall be included in the uncertainty calculation of the measurement to determine if the measurement meets the standards of this Code.

The thermocouple signal conversion should use International Temperature Scale of 1990 (ITS-90) software compensation techniques.

4-9.3.2 Resistance Temperature Detectors. RTDs may only be used to measure temperature from −270°C to 850°C (−454°F to 1,562°F). ASTM E1137 provides standard specifications for industrial platinum resistance thermometers and includes requirements for manufacture, pressure, vibration, and mechanical shock to improve the performance and longevity of these devices. Field verification techniques should be used to demonstrate that the stability is within the uncertainty requirements of this Code.

Primary parameters shall be measured with Grade A four-wire platinum RTDs. Three-wire RTDs are acceptable only if they can be shown to meet the uncertainty requirements of this Code.

Secondary parameters shall be measured with Grade A three-wire platinum RTDs. The four-wire technique is preferred to minimize effects associated with lead-wire resistance due to dissimilar lead wires.

Many devices are available to measure the output resistance. Each of these instruments shall meet the uncertainty requirements for the parameter measured.

4-9.3.3 Thermistors. Thermistors are constructed with ceramic-like semiconducting material that acts as a thermally sensitive variable resistor. This device may be used on any measurement below 149°C (300°F). Above this temperature, many instruments are available to measure the output resistance. Each of these instruments shall meet the uncertainty requirements for the parameter measured.

4-9.4 Calibration of Primary Parameter Temperature Measurement Devices

Primary parameter instrumentation used to measure temperature should have a suitable calibration history such as NIST. The calibration shall be conducted over the temperature range in which the instrument is used. See ASME PTC 19.3 for a more detailed discussion of calibration methods.

4-9.5 Temperature Scale

ITS-90 is realized and maintained by NIST to provide a standard scale of temperature for use by science and industry in the United States.

4-10 DATA COLLECTION AND HANDLING

This subsection presents requirements and guidance regarding the acquisition and handling of test data. The fundamental elements essential to the makeup of an overall data acquisition and handling system are also presented.

This Code recognizes that technologies and methods in data acquisition and handling will continue to change and improve over time. If new technologies and methods become available and are shown to meet the required standards stated within this Code, they may be used.

4-10.1 Data Acquisition System

The purpose of a data acquisition system is to collect data and store it in a form suitable for processing or presentation. Systems may be as simple as a person manually recording data or as complex as a digital computer-based system. Regardless of the complexity of the system, a data acquisition system must be capable of recording, sampling, and storing the data within the requirements of the test and allowable uncertainty set by this Code. Data acquisition shall also ensure that recording of all data is achieved with proper time synchronization and time stamping. It is recommended that a proper automated data acquisition system be used for tests under this Code so that human error can be avoided and correct time stamping with proper time synchronization of each parameter is achieved.

4-10.1.1 Manual System. In some cases, it may be necessary or advantageous to record data manually. It should be recognized that this type of system introduces additional uncertainty in the form of human error, and such uncertainty should be accounted for accordingly. Further, due to their limited sampling rate, manual systems may require longer periods of time or additional personnel for sufficient samples to be taken. Test period duration should be selected with this in mind, allowing enough time to gather the number of samples required by the test. Data collection sheets should be prepared before the test. The data collection sheets should identify the test site location, date, time, and type of data collected, and should also delineate the sampling time required for the measurements. Sample times should be clocked using a digital stopwatch or other sufficient timing device. If it becomes necessary to edit data sheets during the testing, all edits shall be made using black ink, and all errors shall be marked through with a single line and initialed and dated by the editor.

4-10.1.2 Automated System. Automated systems are beneficial in that they allow for the collection of data from multiple sources at high frequencies while recording the time interval with an internal digital clock. Rapid sampling rates serve to reduce test uncertainty and test duration. Automated systems can consist of a centralized processing unit or distributed processing to multiple locations in the plant.

The setup, programming, channel lists, signal conditioning, operational accuracies, and lists of the equipment making up the automated system used to determine primary Class 1 parameters shall be prepared and supplied in the test report.

4-10.2 Data Management

4-10.2.1 Automated Collected Data. All automated collected data should be recorded in its uncorrected, uncalculated state to permit posttest data correction for application of any necessary calibration corrections. Immediately after the test and before the parties to the test leave the test site, copies of the automated collected data should be distributed between the parties to the test to secure against the chance of such data being accidentally lost, damaged, or modified. Similar steps should be taken with any corrected or calculated results from the test.

4-10.2.2 Manually Collected Data. All manually collected data recorded on data collection sheets must be reviewed for completeness and correctness. Immediately after the test and before the parties to the test leave the test site, photocopies of the data collection sheets should be made and distributed between the parties to the test to eliminate the chance of such data being accidentally lost, damaged, or modified.

4-10.2.3 Data Calculation Systems. The data calculation system should have the capability to average each input collected during the test. The system should also calculate standard deviation and coefficient of variance of each instrument. The system should have the ability to locate and eliminate spurious data from use in the calculation of the average. The system should also be able to plot the test data and each instrument reading over time to look for trends and outlying data.

4-10.3 Data Acquisition System Selection

4-10.3.1 Data Acquisition System Requirements. The test procedure should clearly dictate the type of measurements to be made, allowable uncertainty of each measurement, number of data points needed, the length of the test, the number of samples required, and the frequency of data collection to meet the allowable test uncertainty set by this Code. This information will serve as a guide in the selection of data acquisition equipment and system design. The data acquisition system must meet the loop calibration requirements of para. 4-4.2.

4-10.3.2 Temporary Automated Data Acquisition System. This Code recommends the use of temporary automated data acquisition systems for testing purposes. These systems can be carefully calibrated, their proper operation can be confirmed in the laboratory. They can then be transported to the testing area, thus providing traceability and control of the complete system. Temporary instruments are limited in their exposure to the elements and avoid the problems associated with construction and ordinary plant maintenance. Site layout and ambient conditions must be considered when determining the type and application of temporary systems.

4-10.3.3 Existing Plant Measurement and Control System. This Code does not prohibit the use of an existing plant measurement and control system. However, the system must meet the requirements set forth in this Code. The limitations and restrictions of these systems should be considered when deciding whether to use them for performance testing.

Most distributed control systems (DCS) in plants apply threshold or deadband restraints on data signals. This results in data that are only the report of the change in a parameter that exceeds a set threshold value. All threshold values must be set low enough that all data signals sent to the data acquisition system during a test are reported and stored. In addition to deadbands, most DCS include analog-to-digital conversion and apply compression to the signal, which increases uncertainty. As with instrumentation, all systematic uncertainty effects of using the DCS as a data logger must be fully understood and accounted for in the pretest and uncertainty analyses using the guidelines of ASME PTC 19.1 and ASME PTC 19.22.

Most existing plant systems do not calculate flow rates in accordance with this Code, but rather by simplified relationships. This includes a constant discharge coefficient or even expansion factor. A plant system indication of flow rate shall not be used in the execution of this Code, unless the fundamental input parameters are also logged and the calculated flow is confirmed to be in complete accordance with this Code and ASME PTC 19.5.

Section 5
Computation of Results

5-1 INTRODUCTION

This Section presents the computation of corrected performance parameters of an ESS and the correction factors to be applied to measured parameters for alternative test methods. The following corrected parameters are computed:

(a) corrected primary charge energy, $E_{C,\text{corr}}$
(b) corrected primary discharge energy, $E_{D,\text{corr}}$
(c) corrected fuel heat rate, FHR_{corr}
(d) corrected charge power, $P_{C,\text{corr}}$
(e) corrected discharge power, $P_{D,\text{corr}}$
(f) corrected primary energy rate, PER_{corr}
(g) corrected rate of fuel energy flow during discharge, $Q_{D,\text{corr}}$
(h) corrected secondary energy rate, SER_{corr}
(i) corrected rated discharge interval, $\Delta t_{D,\text{corr}}$
(j) corrected overall efficiency, $\eta_{\text{corr,total}}$

The parties to the test shall agree to the test method and the application of correction factors before the test.

5-2 TEST METHODS

Methods of testing are interval or cycle as represented in Figures 5-4.1-1 and 5-4.2-1. Test methods and the type of test may be selected to suit the system under test and the test objectives.

(a) Interval Tests. Interval tests apply to charging and discharging processes. The test may start at any state of charge and operate for any length of time. The state of charge at the beginning and end of the test may be used to extrapolate the rated state of charge. Mass and/or energy may cross the test boundary from the storage reservoir, which is outside the test boundary.

(1) Interval tests may be used with systems for which the change of internal energy of the storage reservoir can be determined by physical measurement. Examples of such systems include the following:

(-a) sensible heat storage of incompressible liquids (e.g., molten salt) in tanks using measurement of the mass flow rate and temperature of the energy storage medium crossing the boundary. The rated state of charge may be extrapolated from the reservoir level measurements.

(-b) latent heat storage in liquid/vapor media (e.g., cryogenic liquids) using measurement of the mass flow rate and temperature of the storage media crossing the test boundary. The rated state of charge may be extrapolated from the reservoir level measurements.

(-c) gravitational storage (e.g., pumped hydro) using measurement of volume flow rate and temperature of the storage media crossing the test boundary. The rated state of charge may be extrapolated from the reservoir level measurements and a profile of the reservoir volume versus depth.

(-d) electrochemical storage (e.g., flow batteries) using measurement of the mass flow rate and valence state of the storage media crossing the test boundary. The rated state of charge may be extrapolated from the reservoir level measurements.

(-e) kinetic storage (e.g., flywheels) using measurement of the rotational speed (rotations per minute). The rated state of charge may be estimated by comparing speed measurements to a reference speed curve.

(2) For the types of systems in (-a) through (-e), interval tests may also provide an estimation of standby losses by

(-a) measurement of the change in temperature of media entering the reservoir during charging vs. that of media leaving the reservoir during discharging

(-b) measurement of the change of reservoir volume or measurement of the change in rotational speed

(3) There may be additional uncertainty when interval tests are performed with systems whose reservoir characteristics make internal energy extrapolation more difficult, such as the following:

(-a) Pneumatic storage (e.g., compressed air) may use measurement of mass flow rate, pressure, and temperature of the energy storage medium crossing the test boundary. However, the internal energy state is path dependent, and bulk reservoir volume and temperature may not be observable; thus, extrapolation to 100% state of charge may require additional assumptions.

(-b) Sensible heat storage in solid media (e.g., concrete) may use measurement of the mass flow rate and temperature of the heat transfer fluid crossing the test boundary. However, the bulk reservoir mass, temperature, and heat capacity may not be observable; thus, extrapolation to 100% state of charge may require additional assumptions.

(b) Cycle Tests. Cycle test methods encompass charge, standby, and discharge intervals over a cycle that begins and ends at the same state of charge. The principal challenge with a cycle test is the determination of the cycle state of charge with sufficient accuracy to begin and end at the same state. Cycle tests may use the interval test correction curves during charging and discharging intervals.

5-3 STATE OF CHARGE

State of charge is a measure of the primary energy available for discharge from the system. Thus, the state of charge is related to both the total energy stored and the discharge efficiency, which may depend on operating and ambient conditions.

Total energy is comprised of internal energy, kinetic energy, and potential energy. Energy is typically stored as one of the three components of total energy:

$$E = U + \mathrm{Kin}E + \mathrm{Pot}E \tag{5-3-1}$$

All terms in this Section are defined in Tables 2-2-1 and 2-2-2.

5-3.1 Internal Energy Storage

Internal energy is an extensive thermodynamic property proportional to the mass of storage medium contained within the storage defined as

$$U = G + TS + pV \tag{5-3-2}$$

Because the conversion from primary energy to internal energy is dependent on the thermodynamic path, the state of charge cannot be known a priori, but is only known after the system is discharged. A vendor may provide a state of charge indication based on observation or modeling of the storage reservoir, the charging and discharging history, and ambient conditions. A test may be performed to calibrate or assess the state of charge indication.

Charging and discharging of storage reservoirs is an inherently unsteady process, and the rate of charge, rate of discharge, and standby duration may affect measured and calculated performance due to path dependence of the internal energy as well as the influence of losses or gains of mass and energy.

(a) Nonreacting Storage Media. If there are no chemical reactions in the storage medium, the change in Gibbs free energy is zero.

For many systems, it is convenient to use intensive properties (i.e., per unit of mass), which are readily measured or calculated.

(b) Sensible Heat Storage in an Incompressible Medium. For bulk storage of incompressible liquids and solids, the change in internal energy equals the change in enthalpy:

$$\Delta U = M\Delta h \text{ or } \Delta u = \dot{m}\Delta t\Delta h \tag{5-3-3}$$

This can be approximated for liquids with constant heat capacity as

$$\Delta U = Mc_p\Delta T \text{ or } \Delta u = \dot{m}\Delta t c_p\Delta T \tag{5-3-4}$$

(c) Compressed Air Energy Storage (CAES). For compressed air systems, internal energy is path dependent, and the compression and expansion of the storage medium depend on the reservoir pressure and temperature and frictional characteristics at the cavern entrance or within the interstices of aquifers.

Deep underground storage reservoirs may require consideration of gravitational pressure in addition to heat transfer, velocity-dependent acceleration, and frictional effects:

$$\begin{aligned}\Delta U &= Q - W \\ &= Q + \int_1^2 V\,\mathrm{dp} + \frac{\Delta s^2}{2g_c} + \Delta z\frac{g}{g_c} + \sum f\end{aligned} \quad (5\text{-}3\text{-}5)$$

where s = velocity of the air.

CAES may require cycle test methods because the work of compression/decompression processes depends on the thermodynamic path by which pressure is changed as well as the rate-dependent frictional effects.

(d) Flow Batteries. For idealized flow batteries, the change in internal energy is the rate of change of Gibbs free energy. (Actual batteries may include enthalpy changes.)

$$\Delta U = \Delta G = n\mathrm{F}e = \dot{m}\Delta t\mathrm{K}e \quad (5\text{-}3\text{-}6)$$

5-3.2 Kinetic Energy Storage

For flywheel energy storage, the change in total energy is computed as follows:

$$\Delta \mathrm{Kin}E = \frac{1}{2}I_m(\Omega^2_{\mathrm{start}} - \Omega^2_{\mathrm{end}}) \quad (5\text{-}3\text{-}7)$$

5-3.3 Potential Energy Storage

For pumped storage, the change in total energy is represented by the change in pressure of the volume, V, of the storage medium:

$$\Delta U = \frac{V\Delta p}{J} \text{ or } \Delta u = \frac{v\Delta p}{J} \quad (5\text{-}3\text{-}8)$$

5-4 TEST OBJECTIVES

The operating disposition during a test may be steady state or it may include transient conditions including transitions between the charging, standby, and discharge modes.

5-4.1 Interval Tests

Interval tests can be used to evaluate performance at specific dispositions, such as rated charge or discharge power. Figure 5-4.1-1 shows an idealized discharge interval test conducted at steady-state power. Illustration (a) shows the flow rates of energy as measured and as corrected. Although the measured energy flow rates are shown as constant, during a test they may vary due to changes in ambient conditions or in the state of charge (such as pressure or temperature of the medium flowing from the storage reservoir). Illustration (b) shows the cumulative corrected primary energy flow during the test. The limits of reservoir capacity can be extrapolated from reservoir-level measurements to determine the corrected rated discharge duration of the system.

Similar curves apply to a charge interval test. Because the state of charge is referenced to the discharge of primary energy, the reservoir's energy storage capacity must be extrapolated.

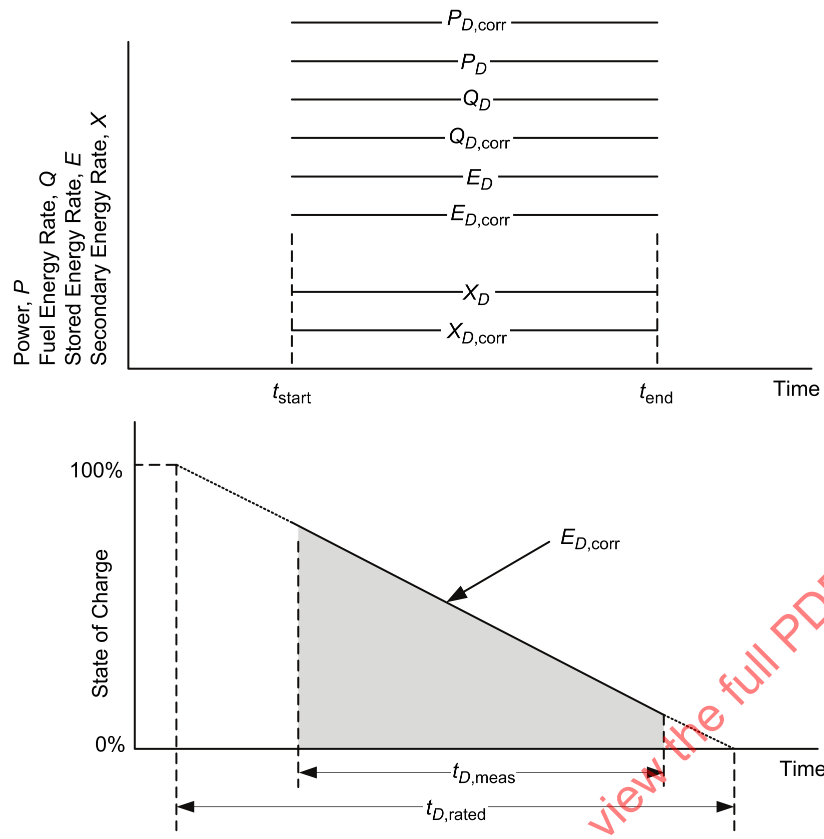
The primary energy rate is obtained by multiplying the stored energy rates for the charging and discharging intervals.

Simultaneous charge and discharge interval tests may be convenient for testing and are acceptable provided there are independent paths and metering to and from storage reservoirs. One example of an acceptable system is multitank thermal storage where charging of one tank does not affect the discharging of a second tank.

5-4.2 Cycle Tests

Cycle tests evaluate overall performance over a cycle of charge, standby, and discharge intervals, beginning and ending at the same state of charge. Cycle tests include the transitions between operating modes. Interval test runs may be conducted during a cycle test. The cycle test may begin at any interval.

Figure 5-4.1-1
Extrapolation of Energy Flow From Storage to Determine Corrected Discharge Duration for Linear ESSs



GENERAL NOTE: For nonlinear ESSs, suitable correction curves may be provided by the manufacturer and agreed to by the parties to the test.

Figure 5-4.2-1 shows an idealized cycle test, ignoring the ramps with constant power during discharging and charging, with the same state of charge at the beginning and end of the test. The standby period may be specified or measured.

In the idealized case, the charge and discharge power is instantaneously available at the start of the respective charge and discharge intervals and is steady throughout the respective intervals. In the idealized case, measurements of material and energy flows crossing the test boundary can be corrected, as is done for an interval test.

In a realistic cycle test, the mass and material flows crossing the test boundary will change at the beginning and end of each interval. Startup and shutdown transients will occur for the charging and discharging processes as they are adjusted to the required disposition. A sequence might include the following steps:

Step 1. Discharge startup transient from zero to a specified disposition, such as rated power output.

Step 2. Discharge at the specified disposition until a specified state of charge is reached.

Step 3. Discharge shutdown transient from a specified discharge disposition to zero output.

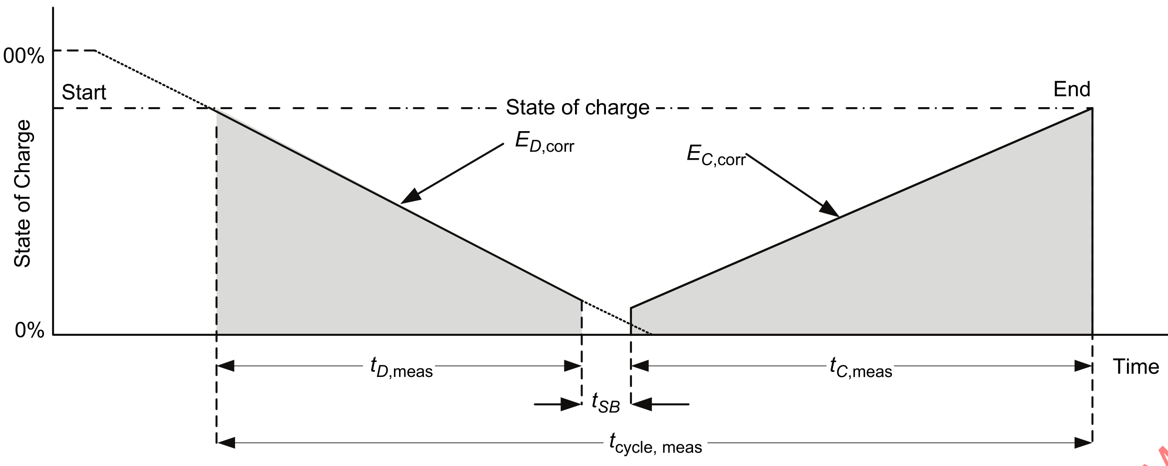
Step 4. Wait during a standby interval; the standby interval can be a specified duration or a duration determined by external factors, such as availability of power for charging or the duration of charging needed to establish an agreed state of charge.

Step 5. Charge startup transient from zero to a specified disposition, such as rated power input.

Step 6. Charge at the specified disposition until the original state of charge is reached.

Step 7. Charge shutdown transient from the specified discharge disposition to zero input.

Figure 5-4.2-1
Idealized Cycle Test Beginning and Ending at the Same State of Charge



5-5 EQUATIONS FOR INTERVAL TESTS

Interval test boundaries exclude the storage reservoirs and measure the flow of mass and energy to and from the storage reservoirs. Interval tests may be conducted over a single interval (e.g., the discharge interval, a standby interval, or a charge interval) or they may be conducted over a sequence. If conducted over a sequence, there is no requirement that the system be returned to the same state of charge at the end of the sequence. Performance metrics can be calculated for each interval and for the overall test.

5-5.1 Discharge Interval

Additive and multiplicative correction factors defined in Table 5-7.1-1 are used to adjust test measurements to a common reference condition.

The corrected discharge output power is

$$P_{D,\mathrm{corr}} = \left(P_{D,\mathrm{meas}} + \sum_{i=1}^{l} \Delta_i\right) \prod_{j=1}^{m} \alpha_j \tag{5-5-1}$$

For systems that do not use fuel for discharge, the corrected fuel input is zero. For systems that use fuel during discharge, the corrected rate of fuel input during discharge is

$$Q_{D,\mathrm{corr}} = \left(Q_{D,\mathrm{meas}} + \sum_{i=1}^{l} \omega_i\right) \prod_{j=1}^{m} \beta_j \tag{5-5-2}$$

The corrected discharge energy from storage is

$$E_{D,\mathrm{corr}} = \left(\Delta U + \sum_{i=1}^{l} \varphi_i\right) \prod_{j=1}^{m} \varepsilon_j \tag{5-5-3}$$

The corrected secondary energy is

$$X_{D,\mathrm{corr}} = \left(X_{D,\mathrm{meas}} + \sum_{i=1}^{l} \xi_i\right) \prod_{j=1}^{m} \psi_j \tag{5-5-4}$$

The corrected discharge primary energy is the average (indicated by overbar) of the corrected discharge power during the discharge interval multiplied by the duration of the discharge interval:

$$Y_{D,\mathrm{corr,cycle}} = \overline{P_{D,\,\mathrm{corr}}\, t_{D,\mathrm{meas}}} \tag{5-5-5}$$

For systems that do not use fuel, the corrected fuel heat rate is zero. For systems that use fuel during discharge, the corrected discharge fuel heat rate is expressed as

$$\mathrm{FHR}_{\mathrm{corr}} = \frac{Q_{D,\mathrm{corr}}}{Y_{D,\mathrm{corr}}} \tag{5-5-6}$$

The corrected discharge stored energy rate from storage is expressed as

$$\mathrm{SER}_{D,\mathrm{corr}} = \frac{E_{D,\mathrm{corr}}}{Y_{D,\mathrm{corr}}} \tag{5-5-7}$$

The corrected discharge secondary energy rate is expressed as

$$\mathrm{XER}_{D,\mathrm{corr}} = \frac{X_{D,\mathrm{corr}}}{Y_{D,\mathrm{corr}}} \tag{5-5-8}$$

For systems with measured mass flow rate, $\dot{m}_{\mathrm{meas}}$, from storage reservoirs rated to contain a mass, M_{rated}, the discharge duration is corrected according to the enthalpy flows from the reservoir:

$$t_{D,\mathrm{corr}} = \frac{M_{\mathrm{rated}}}{\dot{m}_{\mathrm{meas}} \prod_{j=1}^{m} \mu_j} \tag{5-5-9}$$

5-5.2 Charge Interval

Additive and multiplicative correction factors defined in Table 5-7.2-1 are used to adjust test measurements to a common reference condition.

The corrected charge power is

$$P_{C,\mathrm{corr}} = \left(P_{C,\mathrm{meas}} + \sum_{i=1}^{l} \sigma_i\right) \prod_{j=1}^{m} \tau_j \tag{5-5-10}$$

The charge energy is the integral of the charge power over charge time:

$$E_{C,\mathrm{corr}} = P_{C,\mathrm{corr}} t_{C,\mathrm{meas}} \tag{5-5-11}$$

The charge stored energy rate expresses the conversion of charge energy to internal energy of the storage medium:

$$\mathrm{SER}_C = \frac{E_C}{\Delta U} \left(\sum_{i=1}^{l} \kappa_i\right) \prod_{j=1}^{m} \lambda_j \tag{5-5-12}$$

For systems with measured mass flow rate, $\dot{m}_{\mathrm{meas}}$, into storage reservoirs rated to contain a mass, M_{rated}, the charge duration is corrected according to the enthalpy flows into the reservoir, as follows:

$$t_{C,\mathrm{corr}} = \frac{M_{\mathrm{rated}}}{\dot{m}_{\mathrm{meas}} \prod_{j=1}^{m} \pi_j} \tag{5-5-13}$$

5-5.3 Standby Interval

(a) Standby energy flow affects the extensive internal energy of the system, including state of charge or the state of the charge or discharge process. Examples of energy flow include

(1) heat loss from hot thermal ESSs
(2) heat gain into cryogenic storage systems
(3) heat loss from or heat gain into the charge and discharge equipment
(4) mass loss due to leakage from pumped hydro, compressed air, or cryogenic storage systems
(5) self-discharge for batteries
(6) kinetic energy loss for flywheels

(b) Energy may cross the test boundary during standby to maintain state of charge or to mitigate heat loss. Examples that may be metered include

(1) heating or cooling of batteries or their electrolytes
(2) heat tracing of molten salt piping and equipment
(3) molten salt tank immersion heaters

(4) boil-off gas compressors for recondensing cryogenic storage media
(5) flywheel magnetic bearings
(6) house loads

(c) During standby, there may be unmetered influx or efflux of mass and energy such as
(1) heat gain into cold storage media or associated equipment
(2) heat loss from hot storage media or associated equipment
(3) mass loss from surface evaporation of water reservoirs; compressed air leakage; boil-off gas from cryogenic storage tanks; or leakage from hydro reservoirs, joints, glands, or seals
(4) mass gain into hydro reservoirs from precipitation and runoff or surface condensation

(d) There may be additional energy gains and losses that are not directly metered but that are overcome during startup of the charging or discharging process.

(e) The amount of energy flow during standby depends on the ambient conditions and the duration of the standby interval. Determination of standby performance may not be practical or may be uncertain where the state of charge is unobservable or the quantity of unmetered mass or energy is significant.

The corrected standby energy is calculated as follows:

$$B_{D,\mathrm{corr}} = \left(B_{D,\mathrm{meas}} + \sum_{i=1}^{l} \theta_i\right)\prod_{j=1}^{m} \zeta_j \tag{5-5-14}$$

Additive and multiplicative correction factors defined in Table 5-7.3-1 are used to adjust test measurements to a common reference condition.

5-5.4 Roundtrip Primary Energy Rate and Efficiency

The primary energy rate for the system is the product of the rate of conversion of primary energy to internal energy during charging and the rate of conversion of internal energy to primary energy during discharging.

$$\mathrm{PER}_{\mathrm{roundtrip,corr}} = \mathrm{SER}_{C,\mathrm{corr}}\mathrm{SER}_{D,\mathrm{corr}} \tag{5-5-15}$$

The corrected primary energy efficiency for the system is calculated as follows:

$$\eta_{D,\mathrm{corr}} = \frac{Y_{D,\mathrm{corr}}}{(\mathrm{PER}_{\mathrm{roundtrip,corr}}Y_{D,\mathrm{corr}}) + Q_{D,\mathrm{corr}} + (X_{D,\mathrm{corr}} + X_{C,\mathrm{corr}})} \tag{5-5-16}$$

5-6 SECONDARY ENERGY

Secondary flows of heat and power may cross the test boundary during charging and discharging to supplement the primary energy and the fuel energy.

(a) Examples of secondary energy flows during charging that may affect the primary energy power input are
(1) process or waste heat inputs that supplement an electrically heated thermal ESS
(2) process or waste heat inputs that supplement an absorption chiller in an electrically cooled cold storage system
(3) waste cold inputs into a cryogenic cold storage system, such as from liquefied natural gas regasification

(b) Examples of secondary energy flows during discharging that may affect the primary energy power output or the fuel input are
(1) process or waste heat inputs into a cryogenic system for regasification or warming of cold gas
(2) process or waste heat inputs into a thermal ESS

To account for differences from reference conditions, the secondary energy flows may be corrected for the ambient conditions as well as for the mass flow rate and temperature of the secondary energy crossing the test boundary.

Energy retained within the test boundary for use during a subsequent charge or discharge interval is not secondary energy. Examples of secondary energy retained within the test boundary are waste cold that is captured and stored during discharge for cooling of a cryogenic charging system and waste heat from an air compressor that is captured during charging and stored for air heating during discharge.

5-7 CORRECTION FACTORS

The format of the equations in this Section allows decoupling of the appropriate correction effects relative to the measured prime variables of charge/discharge power, fuel heat, and charge/discharge duration. Corrections are calculated for parameters at the test boundary that are different from base reference conditions, which affect measured performance results, and for variance of the storage medium composition within the test boundary from the reference condition.

Correction curves applied to measured performance may be calculated using a performance model of the ESS contained within the test boundary or a method agreed to by parties to the test. The performance model represents the mathematical definition of the expected performance of the ESS at both rated and nonrated conditions. Each correction is calculated by running the performance model with a variance in only the variable to be corrected over the range of deviation from the reference condition. Correction curves are thus developed to be incorporated into the specific plant test procedure document. The model is finalized following purchase of all major equipment and receipt of performance information from all vendors.

Correction factors listed in Tables 5-7.1-1 through 5-7.3-1 are not exhaustive. Additional or alternative correction factors may be appropriate for some ESSs.

Correction factors assume steady-state operating conditions. Additional correction factors may be applied during transient startup or shutdown to account for warm-up and cool-down of charging and discharging components.

5-7.1 Correction Factors for Discharging

See Table 5-7.1-1.

5-7.2 Correction Factors for Charging

See Table 5-7.2-1.

5-7.3 Correction Factors for Standby

See Table 5-7.3-1.

5-7.4 Use of Performance Model

In lieu of applying correction factors to the equations, it is acceptable to apply the performance model after the test using appropriate test data and boundary conditions so that all corrections for the particular test run are calculated simultaneously. An advantage of this approach is that interactions between correction factors are fully compensated. The performance model can be used to develop an uncertainty cloud for performance measurements.

5-7.5 Use of ϕ_1, ε_1, κ_1, and λ_1 Correction Factors

Composition changes may affect the thermodynamic and transport properties of the storage medium and hence the performance of the ESS. The composition of the storage medium may differ from the reference case due to any of the following:

(a) fractionation, such as preferential boil-off of oxygen in liquid air energy storage tanks
(b) degradation, such as conversion of nitrate to nitrite in molten salt systems
(c) reaction with containers and piping

Sampling and analysis of the composition of the storage medium are outside the scope of this Code.

5-8 EQUATIONS FOR CYCLE TESTS

The cycle test boundary incorporates the storage reservoirs, and the cycle test must begin and end at the same internal energy within those storage reservoirs. Additive and multiplicative correction factors defined in Tables 5-7.1-1 through 5-7.3-1 are used to adjust test measurements to a common reference condition. The flow rates of primary energy, secondary energy, and fuel are measured and corrected during the test cycle.

The corrected rate of primary energy flow out of the ESS (i.e., discharge output power) is calculated as follows:

$$P_{D,\mathrm{corr}} = \left(P_{D,\mathrm{meas}} + \sum_{i=1}^{l} \Delta_i\right)\prod_{j=1}^{m} \alpha_j \tag{5-7-1}$$

For systems that do not use fuel for discharge, the corrected fuel input is zero. For systems that use fuel during discharge, the corrected rate of fuel input during discharge is calculated as follows:

$$Q_{D,\mathrm{corr}} = \left(Q_{D,\mathrm{meas}} + \sum_{i=1}^{l} \omega_i\right)\prod_{j=1}^{m} \beta_j \tag{5-7-2}$$

The corrected rate of primary energy flow into the ESS (i.e., charge input power) is calculated as follows:

$$P_{C,\mathrm{corr}} = (P_{C,\mathrm{meas}} + \sum_{i=1}^{l} \sigma_i)\prod_{j=1}^{m} \tau_j \tag{5-7-3}$$

For systems that do not use secondary energy, the corrected rate of secondary energy into the ESS is zero. For systems that use secondary energy, the corrected value is calculated as follows:

$$X_{\mathrm{cycle,corr}} = (X_{\mathrm{cycle,meas}} + \sum_{i=1}^{l} \xi_i)\prod_{j=1}^{m} \psi_j \tag{5-7-4}$$

The corrected primary energy into the system during charging is the average of the corrected charge power during the test cycle multiplied by the duration of the charge cycle:

$$Y_{C,\mathrm{corr,cycle}} = \overline{P_{C,\,\mathrm{corr}}\, t_{\mathrm{cycle}}} \tag{5-7-5}$$

The corrected discharge energy is the average of the corrected discharge power during the test cycle multiplied by the duration of the charge cycle:

$$Y_{D,\mathrm{corr,\,cycle}} = \overline{P_{D,\mathrm{corr}}\, t_{\mathrm{cycle}}} \tag{5-7-6}$$

The corrected standby energy is the average of the corrected discharge power during the test cycle multiplied by the duration of the charge cycle:

$$B_{\mathrm{corr,\,cycle}} = \overline{B_{\mathrm{corr}}\, t_{\mathrm{cycle}}} \tag{5-7-7}$$

The corrected fuel heat rate, corrected primary energy rate, and corrected secondary energy rate are ratios of the relevant corrected quantity (fuel energy, primary energy, and secondary energy) input to the ESS to the primary energy output from the ESS. These ratios may be calculated for the cycle or for charge, standby, and discharge intervals.

For systems that do not use fuel, the corrected fuel heat rate is zero. For systems that use fuel during discharge, the corrected fuel heat rate is expressed as

$$\mathrm{FHR}_{\mathrm{corr,cycle}} = \frac{Q_{D,\mathrm{corr}}}{Y_{D,\mathrm{corr,cycle}}} \tag{5-7-8}$$

The corrected discharge primary energy rate is expressed as

$$\mathrm{PER}_{\mathrm{corr,cycle}} = \frac{Y_{C,\mathrm{corr,cycle}}}{Y_{D,\mathrm{corr,cycle}}} \tag{5-7-9}$$

For systems that do not use secondary energy, the secondary energy rate is zero. For systems that use secondary energy, the corrected discharge secondary energy rate is expressed as

$$\mathrm{SER}_{\mathrm{corr,cycle}} = \frac{X_{\mathrm{corr,cycle}}}{Y_{D,\mathrm{corr,cycle}}} \tag{5-7-10}$$

Discharge duration is measured rather than calculated and may be affected by the composition of the storage medium.

The corrected overall storage efficiency is calculated as follows:

$$\eta_{\mathrm{corr}} = \frac{Y_{D,\mathrm{corr,cycle}}}{Y_{C,\mathrm{corr,cycle}} + Q_{D,\mathrm{corr,cycle}} + X_{D,\mathrm{corr,cycle}} + B_{D,\mathrm{corr,cycle}}} \tag{5-7-11}$$

Table 5-7.1-1
Correction Factors for Discharge Performance

Correction Factor	Description
ω_1, Δ_1, ϕ_1	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference thermal efflux to another process
ω_2, Δ_2, ϕ_2	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference generator power factor
ω_3, Δ_3, ϕ_3	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference steam generator blowdown
ω_4, Δ_4, ϕ_4	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference secondary heat inputs
ω_{5A}, Δ_{5A}, ϕ_{5A}	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference inlet air conditions at the cooling tower or air-cooled condenser air inlet
ω_{5B}, Δ_{5B}, ϕ_{5B}	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference circulation water temperature
ω_{5C}, Δ_{5C}, ϕ_{5C}	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference condenser pressure
ω_6, Δ_6, ϕ_6	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference auxiliary loads
ω_7, Δ_7, ϕ_7	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct for measured power different from specified if test goal is to operate at a predetermined power; can also be used if required unit operating disposition is not as required
ω_8, Δ_8, ϕ_8	Additive correction factors to power, fuel input, and energy input from storage, respectively, to correct to base reference fuel temperature
ϕ_9	Additive correction factor to energy input from storage to correct to base reference composition of the storage medium
α_1, β_1, ε_1, μ_1	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference ambient temperature
α_2, β_2, ε_2, μ_2	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference ambient pressure
α_3, β_3, ε_3, μ_3	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference ambient relative humidity
α_4, β_4, ε_4, μ_4	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference fuel supply temperature
α_5, β_5, ε_5, μ_5	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference fuel analysis
α_6, β_6, ε_6, μ_6	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference grid frequency
α_7, β_7, ε_7, μ_7	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference blowdown mass flow rate
α_8, β_8, ε_8, μ_8	Multiplicative correction factors to power, fuel energy input, energy input from storage, and mass flow rate from storage, respectively, to correct to base reference internal energy of storage
ε_9	Multiplicative correction factor to efflux of energy from storage to correct to base reference composition of the storage medium
ξ_1	Additive correction factor to influx of secondary energy during discharge to correct to base reference secondary energy input
ψ_1	Multiplicative correction factor to influx of secondary energy during discharge to correct to base reference secondary energy input

Table 5-7.2-1
Correction Factors for Charge Performance

Correction Factor	Description
σ_1, σ_2, σ_3	Additive correction factors to primary energy input to correct to base reference ambient temperature, pressure, and relative humidity, respectively
τ_1, τ_2, τ_3	Multiplicative correction factors to primary energy input to correct to base reference ambient temperature, pressure, and relative humidity, respectively
π_1, π_2, π_3	Multiplicative correction factors to mass flow rate into storage to correct to base reference ambient temperature, pressure, and relative humidity, respectively
κ_1	Additive correction factor to influx of internal energy into storage to correct to base reference composition of the storage medium
λ_1	Multiplicative correction factor to influx of internal energy into storage to correct to base reference composition of the storage medium
ξ_2	Additive correction factor to influx of secondary energy to correct to base reference secondary energy input
ψ_2	Multiplicative correction factor to influx of secondary energy to correct to base reference secondary energy input

Table 5-7.3-1
Correction Factors for Standby Performance

Correction Factor	Description
θ_i	Additive correction factor to influx/efflux of standby energy to correct to account for unmetered energy flows
ζ_1	Multiplicative correction factor to influx/efflux of standby energy to correct to base reference temperature

Section 6
Report of Results

6-1 GENERAL REQUIREMENTS

The test report for a performance test should incorporate the following general requirements:

(a) Executive Summary
(b) Introduction
(c) Control Boundary
(d) Calculation and Results
(e) Instrumentation
(f) Results Discussion
(g) Conclusions
(h) Appendices

This outline is a recommended report format. Other formats are acceptable. However, a report of the ESS performance test should contain, as a minimum, this information, described in detail in subsections 6-2 through 6-9.

6-2 EXECUTIVE SUMMARY

The Executive Summary shall be brief and shall contain the following:

(a) general information about the ESS (i.e., the ESS type and operating configuration), the test, and the test objective, including the test objective values (e.g., determination of heat rate, primary energy rate, charge power, discharge power, and storage duration)

(b) date and time of the test

(c) signature of each test coordinator

(d) signature of each reviewer

(e) approval signatures

(f) summary of the results of the test including uncertainty and conclusions reached

(g) comparison with the contract guarantee

(h) any agreements among the parties to the test (e.g., an agreement to allow any major deviation from the test requirements including a description of why the deviation occurred, the mitigation plan, and the impact to the uncertainty of the test due to the deviation)

6-3 INTRODUCTION

The Introduction of the test report shall include the following:

(a) authorization for the test, the object of the test, contractual obligations and guarantees, stipulated agreements, by whom the test is directed, and the representative parties to the test

(b) any additional general information about the ESS and the test not included in the Executive Summary, such as

(1) a historical perspective, if appropriate

(2) a cycle diagram showing the test boundary (see Nonmandatory Appendix A, Figure A-3-1, and Nonmandatory Appendix B, Figures B-2-1 through B-5-1 for examples of test boundary diagrams for specific ESS types or test goal)

(3) description of the equipment tested and any other auxiliary apparatus, the operation of which may influence the test result

(c) a listing of the representatives of the parties to the test

(d) any pretest agreements that were not tabulated in the Executive Summary, including a detailed description of deviations to the test procedure during the test, their resolution, and effect on the test results

(e) the professional affiliations of the test personnel

(f) test goal per Sections 3 and 5

6-4 CONTROL BOUNDARY

As this Code covers different types of ESSs, the test party or parties shall agree on the boundary conditions for the ESS before the test and shall include the same in the test report. The Control Boundary section of the test report shall also include

(a) a suitable schematic of the ESS with all its key equipment
(b) a list of primary inputs and outputs crossing the boundary
(c) a list of secondary inputs and outputs crossing the boundary
(d) a list of primary parameters to be measured
(e) a list of secondary parameters to be measured

6-5 CALCULATIONS AND RESULTS

The Calculations and Results section of the test report should include, in detail, the following:

(a) the method of the test and operating conditions.

(b) the format of the general performance equation that is used, based on the test goal and the applicable corrections. (This is repeated from the test requirements for convenience.)

(c) a tabular summary of measurements and observations, including the reduced data necessary to calculate the results and a summary of additional operating conditions that are not part of the reduced data.

(d) a step-by-step calculation of test results from the reduced data, including the probable uncertainty. See Nonmandatory Appendices A and B for examples of step-by-step calculations for a representative ESS type and test goal.

(e) a detailed calculation of primary energy and/or material flow rates from applicable data, including intermediate results, if required. Examples of primary flow rates are electrical power, fuel flow rates, and, if cogeneration, process flow rates.

(f) detailed calculations of heat input from fuel from any heat engine used to charge the ESS (e.g., coal-fired power plant using ASME PTC 4 and water- or steam-side measurements).

(g) detailed calculations of fuel properties for any heat engine used to charge the ESS (e.g., density, compressibility factor, and heating value). The values of constituent properties used in the detailed calculations shall be shown.

(h) any calculations showing elimination of data for outlier reason, or for any other reason.

(i) a comparison of repeatability of test runs.

(j) correction factors applied because of deviations, if any, of test conditions from those specified.

(k) primary measurement uncertainties, including method of application.

(l) test performances stated under the following headings:

(1) test results computed on the basis of the test operating conditions, instrument calibrations only having been applied

(2) test results corrected to specified conditions if test operating conditions have deviated from those specified

(m) a tabular and graphical presentation of the test results.

(n) discussion and details of the test results uncertainties.

(o) discussion of the test, its results, and conclusions.

6-6 INSTRUMENTATION

The Instrumentation section of the test report shall include the following:

(a) a tabulation of instrumentation used for the primary and secondary measurements, including make, model number, tag name and number, efficiency, uncertainty of each instrument, calibration date, and bias value

(b) a description of the instrumentation location

(c) the means of data collection for each data point (e.g., temporary data acquisition system printout, plant control computer printout, or manual data sheet, and any identifying tag number and/or address of each)

(d) the identification of the instrument used as backup

(e) a description of the data acquisition system or systems used

(f) a complete description of methods of measurement not prescribed by the individual code

(g) a summary of pretest and posttest calibration

6-7 RESULTS DISCUSSION

This Results section of the test report should include the following:

(a) a more detailed discussion of the test results, if required

(b) any recommended changes to future test procedures resulting from a "lesson learned" evaluation

6-8 CONCLUSIONS

The Conclusion of the test report shall summarize the following:
(a) performance parameters obtained from the test
(b) a comparison, if any, with the standard ("guaranteed" or desired) performance parameters
(c) a qualitative and/or quantitative concluding remark on the test results

6-9 APPENDICES

Appendices to the test report should include the following:
(a) the test requirements
(b) copies of original data sheets or data acquisition system printouts, or both
(c) copies of operator logs or other recordings of operating activity during each test
(d) copies of signed valve line-up sheets, and other documents indicating operation in the required configuration and disposition
(e) the results of laboratory fuel analysis
(f) instrumentation calibration results from laboratories or certification from manufacturers

Section 7
Test Uncertainty

7-1 INTRODUCTION

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. It is based on calculations using statistics and probability theory, instrumentation information, calculation procedure, and actual test data. This Code requires uncertainty be reported with a 95% level of confidence.

This Code addresses test uncertainty in

(a) Section 1, which defines maximum allowable test uncertainties above which the test is not acceptable for each type, or configuration, of ESS.

(b) Section 3, which defines the requirements for pretest and posttest uncertainty analyses and how they are used in the test. These uncertainty analyses and limits of error are defined and discussed in para. 3-5.2.1.

(c) Section 4, which describes the systematic uncertainty required for each test measurement.

(d) Section 7 and Nonmandatory Appendix A, which provide applicable guidance for calculating pretest and posttest uncertainty.

ASME PTC 19.1 covers general procedures for calculation of test uncertainty. A sample calculation is shown in Nonmandatory Appendix A.

7-2 PRETEST UNCERTAINTY ANALYSIS

A pretest uncertainty analysis shall be conducted to allow corrective action to be taken before the test, either to decrease the uncertainty to a level consistent with the overall objective of the test or to reduce the cost of the test while still attaining the objective (see para. 3-5.2.1). An uncertainty analysis is also useful for determining the number of observations that will be required.

7-3 POSTTEST UNCERTAINTY ANALYSIS

A posttest uncertainty analysis shall be conducted to determine the uncertainty intervals for the actual test. A posttest uncertainty analysis shall verify the assumptions made in the pretest uncertainty analysis. In particular, the data should be examined for sudden shifts and outliers. The assumptions for random errors should be checked by determining the degrees of freedom and the standard deviation of each measurement. This analysis serves to validate the quality of the test results and to expose problems.

7-4 INPUTS FOR AN UNCERTAINTY ANALYSIS

To perform an uncertainty analysis for an overall ESS, test inputs are required to estimate the uncertainty of each of the required measurements and the sensitivity of each of the required measurements on corrected results. Guidance on estimating the uncertainty and calculating the required sensitivity coefficients can be found in ASME PTC 19.1.

The following is a sample list of some of the items that should be considered when developing a pre- and post- test uncertainty analysis:

(a) calibration methodology

(b) linearity or nonlinearity of instruments

(c) different uncertainties of instruments (e.g., hysteresis or sensitivity)

(d) spatial uncertainty

(e) uncertainty of data acquisition system

(f) method of calibration and corresponding regression

(g) actual operating conditions for instrument versus designed use of instrument, and signal degradation, manipulation, compression, or dead band application before reading

NONMANDATORY APPENDIX A
SAMPLE CALCULATIONS FOR A COMBINED CYCLE POWER PLANT ESS

A-1 GENERAL

This Appendix demonstrates the calculating procedure for an ESS in a combined cycle power plant with thermal energy storage providing 100% of the evaporator duty. The test uses the interval test method applied to separate charge and discharge tests. The numerical values of the corrections and the number of independent variables used to calculate the corrections apply to this example only. Unique corrections shall be developed for each specific plant.

A-2 TEST OBJECTIVES

The performance test goals are accomplished by a discharge interval test and a charge interval test. The overall test goal is achieved by multiplying the corrected stored energy rates from the charge and discharge interval tests. Calculation of standby losses is not a test goal.

(a) Discharge Interval Test. The test goals for the discharge interval test are

(1) corrected net discharge power

(2) corrected net discharge fuel heat rate

(3) corrected net discharge stored energy rate

(4) corrected net discharge interval

(b) Charging Interval Test. The test goals for the charging interval test are

(1) corrected charge power

(2) corrected charge stored energy rate

(3) corrected rated discharge duration

(c) Overall Test Goal. The overall test goal is to determine the primary energy rate.

A-3 PLANT DESCRIPTION

The ESS for this sample calculation is integrated with a 93.45MW-gross combined cycle plant. The entire plant is within the ESS test boundary as shown in Figure A-3-1. Boundaries for the charge interval test and discharge interval test are within the test boundary and exclude the molten salt storage reservoirs.

A-3.1 Equipment

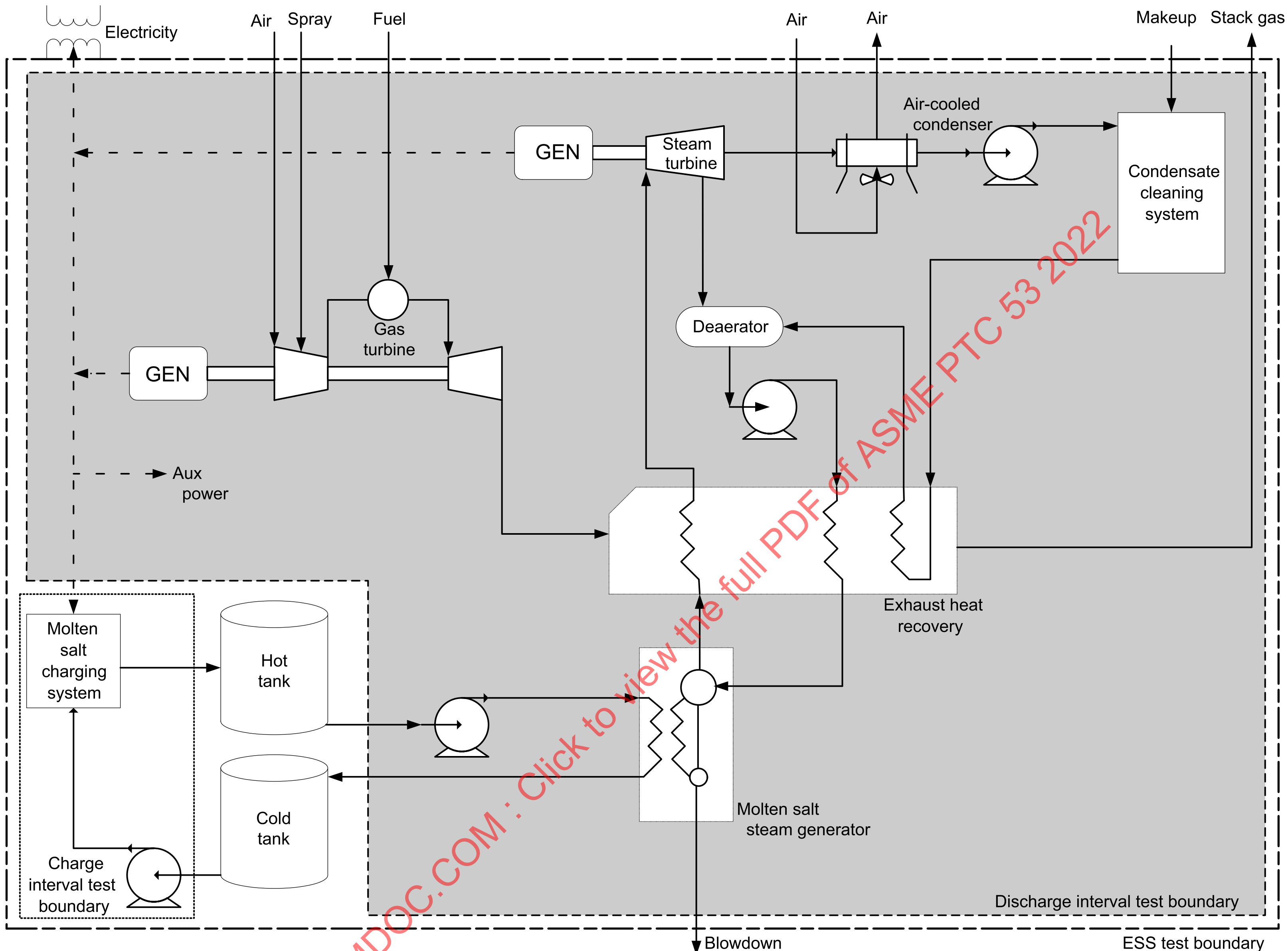
The major equipment items of the ESS are

(a) Molten Salt Storage System (MSSS). The MSSS comprises two molten salt tanks, each with a 31.70 m (104 ft) inside diameter, with a usable height of 12.0 m (39.37 ft). The maximum capacity of the hot and cold tanks is 13 100 metric tons and 14 000 metric tons, respectively, of heat transfer salt (Hitec), which is a eutectic mixture of potassium nitrate, sodium nitrite, and sodium nitrate. Rated average molten salt discharge temperatures are 425°C and 250°C for the hot and cold tanks, respectively. The total salt inventory delivered was 13 000 metric tons, which was melted and distributed within tanks, heaters, and piping.

(b) Molten Salt Steam Generator (MSSG). The MSSG is a single-pressure drum boiler that uses hot salt to produce saturated steam from subcooled feedwater supplied by the heat recovery sensible heater. Blowdown is discharged across the test boundary.

(c) Molten Salt Discharging System. The molten salt discharging system includes a pump to transfer salt from the hot tank through the MSSG to the cold tank.

Figure A-3-1
System Boundary for Energy Storage Combined Cycle Power Plant, With Boundaries for Discharge Test and Charge Test



(d) Molten Salt Charging System (MSCS). The MSCS includes a pump to transfer salt from the cold tank through a heater comprising 12 parallel 10 MW medium voltage resistance heaters. Flow rate and power are controlled to deliver a salt temperature of 427°C at the heaters' exit, which provides a margin to meet the MSSS hot tank rated discharge temperature specification after losses.

(e) Molten Salt Auxiliaries. Molten salt auxiliaries include heat tracing and a nitrogen blanket system.

(f) Gas Turbine Generator (GTG). The GTG produces 49.95 MW at ISO conditions (15°C, 60% relative humidity, sea level) and is an aero-derivative type with water spray intercooling (SPRINT).

(g) Steam Turbine Generator (STG). The STG produces 43.50 MW at ISO conditions, with live steam at 35 bar/425°C, condensed at 0.088 bar by an air-cooled condenser. There is a single extraction at 3.824 bar to provide pegging steam for a deaerator.

(h) Exhaust Heat Recovery. Recovery of exhaust heat is performed by superheater and economizer sections in series with the MSSG and a low-pressure condensate heater to preheat condensate for the deaerator.

(i) Water Treatment System (WTS). The WTS includes blowdown treatment, condensate polishing, and demineralized water for the gas turbine SPRINT.

(j) Step-Up Transformer. The step-up transformer converts medium voltage electricity produced by the GTG and STG and used by the MSCS and plant auxiliaries to high voltage.

A-3.2 Operation

The operation of the ESS includes discharging, charging, and standby modes.

A-3.2.1 Discharge Operating Mode. During discharge, hot molten salt is pumped from the hot tank through the MSSG to produce saturated steam, and the cooled molten salt is transferred to the cold tank. Combustion turbine exhaust gas heats feedwater to the MSSG and superheats steam from the MSSG. Steam exhausted from the turbine is condensed by an air-cooled condenser. The condensate is polished, pumped through a low-pressure exhaust-gas preheater, and deaerated using pegging steam extracted from the steam turbine. Feedwater is pressurized for delivery to the exhaust gas feedwater heater. Blowdown is used to control the accumulation of dissolved solids in the steam generator, and makeup water is introduced to compensate for water lost from the steam cycle.

The combustion turbine operates to effect the discharge of stored energy. Inlet air is filtered and compressed with SPRINT. Fuel heats the compressed air, which produces power before exhausting into the heat recovery system. Exhaust gas is cooled by successive heat transfer coils to provide superheated steam, economized feedwater, and preheated condensate.

Power from the generators is primary energy and crosses the test boundary at the transformer. The system uses fuel energy during discharge. There is no secondary energy during discharge.

A-3.2.2 Charge Operating Mode. During charging, molten salt is pumped from the cold tank through electric heaters that draw power from outside the test boundary. The heated salt is then stored in the hot tank.

Power to the electric heaters is primary energy and crosses the test boundary at the transformer. No fuel or secondary energy crosses the test boundary during charging.

A-3.2.3 Standby Operating Mode. During standby, heat is passively lost from the storage tanks, resulting in a temperature decrease of the molten salt. The decrease is dependent on duration of the standby mode, ambient temperature, and the temperature of the salt within the tanks. Heat losses through the tank bottom into the foundation and earth will vary over the months following plant commissioning until an equilibrium temperature profile is established in the ground.

Electric heat tracing may be activated to maintain the temperature of molten salt piping, pumps, valves, and instruments above the freezing point of the salt (142°C).

During extended standby periods or layup, energy may be added to the salt by periodically circulating the salt through the electric heaters.

A-3.2.4 Startup Losses. Energy lost from the molten salt components, beyond that replaced by operation of the electric heaters during standby, reduces the temperature of the plant equipment. The plant equipment is reheated during startup of charging or discharging by heat transfer from the molten salt or the combustion turbine exhaust, by heat recovery equipment, and by indirect heat transfer to steam cycle components from the molten salt and exhaust heat.

A-4 DISCHARGE INTERVAL TEST

A-4.1 Discharge Interval Test Objectives

The discharge interval test is undertaken in accordance with this Code to measure the following:
(a) corrected net discharge power
(b) corrected net discharge fuel heat rate
(c) corrected net discharge stored energy rate
(d) corrected net discharge interval
The measured values are compared with the rated values listed in Table A-4.1-1.

Table A-4.1-1
Plant Ratings

Parameter	Rated Value
Net discharge power	91 991 kW
Net discharge fuel heat rate	4 877 kJ/kW h (4,623 Btu/kW h) lower heating value
Net discharge stored energy rate	3 251 kJ/kW h (0.903 kW h/kW h)
Net discharge interval	10.0 h

A-4.2 Discharge Interval Test Boundary

The test objectives can be satisfied by a test of the discharge system using the discharge interval test boundary shown in Figure A-3-1, with the storage tanks and charging system outside the test boundary.

The measurement points for the discharge calculation are as follows:
(a) power measured at the plant side of the step-up transformer
(b) fuel input to the gas turbine [specified as lower heating value (LHV) for reference]
(c) inlet air conditions at the entrance to the gas turbine filter house
(d) inlet air conditions to the air-cooled condenser
(e) molten salt flow rate and salt temperature in and out of the MSSG
(f) blowdown flow rate and temperature from the MSSG
(g) makeup water flow rate and temperature

A-4.3 Discharge Rating and Test Conditions

The test requirements are based on fixed unit disposition, which for this example means that
(a) GTG and STG at base load are in steady state
(b) blowdown is isolated
For the sample calculation that follows, the rating, test, and corrected conditions are shown in Table A-4.3-1.

A-4.4 Discharge Correction Factors

This plant does not use secondary energy, so the following fundamental equations apply. All terms are defined in Tables 2-2-1 and 2-2-2.

The corrected discharge power is

$$P_{D,\mathrm{corr}} = \left(P_{\mathrm{meas}} + \sum_{i=1}^{l} \Delta_i\right)\prod_{j=1}^{m} \alpha_j \tag{A-4-1}$$

The corrected fuel input for discharge is

$$Q_{D,\mathrm{corr}} = \left(Q_{\mathrm{meas}} + \sum_{i=1}^{l} \omega_i\right)\prod_{j=1}^{m} \beta_j \tag{A-4-2}$$

Table A-4.3-1
Rating and Test Conditions

Condition	Rating	As Tested
Power	91 991.3 kW	82 208.8 kW
Fuel	124 642 kW (425.29 MMBtu/h)	107 658 kW (367.35 kW)
Ambient air temperature	15.0°C	26.7°C
Ambient air pressure	1.01325 bar absolute	0.951 bar absolute
Ambient air relative humidity	60%	70%
Blowdown flow	0.465 kg/s	0.0 kg/s
Molten salt flow from hot tank	318.9 kg/s	342.6 kg/s
Molten salt temperature		
From hot tank	425.0°C	419.0°C
To cold tank	258.3°C	258.8°C
Molten salt mass available for discharge	11 500 metric tons	11 975 metric tons
Stored energy flow rate from storage	83 030 kW	85 687 kW
Calculated fuel heat rate	4 623 Btu/kW h	4 469 Btu/kW h
Calculated stored energy rate	0.925 kW h/kW h	1.042 kW h/kW h
Calculated discharge duration	10.02 h	9.31 h

The corrected energy input from storage during discharge input is

$$E_{D,\mathrm{corr}} = \left(\Delta U_D + \sum_{i=1}^{l} \varphi_i\right)\prod_{j=1}^{m} \varepsilon_j \qquad \text{(A-4-3)}$$

Corrected fuel heat rate is expressed as

$$\mathrm{FHR}_{\mathrm{corr}} = \frac{Q_{D,\mathrm{corr}}}{P_{D,\mathrm{corr}}} \qquad \text{(A-4-4)}$$

Corrected primary energy rate is expressed as

$$\mathrm{PER}_{\mathrm{corr}} = \frac{E_{D,\mathrm{corr}}}{P_{D,\mathrm{corr}}} \qquad \text{(A-4-5)}$$

For this plant, which uses incompressible liquid (molten salt) as both the energy storage medium and the heat transfer medium, the internal energy term equals the average rate of heat flow from the molten salt storage system over the test interval, indicated by the bar over the quantity on the right-hand side, where $\dot{m}$ is the mass flow rate of salt.

$$\Delta U = \overline{\dot{m} c_p \Delta T} \qquad \text{(A-4-6)}$$

The rated discharge duration is the mass in hot storage divided by the rated discharge mass flow rate. Accordingly, the corrected discharge duration is

$$t_{D,\mathrm{corr}} = \frac{M_{\mathrm{avail}}}{\dot{m}_{\mathrm{rated}} \prod_{i=1}^{8} \mu_i} \qquad \text{(A-4-7)}$$

Other specific simplifying assumptions for this example in regard to the variables in eqs. (A-4-1) through (A-4-7) are described in para. A-4.4.1.

A-4.4.1 Additive Correction Factors. The additive correction factors in this paragraph apply to fuel heat input, ω; power output, Δ; and energy input, ϕ, from storage and during discharge tests.

(a) There is no process steam flow from the plant, so the thermal efflux additive corrections ω_1, Δ_1, and ϕ_1 are zero.

(b) The power factor is specified as a constant value of unity during charging and discharging and will not vary, so the additive corrections ω_2, Δ_2, and ϕ_2 are zero.

(c) The blowdown flow rate is zero so the additive corrections ω_3, Δ_3, and ϕ_3 become zero.

(d) There is no process condensate return to the plant and, because blowdown is isolated, the makeup water requirement is too small to be meaningful, so the additive correction factors ω_4, Δ_4, and ϕ_4 are zero.
(e) Heat rejection is within the test boundary, so the additive correction factors ω_5, Δ_5, and ϕ_5 are zero.
(f) Auxiliary loads are within the test boundary, so the additive correction factors ω_6, Δ_6, and ϕ_6 are zero.
(g) The specified disposition for discharging is baseload, so the additive correction factors ω_7, Δ_7, and ϕ_7 are zero.
(h) Fuel is supplied at approximately the rated temperature, so the additive correction factors ω_8, Δ_8, and ϕ_8 are zero.
(i) Molten salt composition is per specification so the additive correction factor ϕ_9 is zero.
(j) There is no secondary energy input to the plant, so the additive correction factor ξ_1 does not apply.

A-4.4.2 Multiplicative Correction Factors. The multiplicative correction factors in this paragraph apply to discharge power, α; thermal heat from fuel during discharge, β; thermal heat input from stored energy during discharge, ε; and mass efflux from storage, μ.
(a) The ambient air temperature at the test boundary varies from the reference condition, so multiplicative corrections α_1, β_1, ε_1, and μ_1 apply.
(b) The ambient air pressure at the test boundary varies from the reference condition, so multiplicative corrections α_2, β_2, ε_2, and μ_2 apply.
(c) Relative humidity of ambient air at the test boundary varies from the reference condition, so multiplicative corrections α_3, β_3, ε_3, and μ_3 apply.
(d) The fuel supply temperature during the test is constant at the design value, so multiplicative corrections α_4, β_4, ε_4, and μ_4 are unity.
(e) The fuel composition is relatively close to the design value, so multiplicative corrections α_5, β_5, ε_5, and μ_5 are unity.
(f) The grid frequency during the test is constant at the design value, so multiplicative corrections α_6, β_6, ε_6, and μ_6 are unity.
(g) The blowdown is isolated during the test to establish a known flow rate, so multiplicative corrections α_7, β_7, ε_7, and μ_7 apply.
(h) Losses from the thermal storage system (hot and cold tanks, piping, and pumps) affect the temperature of salt crossing the test boundary, so multiplicative correction factors α_8, β_8, ε_8, and μ_8 apply.
(i) The molten salt composition is as delivered by the vendor, so the multiplicative correction ε_9 is unity.
(j) There is no secondary energy input to the plant, so the multiplicative correction factor ψ_1 does not apply.
The test equations for this specific plant under discharge test become

$$P_{D,\text{corr}} = P_{D,\text{meas}} \alpha_1\, \alpha_2\, \alpha_3\, \alpha_7\, \alpha_8 \tag{A-4-8}$$

$$Q_{D,\text{corr}} = Q_{D,\text{meas}}\, \beta_1\, \beta_2\, \beta_3\, \beta_7\, \beta_8 \tag{A-4-9}$$

$$E_{D,\text{corr}} = \left(\dot{m}_{\text{discharge}} c_p \Delta T\right)_{\text{meas}} \varepsilon_1\, \varepsilon_2\, \varepsilon_3\, \varepsilon_7\, \varepsilon_8 \tag{A-4-10}$$

$$t_{D_{\text{corr}}} = \frac{M_{\text{rated}}}{\dot{m}_{\text{meas}}\, \mu_1\, \mu_2\, \mu_3\, \mu_7\, \mu_8} \tag{A-4-11}$$

A-4.5 Plant-Specific Correction Factors

A process model established performance at the rated conditions and was used to assess the performance at off-design conditions to develop correction factors for the following variations from the rated conditions:
(a) ambient temperature
(b) ambient pressure
(c) ambient relative humidity
(d) blowdown flow rate
(e) molten salt temperature

A-4.5.1 Ambient Temperature Correction. The ambient temperature affects flow through the combustion turbine and heat recovery system and the condensing temperature of the steam cycle. Low ambient temperature performance as shown in Table A-4.5.1-1 reflects control system interactions. Polynomial curve fits of the form $c = k_0 + k_1T + k_2T^2 + k_3T^3$ were developed from data shown in Table A-4.5.1-1 and are plotted in Figure A-4.5.1-1 . Coefficients are listed in Table A-4.5.1-2.

Table A-4.5.1-1
Predicted Performance at Different Ambient Temperatures

Ambient Temperature, °C	Net Power, kW	Fuel, MMBtu/h	Energy From Storage, kW	Salt Flow Rate, kg/s
40	74 161.9	346.6	84 815.76	325.878
35	78 445.7	362.5	84 318.99	323.914
30	82 754.3	381.41	83 876.81	322.178
25	86 827.7	399.94	83 470.33	320.588
20	89 695.5	413	83 252.42	319.743
15	91 991.3	425.29	83 030.46	318.879
10	93 791.2	436.63	83 075.06	319.061
5	93 792.2	436.28	82 515.6	316.798
0	93 249.1	433.08	85 706.58	329.672

Figure A-4.5.1-1
Ambient Temperature Multiplicative Correction Factors

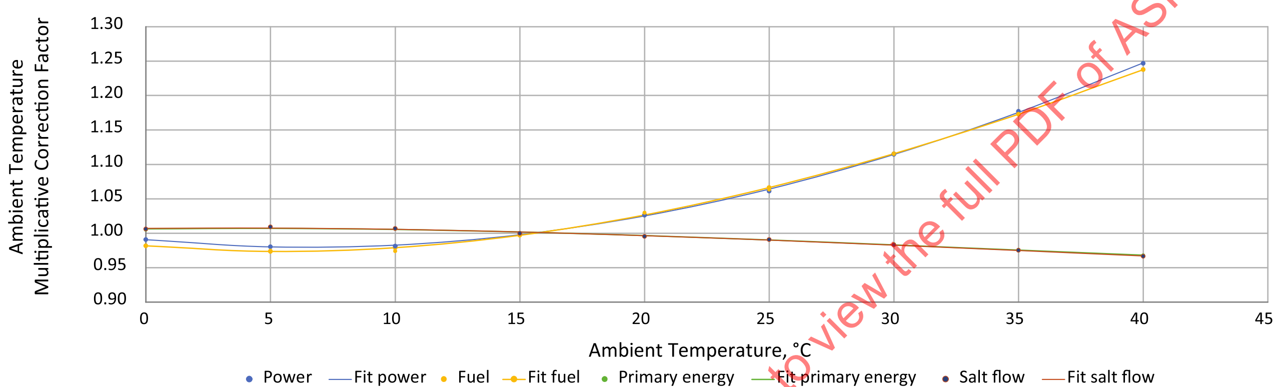


Table A-4.5.1-2
Coefficients for Ambient Temperature Correction Factors

Ambient Temperature Correction Factor	Coefficient			
	T^3	T^2	T^1	T^0
α_1	−1.63507 E−07	0.00023344	−0.002718763	0.987024
f_1	−2.43924 E−06	0.000341341	−0.003604555	0.982492
ε_1	3.12945 E−06	−0.000244001	0.004920737	0.974647
μ_1	3.27358 E−06	−0.000254845	0.005146568	0.973441