




Utility-Scale Power Tower Solar Systems: Performance Acceptance Test Guidelines

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NATIONAL RENEWABLE ENERGY LABORATORY

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Cover photo caption:

This 20-megawatt Gemasolar concentrating solar power plant, in Fuentes de Andalucia, Spain, is the first commercial plant in the world to use molten salt thermal storage in a central tower configuration with a heliostat field. *Photo by Greg Glatzmaier, NREL 19807; Gemasolar Plant owned by Torresol Energy*

Preface

The purpose of these Guidelines is to provide direction for conducting performance acceptance testing for large power tower solar systems that can yield results of a high level of accuracy consistent with good engineering knowledge and practice. The recommendations have been developed under a National Renewable Energy Laboratory (NREL) subcontract and reviewed by stakeholders representing concerned organizations and interests throughout the concentrating solar power (CSP)[1] community. An earlier NREL report[2] provided similar guidelines for parabolic trough systems. These Guidelines recommend certain methods, instrumentation, equipment operating requirements, and calculation methods. When tests are run in accordance with these Guidelines, we expect that the test results will yield a valid indication of the actual performance of the tested equipment. But these are only recommendations—to be carefully considered by the contractual parties involved in the acceptance testing—and we expect that modifications may be required to fit the particular characteristics of a specific project.

These Guidelines do not specify means to compare test results to contractual guarantees. A key presumption in this report is that the parties to a commercial test will address that issue, as well as agree on other important issues with regard to testing protocol and evaluation of test results. The approach taken in these Guidelines is that the measured test results will be compared to projections from a performance model based on the measured meteorological conditions and agreed-upon solar system characteristics.

The scope of the solar system discussed in these Guidelines does not include a thermal energy storage (TES) system. But even if the scope did include a TES system, the methods of testing the solar field/heat transfer fluid system itself would be similar, if not identical, to the guidance given in this document. A separate set of tests and objectives would be required for TES system acceptance.

An American Society of Mechanical Engineers (ASME) committee is working on *Performance Test Code*[3] *52 – Concentrating Solar Power Plants* that should supplant this Guideline within several years. This work will be provided to that committee as a reference for its deliberations.

[1] As used here, CSP refers to concentrating solar systems for thermal power plants, also sometimes described as CSTP (Concentrating Solar Thermal Power) plants.
[2] "Utility-Scale Parabolic Trough Solar Systems: Performance Acceptance Test Guidelines", NREL/SR-5500-48895, May 2011.
[3] Often abbreviated as PTC.

Definitions and Description of Terms

For further reference, ASME *PTC 2 – Definitions and Values* contains definitions of terms and values of physical constants and conversion factors common to equipment testing and analysis.

Definitions

- ***acceptance testing:*** The evaluating action(s) to determine if a new or modified piece of equipment satisfactorily meets its performance criteria, permitting the purchaser to "accept" it from the supplier.
- ***accuracy:*** The closeness of agreement between a measured value and the true value.
- ***aperture area:*** The active mirror collecting area of the heliostats, i.e., the projection of the reflective surface less gaps between the reflector panels on a (nominally) flat plain between the rim edges.
- ***bias error:*** See *systematic error*.
- ***calibration:*** The process of comparing the response of an instrument to a standard instrument over some measurement range and adjusting the instrument to match the standard, if appropriate.
- ***cleanliness factor:*** A factor that describes the cleanliness, or soiling, of the reflective surface (e.g., glass mirrors or silvered film) of the heliostats; specifically, at any given time, the actual reflectivity relative to the design or as-new reflectivity.
- ***direct normal radiation:*** Concentrating collectors utilize the direct beams of radiation from the sun, as only these (in contrast to ambient diffuse radiation) can be accurately reflected. The intensity is measured as W/m^2 (instantaneous power) or Wh/m^2 (energy over time) on a plane normal to the sun's rays.
- ***field multiple:*** Equals [(heliostat field aperture area) / (heliostat field aperture area sufficient to deliver the design solar thermal output power at stated conditions of DNI and time of year)]
- ***instrument:*** A tool or device used to measure physical dimensions of length, thickness, width, weight, or any other value of a variable. These variables can include: size, weight, pressure, temperature, fluid flow, voltage, electric current, density, viscosity, and power. Sensors are included in this term that may not, by themselves, incorporate a display but transmit signals to remote computer-type devices for display, processing, or process control. Also included are items of ancillary equipment that directly affect the display of the primary instrument, e.g., an ammeter shunt. Also included are tools or fixtures used as the basis for determining part acceptability.
- ***measurement error* (δ):** The true, unknown difference between the measured value and the true value.
- ***parties to a test:*** Those persons and companies contractually interested in the test results.
- ***precision error:*** See *random error*.

- ***primary variables:*** Those variables used in calculations of test results.
- ***random error* (ε):** Sometimes called precision; the true random error, which characterizes a member of a set of measurements. ε varies in a random, Gaussian-normal manner from measurement to measurement.
- ***random uncertainty*:** Estimate of ± limits of random error within a defined level of confidence. Often given for 2-σ (2 standard deviations) confidence level of about 95%.
- ***rated solar thermal design power (or capacity):*** The rated solar power is the receiver thermal output at the nominal design point. The design point is associated with a day of the year, a time of the day, and a DNI. The rated power is independent of the storage system type and capacity, and is independent of the power conversion cycle.
- ***reference conditions:*** The values of all the external parameters, i.e., parameters outside the test boundary to which the test results are corrected.
- ***secondary variables:*** Variables that are measured but do not enter into the calculation.
- ***serialize:*** Means that an instrument has been assigned a unique number and that number has been permanently inscribed on or to the instrument so that it can be identified and tracked.
- ***solar multiple:*** The solar multiple is the (design receiver thermal power) / (design turbine cycle thermal power).
- ***solar system thermal efficiency:*** Ratio of the solar thermal power output of the solar system normalized by the product of the direct beam radiation and the total aperture area of the solar field. See Equation (Eqn.) 3-2.
- ***systematic error* (β):** Sometimes called bias; the true systematic or fixed error, which characterizes every member of any set of measurements from the population. It is the constant component of the total measurement error (δ).
- ***systematic uncertainty* (B):** An estimate of the ± limits of systematic error with a defined level of confidence (usually 95%).
- ***test boundary:*** Identifies the energy streams required to calculate corrected results.
- ***test reading:*** One recording of all required test instruments.
- ***test run:*** A group of test readings that satisfy the stated criteria for test conditions, e.g., with regard to thermal stability.
- ***traceable:*** Records are available demonstrating that the instrument can be traced through a series of calibrations to an appropriate ultimate reference such as the National Institute for Standards and Technology (NIST).
- ***uncertainty* (U):** ±U is the interval about the measurement or result that likely contains the true value for a certain level of confidence.
- ***working fluid:*** general term for the fluid heated in the receiver by solar energy reflected by the heliostat field. It can be water-steam, molten salt, or gaseous depending on the power tower type.

Abbreviations and Acronyms

COD	commercial operation date
CSP	concentrating solar power; same as CSTP (concentrating solar thermal power)
DSC	digital scanning calorimetry
DHI	diffuse horizontal irradiance
DNI	direct normal irradiance (for power); also, direct normal insolation (for energy)
EPC	engineering, procurement, and construction (contractor)
Eqn.	equation
GHI	global horizontal irradiance
HTF	heat transfer fluid
HX	heat exchanger
IPP	independent power producer
mrad	milliradian – a measure of optical error
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
OJT	on-the-job training
PTC	performance test code
RSR	rotating shadowband radiometer
RTD	resistance temperature detectors
SAM	System Advisor Model, produced by NREL, Sandia National Labs, and DOE
SF	solar field comprised of individual heliostats
SM	solar multiple
SRC	steam Rankine cycle
STG	steam turbine generator set
TC	thermocouple
TES	thermal energy storage
WF	working fluid

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Executive Summary

Prior to commercial operation, large solar systems in utility-size power plants need to pass performance acceptance tests conducted by the engineering, procurement, and construction (EPC) contractor or owners. In lieu of the present absence of ASME[4] or other international test codes developed for this purpose, the National Renewable Energy Laboratory has undertaken the development of interim guidelines (the Guidelines) to provide recommendations for test procedures that can yield results of a high level of accuracy consistent with good engineering knowledge and practice. The Guidelines contained here follow the general approach of the earlier NREL report[2] on parabolic trough collector fields, but in this case are specifically written for power tower[5] solar systems composed of a heliostat (reflector) field directing the sun's rays to a receiver (heat exchanger) on a high central tower. The working fluid in the tower receiver can be molten salt, water/steam, air, CO_2, or other suitable fluids, each with its own particular attributes.

The fundamental differences between acceptance of a solar power plant and a conventional fossil-fired plant are the inherently transient nature of the energy source and the necessity to use a performance projection model in the acceptance process. These factors bring into play the need to establish methods to measure steady-state performance, comparison to performance model results, and the reasons to test and model multi-day performance within the scope of the acceptance testing procedures. The power block and balance-of-plant are not within the boundaries of this Guideline. The current Guideline is restricted to the solar thermal performance of power tower systems, and has been critiqued by a broad range of stakeholders in concentrating solar power development and technology.

The test parties must agree on the boundary locations. An example of the solar system boundary is shown in Figure ES-1 wherein the inputs are the solar resource, inlet working fluid, and internal solar system parasitic power[6], and the sole output is the increase in enthalpy of the working fluid. Configurations with water/steam and air working fluids are direct systems in which heat is added directly in the receiver to the working fluid of the power cycle. In an indirect system such as a molten salt configuration, heat is added to a molten-salt heat transfer fluid and subsequently transferred to the power-cycle working fluid in a steam generator train, though this heat exchange occurs outside of the test boundary. Other combinations under development include, for example, volumetric air receivers coupled to steam Rankine cycles, and salt or volumetric receivers coupled to high-temperature air or supercritical CO_2 Brayton cycles.

The appropriate test boundary locations for the measurement of thermal performance should be chosen by the test parties based on the equipment configurations and test requirements. The

[4] The ASME has formed a committee to develop a test code for utility scale CSP systems, namely PTC 52. We expect that PTC 52 code will be published in 2013 or later. Many of the members of the Power Tower section of that committee have contributed to this report. PTC 52 will cover performance tests other than acceptance tests as well.

[5] Also commonly known as central receiver systems.

[6] The parasitic power required for operation of the heliostat tracking and control system, piping heat trace and pumping of the working fluid through the receiver, should be recorded for comparison to solar system specifications, but is not directly included as part of the test results on thermal energy delivery to the power cycle or TES system. The testing parties need to agree prior to tests on the pass/fail criteria for this element.

scope of these current Guidelines does not include a thermal energy storage system within the test boundary.

Performance acceptance tests are to be conducted with accuracy defined in clearly stated procedures that are agreed upon between the parties involved. These Guidelines deal with issues specific to utility-scale power tower solar systems. However, applicable performance test codes (PTCs) developed by ASME for other types of energy systems have very useful information for developing a detailed Test Plan based on these Guidelines, and are appropriately cited in these report. For example, applicable PTCs provide a general framework and information about instrumentation, data acquisition, data reduction, testing procedures, uncertainty levels, and test reports.

Two primary types of test runs are to be conducted. The first – the Short-Duration Steady-State Thermal Power Test (Power Test) – measures the thermal power output of the solar system under clear-sky conditions over a short period, during which thermal equilibrium and stable steady-state conditions exist, and compares the measured results to performance model projections for those conditions. The purpose of this test is to determine with minimal uncertainty whether the solar field is producing thermal power at the expected level, given the present irradiation and ambient weather conditions. If required by agreement, a Power Test is run at full output to prove the ability to reach design capacity. Solar system thermal efficiency can also be measured from the Power Test data. Important issues related to both stabilized test conditions and thermal equilibrium are dealt with in detail in the Guidelines. Power Test durations are typically run in fractions of an hour, but for reason of demonstrating repeatability and clear sky conditions permitting, the period over which tests are run can span up to 10 days or more.

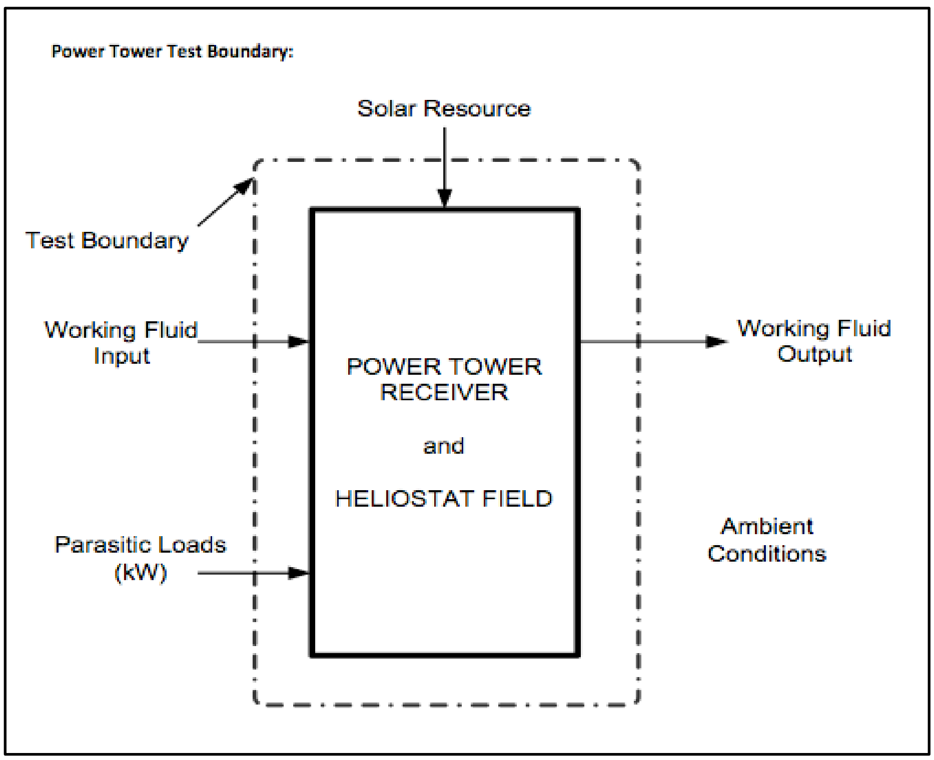


Figure ES-1. Schematic of solar system boundary and performance model.
Illustration from Working Committee on ASME PTC 52

The second test type – the Long-Duration Production (or Reliability) Test (Production Test)– is a continuous multi-day energy test that gathers multiple detailed daily thermal energy outputs and compares the results to projections from a performance model. Both clear-sky and partly cloudy conditions are acceptable. Additionally, the functionality of the solar system should be observed with regard to such items as daily startup, normal operation, standby and shutdown. Production Test durations are typically 10 to 30 days, though shorter or longer durations may be agreed upon by the testing parties. In some cases, the warranty agreement may require this test to be run seasonally, or in a scenario that includes Provisional Acceptance of the solar system followed at a later time by Final Acceptance.

Test method protocols are recommended for both the short-duration thermal Power Test and multi-day continuous Production Test. Of special importance are the criteria that must be satisfied by the short-duration Power Test. The recorded data can be viewed as having two components – the actual test measurements and the uncertainty interval associated with those measurements and other test conditions. Both are closely examined within these Guidelines, especially the magnitude of uncertainty in the results, and recommendations made on acceptable limits.

For the Power Test, the solar system must be in thermal equilibrium prior to testing. This requires stable characteristics in the solar resource (Direct Normal Irradiance) and other relevant ambient conditions, such as wind speed, and certain system conditions. Once thermal equilibrium has been reached, the criteria for valid thermal power measurements (i.e., valid test runs) are primarily based on the level of uncertainty in the test results calculated using standard practice. Systematic uncertainties are typically the dominant consideration.

However, and very importantly, it must be recognized that the purpose of these Guidelines is to provide information so that the testing parties can settle on project-specific, agreed-upon criteria and other test issues important to the overall purpose of the tests. For any given project, the tests will be conducted in accordance with a Test Plan written by the testing parties that may or may not include the recommendations made in this document. The intent of these Guidelines is to provide insights into the issues and test methods that are critical to formulating a valid Test Plan, and to lay the groundwork for accurate test results.

1 Introduction

1.1 Technology Description

In power tower concentrating solar power (CSP) systems, numerous nominally flat, sun-tracking mirrors, known as heliostats, focus sunlight onto a receiver at the top of a tall tower. Figure 1-1 shows the basic elements of a power tower configuration.

Two commercial solar tower system configurations are in active commercial development today. In one configuration, called the indirect configuration, a working fluid[7] other than water or gas is heated in the receiver, held in a TES system if present, and then sent to a steam generator train to produce steam that, in turn, drives a conventional turbine generator to produce electricity. Current commercial designs using this concept are using molten nitrate salts[8] as the working fluid because of its superior heat-transfer and energy-storage capabilities.

In the other configuration, called the direct configuration, water/steam is used as the working fluid, heated in the receiver and sent directly to the Rankine turbine inlet. The direct steam solar receiver may have separate receiver sections for steam generation, superheating, and even reheating if applicable. Another direct configuration, not yet commercialized, is to use a gas working fluid like air or CO_2 to drive a Brayton or Rankine cycle power system.

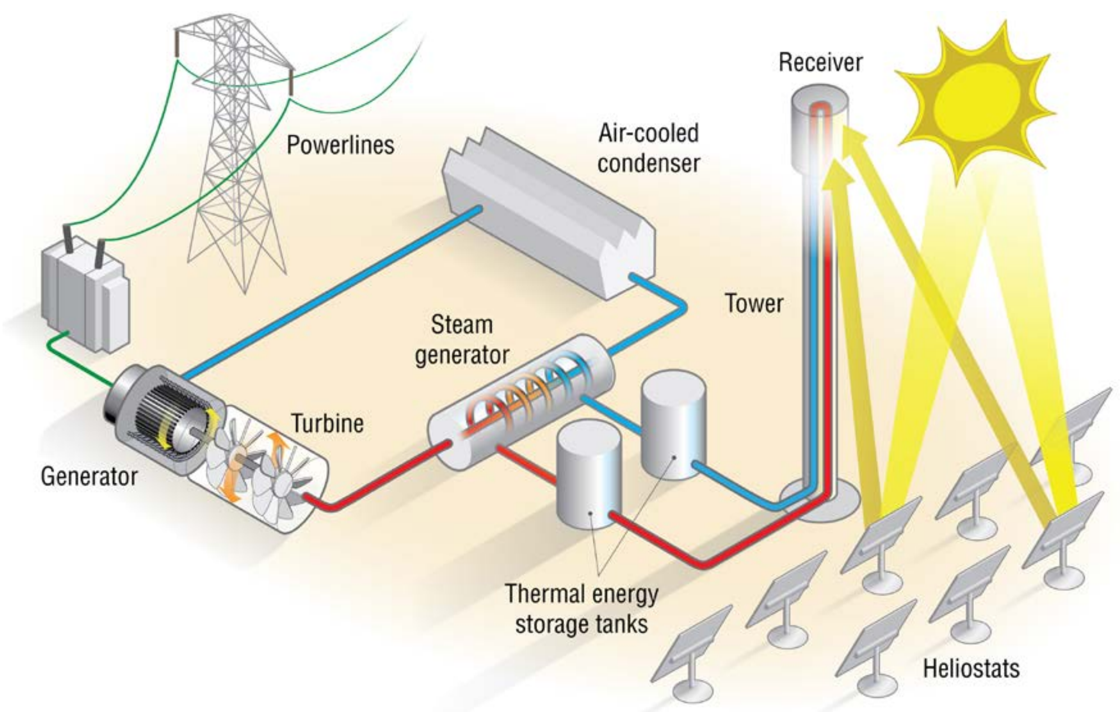


Figure 1-1 Basic subsystems of a molten salt power tower configuration.
Illustration by Al Hicks, NREL

[7] Also termed HTF, or heat transfer fluid
[8] Typically a mixture of 60% sodium nitrate and 40% potassium nitrate by weight

The key components – the heliostat field and receiver – vary in configuration and capacity depending on the system type and commercial design decisions. In a molten salt power tower plant configuration, a thermal energy storage (TES) system is included to provide dispatchability, which results in the ability to shift power output to meet grid demand patterns and to produce a consistent output during intermittent solar conditions. During summer months, for example, solar plants typically operate for up to 10 hours a day at full-rated electric output without TES. However, as illustrated in Figure 1-2, as an example, significant additional full-load generation hours can be efficiently added or shifted if TES is available, allowing a solar plant to meet the morning and evening winter peaks that many utilities in the southwest United States experience. TES is integral to molten salt power tower technology because molten salt is used as the working fluid in the receiver.

Another approach is to configure the systems as hybrid solar/fossil plants. For example, a secondary backup fossil-fired capability can be used to supplement the solar output during periods of low solar irradiance. An alternate hybrid configuration utilizes a solar system to supply supplementary steam to a gas-fired combined cycle power plant.

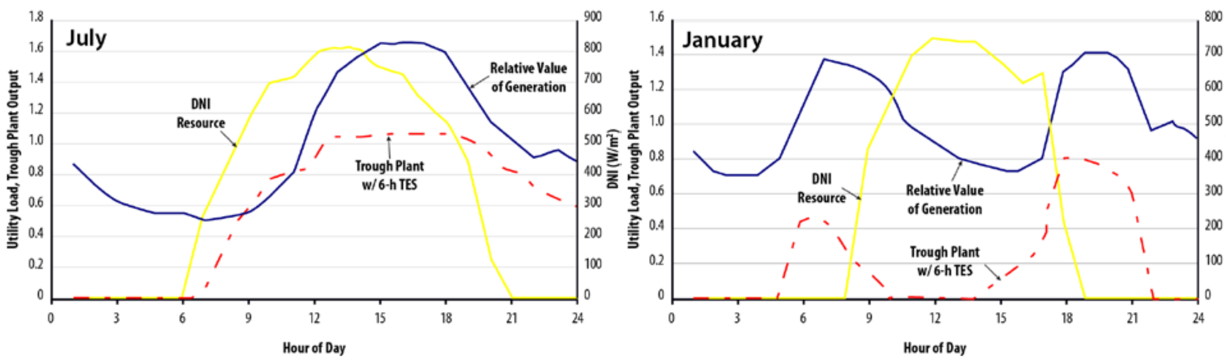


Figure 1-2. CSP plant operation better matching the utility load profile by utilizing TES (in this case, with a parabolic trough plant). ***Illustrations from Abengoa Solar***

In solar plants that are configured with TES systems, the solar field is typically increased in size to increase the collected energy. For example, on a clear day, a large solar field might provide enough energy in the morning and afternoon hours to both drive the turbine at full load all day and also charge the TES system to full capacity. For a given plant and utility application, the size of the solar field can be optimized for the local solar resource, grid demand pattern, electricity revenues (e.g., if time-of-use revenue multipliers are applicable), and financial parameters. For this purpose, a reference solar field size is determined at a nominal hourly direct normal irradiance and heliostat field design parameters at rated solar thermal power capacity sufficient to operate the electric generator at full load, and this is labeled as field multiple = 1. Larger heliostat fields are identified as field multiple >1. For plants with no TES in a high DNI region, the financially optimum heliostat field size will typically fall in a field multiple range of 1.4 to 1.5. For plants with TES, field multiple values of 2.0 and higher will typically be chosen. With a very high field multiple and sufficient TES, a solar plant can be configured to operate as a base-load plant. This, in fact, is the design configuration of the Gemasolar plant shown on the cover of this report.

1.2 Need for Guidelines

Solar thermal power plants are being proposed with large turbine capacities and, if significant TES is included in the system, can require solar fields with over a million square meters of reflector aperture in an area of high solar resource, and even larger solar fields in areas of less solar resource. Individual power tower systems are being installed with turbine capacities of 100-300 MW. The land requirement for a large plant with TES is roughly about 10 acres (~4 hectares) per MWe net. Heretofore, developers, debt providers, owners, and engineering, procurement, and construction (EPC) contractors that purchase and must determine acceptability of these systems have had no standardized test guidance for reference or use that is specifically associated with the performance of these large and capital-intensive solar fields.

The fundamental differences between acceptance of a CSP solar system and acceptance of a conventional fossil-fired system are the inherent transient nature of the energy source, and the need to use a performance projection model[9] in the acceptance process. These factors bring into play the impacts of transient processes, uncertainties introduced by a model, and the need to test, or model, seasonal or annual performance within the scope of the test procedure in order to capture significant impacts on performance.

The Guidelines presented in this report are intended to provide guidance for the planning, preparation, execution, and reporting of performance test results on large-scale (utility-scale) power tower solar systems that are made up of the solar field and receiver subsystems.

It is anticipated that an official Performance Test Code (PTC) developed by the American Society of Mechanical Engineers (ASME) will, at some future time, supersede the trough and tower Guidelines developed by NREL. That code—ASME *PTC 52 - Concentrating Solar Power Plants*—is being planned to address each of the CSP technologies. Typically, it takes several years to complete the preparation and approval of a PTC.

[9] Use of a performance model in place of correction curves is also a trend in the testing of fossil-fuel power systems, solar PV plants and solar parabolic trough plants.

2 Objectives and Scope

The objective of this document is to provide Acceptance Test Guidelines for the solar system of power tower power plants. The solar system includes the heliostats and receiver subsystems. The receiver heats the working fluid by radiation reflected by the heliostat field. Solar heat exchangers[10] (indirect system only), the power block, the TES system, and the balance-of-plant (BOP) are not within the boundaries of this protocol. ASME *PTC 46 - Overall Plant Performance* would be the appropriate code for performance and acceptance testing of the power island.

Specifics on the type, duration, and frequency of tests for a particular project should be separately defined in a Test Plan that is part of the contractual agreement between the party turning over the solar system and the party taking control of the solar system. The Test Plan is a commercial agreement that will dictate the required testing for the transaction. This Guideline has been prepared to recommend and provide guidance for several tests that can be used to meet the objectives of the contractual agreements.

2.1 Parties to the Acceptance Tests

There are a large number of commercial scenarios under which Acceptance Tests on the solar system would be conducted. One such possible scenario is given below for purposes of illustration and clarity. Although this example is intended to help place various steps or responsibilities in perspective, it does not imply that other, equally valid, representative scenarios do not exist. The most important point is that the objective of these Guidelines is to present viable test methods that are applicable to acceptance testing of large power tower solar systems, regardless of the relationships of the parties involved.

2.2 Example Project Scenario

- Test requirements are agreed upon between the EPC contractor and the solar system technology provider. The technology provider is selected by the EPC contractor, either independently or by agreement with the developer/owner.
- The EPC contractor sequentially carries out the solar system commissioning, startup, and acceptance testing with the owner's engineer observance. Performance acceptance tests are to be conducted after the solar system is commissioned and is ready for turnover from the technology provider to the EPC.
- In addition, Acceptance Tests may be conducted as part of the agreed-upon conditions to achieve Provisional Acceptance and/or Final Acceptance.

2.3 Pass / Fail Criteria

To be clear, the criteria for passing or failing the Acceptance Tests recommended in this report are a contractual matter to be agreed upon by the test parties.

[10] Other than the central receiver itself.

2.4 Readiness for Acceptance Tests

While the conditions to start the acceptance tests are subject to contract conditions, in a typical IPP project development the acceptance test of the applicable system occurs after commissioning of the system by the EPC construction and startup teams. Commissioning involves mechanical, electrical, instrumentation, and functional checks and walk-throughs to bring the system to an operating condition suitable for commercial operation and acceptance testing. All critical punch-list items from the walk-throughs are complete at this time, as well as most lower-tier punch-list items. When the system is fully operational under normal operating conditions and performs all required functions, it is turned over to the responsible party (e.g., the EPC startup team) for acceptance testing. At this point, the performance of the solar system has not yet been rigorously tested, nor the system accepted by the owner.

2.5 Unique Characteristics of Solar System Acceptance Tests and the Role of a Performance Model

An Acceptance Test of fossil-fired equipment, such as a boiler or combined-cycle plant, is a steady-state test based on thermal equilibrium, characterized by a controlled, steady heat input and a measurable output. Although in practice it requires care to achieve and maintain steady-state conditions, it is greatly facilitated by the fact that the input energy is controllable. In simple terms, a steady-state test is passed if the measured capacity or efficiency of the system meets the specified value. An important characteristic of the fossil-fired power system is that it often operates at or near its nameplate capacity.

A solar system, on the other hand, is characterized by the continuous movement of the sun and the changing heat input to the solar field. These characteristics complicate the achievement of steady operating conditions during the test period. Furthermore, there are many daylight hours during the year when the solar system is not operating at capacity because of the diurnal and seasonal nature of the solar resource, although this is less true of power tower projects utilizing dual-tracking heliostats compared to single-axis tracking parabolic trough projects.

The predicted performance of the solar system depends on the exact location of the sun and the specified characteristics of the solar heliostats and receiver system. Because of the variable nature of the solar resource, a performance model (computer code) is required to predict the performance for given input conditions.

2.6 Utility-Scale Solar System Performance Acceptance Tests

This Guideline recommends a set of tests for use in the acceptance of a utility-scale solar system using power tower technology. All or selected tests from this group can be chosen by agreement between the Parties to a test. The data collected for each test are identical in nature. The tests, described in detail in Section 0, are the following:

1. Short-Duration Steady-State Thermal Power Test (Power Test)
2. Long-Duration Production (or Reliability) Test (Production Test)

2.7 Solar System Boundaries

The current version of these Guidelines does not include a TES system or power block. The solar system boundary is defined for purposes of these Guidelines to include the solar heliostat field and the tower receiver, as shown in Figure 2-2, and to be at appropriate locations within the receiver inlet and exit piping. The solar radiation, working fluid and parasitic power input cross the system boundary as shown.

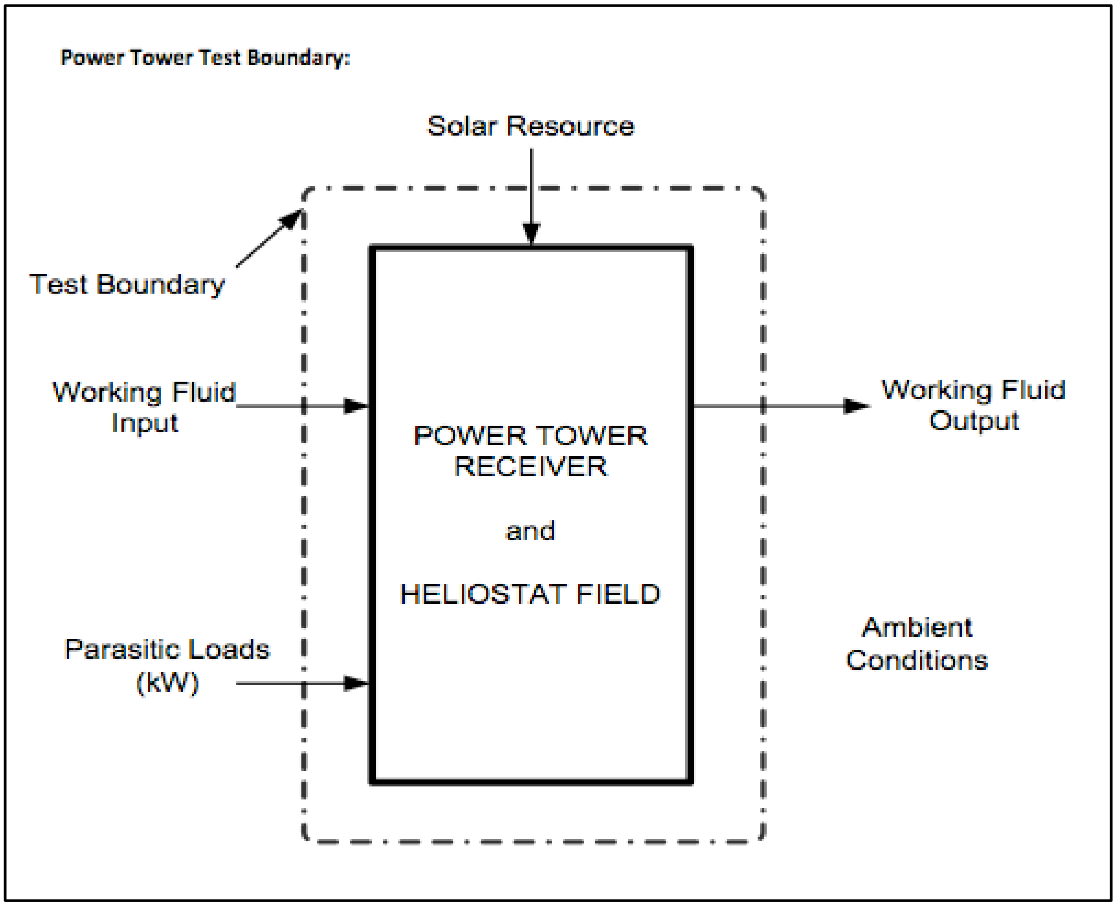


Figure 2-2. Schematic of solar system boundary and performance model.
Illustration from Working Committee on ASME PTC 52

3 Test Definitions

3.1 Performance Acceptance Test Guidelines

This section elaborates on the objectives and elements of the two types of acceptance tests for large power tower solar systems identified in Section 0. Performance acceptance tests are to be conducted with acceptable accuracy according to clearly stated procedures agreed upon between the parties involved. These Guidelines deal with issues specific to utility-scale power tower solar fields, for which no ASME PTC yet exists. However, applicable PTCs developed by ASME for other types of energy systems have very useful information for developing a detailed Test Plan, and are appropriately cited in following sections. For example, PTCs provide a general framework and information about instrumentation, data acquisition, data reduction, testing procedures, uncertainty levels, and test reports. However, note that many details are specific to a project and need to be stipulated in the context of the overall Test Plan.

The performance test procedures described in this report are generally applicable to Acceptance Tests prior to commercial operation or to warranty tests stemming from contractual obligations. However, the goals inherent in these two different purposes suggest that the durations and pass/fail criteria agreed upon by the test parties are likely to be different for each purpose.

In nonlegal language, the owner(s) of the power plant need to know if they are getting what they paid for. Because the solar resource is always changing, the ASME requirement of thermal equilibrium in PTCs, which is necessary for accurate results and low uncertainty, can only be achieved in short-duration tests. Without question this provides good information to the owner. The owner also needs to know if the long-term performance over time matches that predicted by the performance model. As the requirements for thermal equilibrium will only be satisfied for intermittent midday time periods, the uncertainty in the performance test measured results will be measurably higher due to nonequilibrium effects.

These conditions have led to defining the two types of tests for acceptance and warranty needs. The principal purpose of these Guidelines is to define the test conditions for these tests, leaving it to the testing parties to agree upon and lay out in the Test Plan the specifics of duration, acceptable accuracy, and similar issues. Criteria to judge successful completion of the tests are left to commercial agreements between the test parties.

Commercial agreements may require that, at some stage, the rated solar thermal design power (or capacity) be measured at appropriately high solar resource conditions. If such conditions do not exist in the period at the end of commissioning and turnover of the solar system, then provisional tests can be carried out, with a final Power Test at design capacity to follow when solar conditions allow.

3.2 Specific Test Objectives

The thermal power output of the solar field during a short-duration test period will vary primarily with the magnitude of the solar resource and the time of day and season. The purpose of the Power Test is to measure the thermal power output of the solar system under clear-sky conditions over a short period during which thermal steady-state equilibrium conditions exist, and to compare the measured results to performance model projections for those parameters. Secondary impacts on power output result from variations in wind speed and ambient dry-bulb temperature. Thermal steady-state conditions can be expected for power tower systems at most times of the year for short test-run durations. Acceptable systematic uncertainties are the dominant consideration.

The key characteristics of the test methods are provided immediately below for both the short-duration thermal Power Test and multi-day long-duration continuous Production Test. Details of the tests are described in section 3.4. Of special importance are the criteria that must be satisfied by the short-duration Power Test. The recorded data can be viewed as having two components – the actual test measurements and the uncertainty interval associated with those measurements and other test conditions calculated using standard practice. This requires stable characteristics in the solar resource (the Direct Normal Irradiance) and other conditions. Once thermal equilibrium and test condition stability have been reached, the criteria for valid thermal power measurements (i.e., valid test runs) are primarily based on the level of uncertainty in the test results calculated using standard practice.

The essence of these tests and their relevant characteristics are described below.

- <u>Short-Duration Steady-State Thermal Power Test (Power Test)</u>
    - Clear-day tests run at a thermal equilibrium condition
    - Tests akin to ASME performance tests are run on equipment with a steady energy source
    - Requirements specifying that equipment shall be operated within the pressure, temperature, and flow limits specified by the equipment vendors
    - Comparison of measured performance to model projection
    - Requirement to repeat tests over hours/days to prove replicability
    - Option to use the tests, if all parties agree, to aid in validation of the performance model used for purposes of annual projection.
- <u>Long-Duration Production Test (Production Test)</u>
    - Length of duration is specified in the contract, ranging from several days (e.g., up to 15) to months to years
    - Test covers complete operation from morning startup to evening shutdown, and overnight parasitic thermal and electrical losses
    - Extra factors are included that are not part of the short-duration Power Tests, e.g., startup transients, freeze protection, variable irradiance, inclement weather conditions, and shutdown transients
    - Equipment shall be operated within the pressure, temperature, and flow limits specified by the equipment vendors
    - The primary goal is to validate the accuracy of the performance model over time for comparison to contractual projections.

Used appropriately, there are two other specific uses of the Power Test tests, namely in the Capacity Test and in the calculation of solar system thermal efficiency.

- Capacity Test
  - Short-duration Power Test to <u>prove design capacity</u>
  - Test to be run at specified minimum solar conditions, or higher
  - No comparison to model projection unless required
  - Typical duration is over a number of hours within a period of several days
- Solar system thermal efficiency calculation
  - Derived from the results of the Power Test by normalizing with the solar power to the heliostat field (specifically, the DNI times the tracking heliostat area)
  - To be examined if designated by the Parties to the test
  - Measured efficiency performance to be compared to model projection
  - If agreed among participating parties, the test can satisfy or aid in the validation of the performance model used for purposes of annual projection.

3.3 Solar Resource and Other Factors

The tests are to be run on clear days during any time of year. Even with a high DNI, which can be experienced on a clear winter day, the important solar resource term that dictates the thermal energy input into the receiver is found to be relatively steady during midday periods throughout the year.

During the performance test period, the solar systems should not be operated beyond their specified or suggested operating limits for solar resource, ambient temperature, or wind speed as provided by the solar system supplier(s).

Calculation of the mass flow typically requires measurement of the volumetric flow rate and knowledge of the working fluid density (i.e., that of molten salt, water-steam, or gas) as a function of temperature. Calculation of the thermal power requires knowledge of the enthalpy. In the case of an indirect molten salt receiver system, these properties of the working fluid are recommended to be measured prior to the test, per agreements between the test parties.

3.4 Power and Energy Calculations

<u>Delivered Power Calculation</u>

The thermal power output of the solar system is to be calculated from the change in enthalpy in the receiver working fluid. Across the inlet/outlet points, the delivered thermal power can be computed from:

$$P_{measured} = \dot{m}\,\Delta \mathrm{h}_{\mathrm{rec}} \qquad \text{(preferred method if data is available)}$$

$$= \dot{m}\int_{\mathrm{T_{rec,out}}}^{\mathrm{T_{rec,in}}} \mathrm{C_p} \cdot \mathrm{dT} \quad \text{if specific heat } \mathrm{C_p} \text{ is used}$$

$$= \dot{m}\overline{\mathrm{C}}_{\mathrm{p}} \left(\mathrm{T_{rec,in}} - \mathrm{T_{rec,out}}\right) \qquad \text{(Eqn. 3-1)}$$

where

- P = Solar thermal power
- $\dot{m}$ = Working fluid mass flow rate
- Δh_{rec} = Enthalpy difference between inlet and outlet of receiver
- $\overline{C}_p$ = Integral average specific heat of working fluid
- $T_{rec,in}$ = Working fluid average bulk inlet temperature to solar receiver
- $T_{rec,out}$ = Working fluid average bulk outlet temperature from solar receiver

<u>Efficiency Calculation, if part of specified test protocol</u>

The solar thermal efficiency based on DNI is computed from:

$$\eta_{measured} = \frac{P_{measured}}{DNI \cdot A_{aperture}} \qquad \text{(Eqn. 3-2)}$$

where

- η = thermal efficiency
- $A_{aperture}$ = heliostat aperture area in tracking mode during the test

The heliostat aperture area in active tracking will be used for the $A_{aperture}$ term. Note that if the solar field condition for the test includes stowed heliostats, then the receiver thermal losses may be high relative to the active tracking area, resulting in a lower thermal efficiency. The performance model projection must include the ability to account for this condition.

<u>Multi-Day Production Test</u>

The objective of this test is to gather continuous daily thermal energy output (integrated power output using Eqn. 3-1; thermal efficiency from Eqn. 3-2) and to compare the results to projections from a performance model. <u>Both clear sky and partly cloudy conditions are acceptable.</u> Conditions in which cloud cover unevenly affects portions of a large solar field will need to be treated on a case-by-case basis, and agreed upon by both parties. In the event of multi-day, fully cloudy or rainy weather—and perhaps in the event of nonuniform shadowing if agreed—the test should be terminated and then restarted when appropriate. Additionally, the functionality of the solar system should be observed with regard to such items as daily startup, normal operation, and shutdown.

It is recommended, based on similar typical tests on power systems, that the test be at minimum a continuous 10-day test with data acquisition on short time steps (e.g., 10-second intervals for an average value) to accurately capture morning startup, evening shutdown, and weather events. However, there is no hard, strong justification for these time durations or intervals, and specifics on duration of the test, data acquisition requirements, and contingencies in case of operational problems are to be agreed upon between the testing parties. It is also recommended that a stop/start pattern be permitted in the Test Plan if other circumstances not related to the solar system require that the test be temporarily suspended due to, for example, shutdown of the power block.

The measured energy output results over time are to be compared to the values predicted by the performance model using the input characteristics agreed upon by both parties, e.g., the same model technical input as used for pro forma calculations and delivered by the equipment supplier or EPC contractor at contract signing. The input values to the performance model are also to be agreed upon by both parties and are to include the local DNI data and other appropriate weather conditions, specified warranty characteristics of the solar field, and mutually acceptable adjustments for the operating condition of the solar field (e.g., number of heliostats in tracking mode). Treatment of the reflectivity values of the reflectors is discussed in Section 0.

Because of the use of a performance model, no test-correction curves are involved because the model contains internal algorithms that adjust for off-design conditions. The contract shall define any commercial tolerance (which may or may not be linked to test uncertainty) allowed for in the pass/fail criteria (to be specified in the Test Plan).

3.5 Performance Model Projection and Comparison to Measured Result

The performance model used for either acceptance test must be mutually acceptable to both test parties, typically using the system characteristics also used for the project financial projections. The input parameters for the performance model should be identical to those used in the commercial projections for the power plant. The weather file—DNI, wind speed, ambient dry-bulb temperature—should be the actual weather file with the time stamps perfectly synchronized with the measured test data. The atmospheric attenuation must be calculated by appropriate models, within the Performance Model, agreed upon by the test parties.

The possible exception to this rule is the cleanliness condition of the solar field reflectors. This issue is treated in Section 0.

The <u>measured</u> power value must take into account the uncertainty intervals for each quantity.[11] The measured quantity has an uncertainty interval associated with it, and the result is a band defined by the measurement plus or minus (±) its uncertainty interval.

In principle, the same requirement is true of the value projected by the performance model. However, because the performance model is the same as that used in the commercial projections, <u>it is taken to have no uncertainty except that associated with the weather input and average mirror reflectivity value</u>. <u>Validation of the model algorithms and accuracy</u> is assumed to be part of the contractual agreement between the Parties to the tests and is outside the scope of this Guideline.

Although ambient temperature and wind speed have a secondary influence on the results, the parameters in Eqn. 3-1 dominate the uncertainty. The uncertainty band for the result is very important and must be given in the test results. How comparison is made of the measured value to warranted levels is a commercial issue to be agreed upon by the parties and is beyond the scope of these Guidelines or ASME PTCs.

[11] That is, the uncertainty bands need to overlap for a valid test run.

3.6 Working Fluid and Solar System Parasitic Power Consumption

This measurement is for information only, unless otherwise guaranteed, and should include the instantaneous total parasitic power requirement for pumping the working fluid through the tower and subsequent steam generators (if present), as a function of flow rate, during each test period and test run (a subset of the test period). Similarly, the solar field parasitics for the heliostat drive and control system should be measured.

4 Comments on Test Methods

4.1 Introduction

Ideally, the performance tests should be carried out in thermal equilibrium (steady-state) condition. Neither goal is completely possible because of the effects of a changing heat source and changing ambient conditions. Failure to achieve either goal contributes to uncertainty in the test results.

ASME PTCs 4 and 46 assert that thermal steady-state is defined as an operating condition in which the system is at thermal equilibrium, and that the guiding criterion for steady-state test conditions is that the average of the data reflects equilibrium between energy input and energy output to thermal and/or electrical generation. The continuously varying energy input from the sun, combined with other solar field characteristics, make this a particularly challenging objective.

The power tower receiver represent a potential thermal lag to the system, that is, when the solar radiation hitting the receiver changes the impact on the receiver outlet conditions will be delayed due to the thermal mass of the receiver equipment. This effect may be very small or may need to be taken into consideration due to factors such as steam drums in a water/steam tower. The EPC will need to evaluate the situation for a particular receiver design.

4.2 Solar Field Test Conditions

4.2.1 Solar Field Area, Thermal Power Output, and Design Capacity

Typically, the solar system will be larger than required for delivery of rated design solar thermal power during late spring and summer.[12] At the high DNI levels, the peak solar thermal power output of the solar system will often be at or above the design capacity. For configurations without TES, the allowable thermal output may be constrained by the design flux limit of the receiver and the thermal input of the power block or the associated turbine-cycle heat rejection at its design conditions for direct systems. To monitor this effect in a power tower field, the test

[12] In CSP plants that are configured with TES systems, the solar field is typically increased in size to raise the energy collected. For example, on a clear day, a large solar field can provide enough energy in the morning and afternoon hours to both drive the turbine at full load all day and also to charge storage to full capacity. For a given plant and utility application, the size of the solar field can be optimized for the local solar resource, grid demand pattern, electricity revenues (e.g., if time-of-use revenue multipliers are applicable), and financial parameters. For this purpose, a reference solar-field size is determined at a nominal hourly DNI level and at solar-field design parameters, and this is labeled as field multiple = 1. Larger solar fields are identified as multiples of the SM. For plants with no TES, the optimum solar-field size will typically fall in a field multiple range of 1.4–1.5. For plants with TES, field multiple values of 2.0 and higher will typically be chosen.

records must show exactly when each heliostat (identified by position and identifying number) was in a tracking mode, and show the active tracking area as a function of time on the test data record. The Test Plan should specify the exact procedure to be used under such high irradiance conditions.

If the test parties agree that demonstration of the full design capacity of the solar system is a requirement, the Thermal Power Test should be run at the rated design solar thermal output specification if possible, with the measured results compared to the projection of the solar performance model using the tracking aperture area of the solar field.

For lower-irradiance periods during the year, the solar thermal output may be less than the rated design output, though useful for efficiency demonstration purposes. If required by the test parties, final acceptance of the solar system may require a test at a time of year when a higher DNI condition occurs and the performance model indicates that design solar thermal output can be achieved.

4.2.2 Stability of Energy Input to the Receiver in a Tower System

A major question in the testing is the stability of the thermal resource for the short-duration Power Test. The two important considerations for power tower technology are the type of power tower system, namely Cavity Receiver/North Field or External Receiver/Surround Field (see Figure 4-1), and the time of year. To examine these issues, model runs were conducted with SAM for selected days for Daggett, California given a fixed set of operating heliostats. In these runs, the optical efficiency includes: cosine effect, atmospheric attenuation, mirror reflectivity, cleanliness, receiver absorptivity, spillage, blocking, and shadowing. Results are shown in Figure 4-1 for a clear summer day. Note that for a midday period of about 2 hours, the variation of power delivered by the receiver is generally within a +/- 1% variation for both tower configurations.

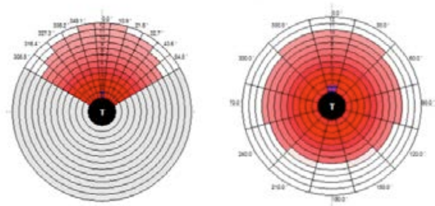
Model runs for clear days in March and December gave very similar results for midday variations, suggesting that thermally stable testing can be conducted for either power tower configuration during a short midday period. Data on those results are presented later in this report.

4.2.3 Solar Field Reflectivity

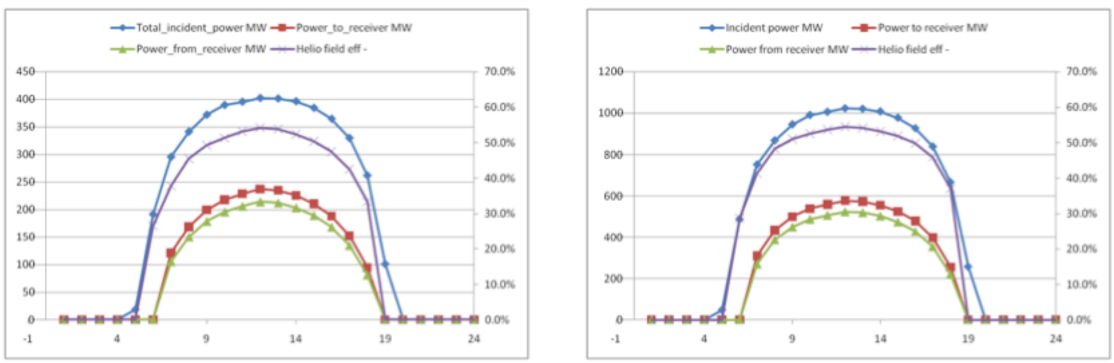
The solar thermal output of the solar field is directly proportional to heliostat cleanliness, which is characterized in most solar performance models by a cleanliness, or soiling factor.[13] The projected performance of the solar field at the time of contract signing is typically based on a specified average reflectivity. The decision on the cleaning and reflectivity measuring issue is very important to both the performance of the solar field and the uncertainty in the results.

In normal operation, the reflectors are cleaned according to methods and wash frequency that are specific to the site location, operation and maintenance (O&M) organization, and optimization of water and labor costs versus performance gains. Heliostat reflectivity is typically returned to a high level after cleaning. The EPC contractual documents may contain the O&M mirror washing plan agreed upon by the parties.

[13] The cleanliness factor is one of a number of factors in the optical efficiency term of the collectors.



a) Configurations: Cavity/North External/Surround



Hour	Total incident power MW	Field efficiency %	Power to receiver MW	Power from receiver MW	%
10	389.47	51.3%	217.78	196.07	
11	395.39	53.1%	228.82	206.43	-2.2
12	402.15	54.2%	237.34	214.43	1.6
13	401.31	53.8%	235.14	212.4	0.6
14	396.23	52.3%	225.9	203.77	

Hour	Total incident power MW	Field efficiency %	Power to receiver MW	Power from receiver MW	%
10	990.2	52.5%	538.79	487.79	
11	1005.3	53.7%	559.39	507.31	-1.9
12	1022.5	54.5%	577.46	524.3	1.4
13	1020.3	54.2%	572.84	519.91	0.5
14	1007.4	53.2%	555.07	503.48	

b) Sample results for a clear June summer day in Daggett, California

Figure 4-1. Model data on power tower energy input stability. ***Illustrations by Gregory Kolb, Sandia National Laboratories, and Mike Wagner, NREL***

For acceptance testing, agreements need to be reached between the testing parties on (a) heliostat washing during the test period and (b) the cleanliness factor used in the model for comparison to the measured power delivery.

One approach could be that the heliostats could be washed – at the time of acceptance testing - on a schedule similar to that proposed for normal operation. That is, prior to and during the multi-day test period, operators would wash the heliostats using the normal planned O&M schedule and procedure in the solar field O&M plan. For a large plant, it could take one or several weeks to complete the washing cycle. A second choice could be to carry out no heliostat washing at all during the short-duration Power Test or multi-day test periods, though this approach is not recommended.

Regardless of the approach to heliostat washing, sufficient reflectivity readings should be taken to characterize the average reflectivity of the solar field for use in the performance model, with an appropriate uncertainty interval applied to the average solar field reflectivity value. The testing parties need to agree on methods to optimize the spatial sampling to obtain a valid statistical average. This will likely require an additional quantity of instruments beyond the normal number at the plant. It is not possible in this general Guideline to specify in advance the number of required readings because of the site-specific character of both the solar field configuration and the soiling mechanisms at the site.

And, further complicating this issue, to our knowledge only a few published works treat the development of methods to determine statistically valid reflectivity averages in large solar fields using a reduced number of readings. One such study was carried out in 2006 on a small power tower heliostat field at the Plataforma Solar de Almeria test facility in Spain.[14]

Also, experience was gained at the Kramer Junction SEGS plants in the 1990s, in which specific solar collector assemblies (SCAs) to be measured were chosen at random based on a pattern regarding the area of the solar field from which they were selected. Four SCAs were chosen from the exterior zone near the edges of the field where degradation rates are higher, eight SCAs were selected from the interior zone, and the final eight SCAs were selected from the intermediate zone characterized by medium degradation.[15]

4.3 Criteria for Adequate Test Durations and Conditions

Variations in the key test parameters should be low enough to contribute only in a minor way to the uncertainty band in the results. The solar system must be in a stable thermal condition (thermal equilibrium) prior to testing. This requires stable conditions in the:

- Working fluid inlet enthalpy to the receiver
- Working fluid outlet enthalpy from the receiver
- Mass flow rate
- Magnitude of the effective radiation input to the heliostat field.

The energy delivered by the power tower receiver will be dictated by the stability of the parameters listed above. An important condition is that the energy output measurement is coincidental, or in sync, with solar input to the tower panels, which in turn depends on the thermal inertia effects dictated by the receiver design and the working fluid flow rate. For example, a change in the radiation input to the receiver panels will result in a change in the working fluid outlet temperature and, in turn, the thermal output. If these changes were both (ideally) instantaneous, the energy output would be in sync with the radiation change. If the receiver has significant thermal inertia, or a low working fluid velocity, the measured energy output would likely not be in sync with the solar input. In a test condition, therefore, the

[14] Fernandez-Reche, J., "Reflectance measurement in solar tower heliostats fields," Solar Energy 80 (2006)

[15] Cohen, G; Kearney, D.; Kolb, G. "Final Report on the O&M Improvement Program for CSP Plants", excerpt from Appendix E on Mirror Cleanliness, Sandia National Laboratory Albuquerque, SAND99-1290, June 1999.

measured energy output value change would lag the predicted energy output value change from a performance model. This lag could vary from fractions of a second to many minutes.

In general, the throughput velocity of the working fluid and the thermal inertia of the receiver are the two important characteristics affecting this comparison. Air and molten salt receivers are expected to be more thermally responsive than water/steam receivers, but in any case specific receiver design features need to be considered. For the expected condition of a high input flux on the receiver (e.g., >80% of full receiver capacity), both molten salt and air receivers should have a thermal lag of less than 2 minutes, while steam-water receivers with a steam drum may require from 5 to 15 minutes to achieve equilibrium. For the latter configuration, a reasonable approach may be to require a test condition in which the steam drum pressure is observed to be constant for 15 minutes prior to a Power Test, and is held constant at that level during the test. Note that these are general observations and require pre-test observation on the attainment of equilibrium conditions to set requirements for a specific receiver design.

Once thermal equilibrium and test condition stability have been reached, the criteria for valid power measurements (i.e., valid test runs) are primarily based on the level of uncertainty in the test results calculated using standard practice. Systematic uncertainties are the dominant consideration.

Table 4-1 shows an illustrative set of stabilization criteria for these conditions based on the influence of the variability of the test parameter on the total uncertainty of the test results (see Section 6, Evaluation of Measurement Uncertainty, for more details on uncertainty analysis). The variability defined in Table 4-1 is defined as the standard deviation of the mean $s_{\bar{X}}$ as described by Eqn. 6-1 divided by the average value of the parameter over the test run period. Based on the examples provided by Tables 6-1 through 6-4, a combination of the allowable variations given in Table 4-1 will result in a negligible increase in the total uncertainty of the result. It cannot be overemphasized, however, that final stabilization criteria for a specific project will be strongly influenced by the design of the solar system and associated instrumentation, and finally determined by the agreements between the testing parties.

Table 4-1. Example Stabilization Criteria for Short-Duration Steady State Power Tests of a Utility-Scale Power Tower Solar Field

Parameter	Allowable variability over test period $s_{\bar{X}}/\bar{x}$ (%)
Working fluid volumetric flow rate, m^3/s	0.5%
DNI, W/m^2	0.5%
Receiver inlet temperature	0.2%
Receiver outlet temperature	0.2%

These criteria are to be applied to evaluate test conditions for stability. In general, the potential test period for any given day will occur between 9 a.m. and 4 p.m. Analysis of DNI data for several solar locations indicated that the variability will be much smaller than the example values assigned in Table 4-1. For example, 5-second DNI data collected over a 15-minute period (180 data points) varied by approximately ± 3.5 W/m^2 from an average value of 970 W/m^2. The related standard deviation of the data was 1.88 W/m^2. For this instance, the variability as defined in Table 4-1 is calculated by dividing the standard deviation of the mean ($1.88/\sqrt{180}$) by the average DNI value of 970, resulting in a variability of less than 0.02%.

Table 4-2. Example Conditions for Testing Periods, Durations and Data Points for Short-Duration Steady State Power Tests

Daily Test Period	0900-1600 (9a.m.-4p.m.)
Pre-Test Steady-State Run	Approx. 30-45 minutes
Test Run Duration	Approx. 15-30 minutes
Test Run Data Points	10-second averages
# of Test Points in Test Run	90 - 180
Maximum Wind Speed	Approx. ≤ 13 m/s
Minimum DNI	Approx. 500 W/m^2

4.4 Criteria for Valid Test Results

A valid test result must satisfy the requirements of thermal equilibrium, stabilized test conditions, suitably low uncertainty, and repeatability. Valid test run results, over approximately 15 to 30-minute durations, obtained during a single stable test run period should be averaged. Invalid test runs are those for which the run uncertainty intervals are not within acceptable limits, or if the test run result falls outside the uncertainty intervals of the test runs being compared. A limit should be set by the testing parties on the number of outlier test runs permitted.

4.4.1 Thermal Equilibrium and Stabilized Test Conditions

The criteria applied to the pre-test run period, and illustrated in Table 4-1, must continue to be satisfied through the test run period.

4.4.2 Repeatability

Repeatability of multiple test run results lends confidence to the methods incorporated in the testing. Accounting for the requirements for equilibrium and steady-state conditions, numerous 15- or 30-minute test run results can be taken within the daily approximately 4-hour test window.

Invalid test runs are those that individually have total uncertainty intervals outside acceptable limits, or for which the test results are not within the uncertainty intervals of each other. A limit should be set on the number of invalid test runs that are permissible during a test run period, e.g., 10%.

It is recommended that this pattern be conducted during the best daily time periods (function of season) and repeated on three separate days during a 10-day window. In practice, once the solar system test conditions are set up, the data acquisition system can be run continuously during the full test-run period on the selected days, and the data can then be examined for suitable periods that satisfy the test run conditions for stability.

The results of each test run, or an average of test runs close together in time, should be compared to the performance model output(s). However, the uncertainty of the average calculation will be the same as the uncertainty of an individual result.

5 Instrument Selection

5.1 Required Data

The defining equations for the solar system acceptance tests are straightforward. The power output of the solar system is calculated from Eqn. 3-1 for both types of tests. Eqn. 3-2 adds the need for measurement of the DNI, and the model input data require measurement of the reflectivity of the heliostats. Together, the tests require the measurement of or accurate data on the following:

- Working fluid volumetric flow rate
- Working fluid physical properties of (a) density, specific heat, and temperature, or (b) steam pressure (P), temperature (T) and quality (X) for steam qualities less than 100 percent, in order to determine inlet and outlet enthalpy
- Direct normal irradiance (DNI)
- Mirror reflectivity average or pattern
- Ambient wind velocity, (optionally) wind direction, dry-bulb temperature, and relative humidity
- Latitude, longitude and elevation of the DNI instrument
- Year, day of year, time of day.
- Heliostat coordinates relative to the tower receiver
- Tracking activity or availability for each heliostat during the test duration
- Atmospheric attenuation
- Atmospheric visibility (or other means of assessing atmospheric attenuation)
- Performance profile (or attributes) for each heliostat or heliostat sector
- Solar system parasitic power (including both receiver and heliostat field).

Following ASME PTC guidelines, these values are defined as primary or secondary variables in Table 5-1, and the source of the data is indicated. Primary variables are those that are required to calculate the results of the test. Secondary variables are variables of interest but are not required to calculate results.

Table 5-1. Parameters Required for Determining Thermal Power Output and Efficiency of the Solar System

C – calculated   M – measured   P – physical property
Pri – primary variable   Sec – secondary variable

Primary Term	Parameter	Typical Influence	Typical Source
Solar Field Power	Energy out of receiver	Pri	C
	Working fluid volume flow	Pri	M
	Working fluid density	Pri	P
	Working fluid specific heat	Pri	P
	Working fluid temperature entering receiver	Pri	M
	Working fluid leaving receiver	Pri	M
	Steam conditions (P/T) leaving receiver	Pri	M
	Receiver absorptivity	Pri	M
	Heliostat performance profile (or characteristics)	Pri	M
Solar Input	Energy in	Pri	C
	Solar resource: DNI	Pri	M
	Effective area and position of heliostats	Pri	P
	Solar time	Pri	M
	Latitude and Longitude	Sec	M
Other	Dry-bulb temperature	Pri	M
	Relative humidity / Wet-bulb temperature	Pri	M
	Field visibility (attenuation)	Pri	C
	Wind velocity	Pri	M
	Wind direction	Sec	M
	Average heliostat reflectivity	Pri	M
	Visual range (from local airport or observation)	Pri	M

5.2 Comments on Instruments and Measurements

It is not the purpose of this Guideline to provide a complete treatise on measurement methods, systems, or their accuracy. Rather, the user of this Guideline should review the general considerations on engineering measurements as applied to these acceptance tests based on a thorough study of ASME PTCs relevant to this application. However, specific information on specific types of instruments is provided below with regard to measuring devices required to measure the variables noted previously—particularly at the working fluid flow conditions encountered in utility-scale power tower systems and for solar-unique variables.

An instrument is a device for determining the value or magnitude of a quantity or variable. The variables of interest are identified above. Measurements may be direct or indirect. For example, measuring the temperature of the working fluid with a thermocouple or resistance temperature detector (RTD) is a direct measurement. Measuring the flow rate of the working fluid by use of a pitot tube or pressure drop across an orifice is an indirect measurement. Because of physical limitations of the measuring device and the system under study, practical measurements always have some error. The accuracy of an instrument is the closeness with which its reading approaches the true value of the variable being measured. Random error refers to the reproducibility of the measurement, that is, with a fixed value of a variable, how much successive readings differ from one another. Sensitivity is the ratio of the output signal or response of the instrument to a change in input of the measured variable. Resolution relates to the smallest change in measured value to which the instrument will respond.

Errors other than human error may be classified as systematic or random. Systematic errors are those due to assignable causes; these may be static or dynamic. Static errors are caused by limitations of the measuring device or the physical laws governing its behavior. Dynamic errors are caused by the instrument not responding fast enough to follow changes in the measured variable, e.g., lag in a temperature reading. Random errors are those due to causes that cannot be directly established because of random variations in the system.

There are several essential parts to an instrument measurement system, namely:

- Primary sensing element
- Transmitting means or system
- Output or indicating element
- Data processing, communication and storage system.

Considerable literature exists on the accuracy, installation, data acquisition, and data storage of measurement devices and systems, from both independent sources and from suppliers of the devices and data acquisition systems. The ASME has spent considerable effort to supply valuable recommendations on this subject (see appropriate PTCs, e.g., on flow and pressure measurement). The primary considerations are selection of the measurement device and system, calibration, and estimation of the systematic uncertainty. Random errors need to be estimated from repeated test runs or by analytical means.

5.3 Temperature Measurement

Resistance temperature detectors (RTDs) or thermocouples (TCs) are judged to be the most appropriate sensors to measure fluid temperature in the working fluid stream. Table 5-2 summarizes the important characteristics of each for this application. Both are suitable, but as noted in the text below, the higher accuracy of the RTD suggests it is better suited for acceptance testing.

The RTD element can be made of different metals depending on the application, but platinum appears to be the most popular and is highly accurate. RTDs have a narrower operating range and a slower response time than thermocouples, but are potentially more accurate. For short-duration performance testing purposes, accuracy is more important than durability (and ease of wire installation without affecting accuracy is desirable); these factors favor the choice of RTDs. Some RTDs can have significant drift during the break-in period, which must be considered. Their slower relative response than thermocouples is likely not an issue for performance testing but it needs to be considered if they are used in control loops. However, the lower relative durability of an RTD is a significant consideration if the device will be installed permanently. Also note that either sensor type can be integrated with the recommended flow instrument (e.g., Annubar or vortex meter).

Data measurement devices must be allowed to reach thermal equilibrium in the environment where the measurements will be taken. Thermocouple lead wires shall be placed in a nonparallel position relative to electrical sources to avoid possible electrical interference.

5.4 Flow Measurement

Accurately measuring the volumetric flow rate of the working fluid is a significant engineering challenge, particularly in the large pipes that characterize utility-scale CSP projects. ASME PTC 19.5 – Flow Measurement is the primary reference for flow measurements. ASME PTC 6 - Steam Turbines and ISO 5167[16] provide further information on flow measurement techniques. These sources include design, construction, location, and installation of flow meters, connecting piping, and computations of flow rates. For the conditions of a solar system thermal test, a number of flow measurement devices are suitable and must be evaluated on the basis of the most important criteria for the necessary measurement. Table 5-3 provides data on several instruments that appear suitable for this measurement, but is not intended to be all-inclusive.

[16] ISO 5167 (International Organization for Standardization) Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full. Part 1: General principles and requirements; Part 2: Orifice plates; Part 3: Nozzles and Venturi nozzles; Part 4: Venturi tubes

Table 5-2. Temperature Measurement Devices

Sensor Type	**Resistance Temperature Detector (RTD)** Platinum 4-Wire	**Thermocouple** Type K
Accuracy for Temperature Range, ± °F	~1.5°F (0.8ºC) (DIN/IEC 60751 Class A, higher accuracy obtainable; e.g. 1/3 DIN or 1/10 DIN, if desired) [see Note 1 Refs]	~2.5°F (1.4ºC)
Suitable for 750°F	Yes	Yes
Insertion Requirement	Thermowell	Thermowell
Response Time	Decent (~30 s)	Good (depends on thermowell and thermocouple geometry, but generally better than RTD)
Stability	High	High
Repeatability	Very Good	Good
Drift	0.1°–0.3°F (0.06°–0.17°C) per month (can be higher in break-in period)[1]	0.15°–0.4°F (0.08°–0.22°C) per month.[1] May increase with cycling.
Linear	Very Good	Good
Covered by PTC 19.3 [see Note 2 Refs]	Yes	Yes
Durability/Life	Good (more reliable types can experience higher drift during first several months; then stable)	Better
Cost	Medium (industrial) to High (precision)	Low to Medium
Suitable	Yes	Yes

Table 5-2 Notes

1) Primary element and the transmitter should be calibrated before and after the test in accordance with manufacture's specifications to ensure that the expected accuracy is met. This exceeds the DIN/IEC 60751 requirement, and is intended to improve instrument accuracy.

2) References:

1. EPRI-TR-106453 "Temperature Sensor Evaluation" (6/1996)
2. ASME *PTC 19.3 - Temperature Measurement*
3. ASME *PTC 46 – Overall Plant Performance*
4. http://www.omega.com/

Table 5-3. HTF Flow Measurement Devices

ID	Instrument Type	Units	Orifice, Nozzle, & Venturi	Ultrasonic (Clamp-On)	Ultrasonic (Insert-Type)	Insertion Vortex
01	Indicative Price Range	$/D^2 (D=inch)	46–220 (Venturi)	18–225	33–139	4–47
02	Volumetric Accuracy	+/- %	≤ 1.0–1.5	1.2	≤ 1.0	1.2
03	Maximum Turndown Ratio	---	4:1 (and greater)	30:1	15:1–150:1	7.5:1–15:1
04	Permanent Pressure Drop	psi	0.5–1 (Venturi)	None	None	Minimal (avg pitot tube)
05	Vena-Contracta Pressure Drop	psi	4 (Venturi)	None	None	Minimal
06	Suitable for Operation up to 400°C	Yes/No	Yes	Yes	Yes	Yes
07	Calibration Requirements	---	Moderate	Minimal	Minimal	Significant
08	Repeatability	%	0.1	0.15	0.1–0.3	0.1
09	Piping Requirements (Diameters Upstream, Downstream)	Dia.	3–30U, 3–10D	10–40U, 5–10D	10U, 5D	10–12U, 5D
10	Pipe Size Limitations	---	All Sizes	All Sizes	All Sizes	Up to 12”
11	ASME MFC Specification	---	3M	5M	5M	6M
12	Conclusion	---	Suitable	Suitable	Suitable	Suitable

Table 5-3 Notes

General magnetic meters were not included because they will not work due to low HTF electrical conductivity. Coriolis meters were not included because of pipe size limitations. Insertion turbine meters are included, although accuracy is questionable. All meters are subject to severe inaccuracies if a two-phase flow is present.
Units: Inches*2.54 = cm ; psi/14.5 = bar ; psi*6895 = Pa.

01 D is nominal pipe size in inches. In general, the lower end of the costs, in $/D^2 are representative of 36” pipe; the higher costs are representative of 10” pipe. Note, a portion of the insert-type ultrasonic and Venturi meter costs include piping/components (e.g. the pipe spool) that would otherwise be accounted for in the piping system costs where insertion or clamp-on devices are employed.

02 Accuracy is over the turndown range. Most listed accuracies are for calibrated meters.

03 The turndown ratios listed are for a maximum pipe velocity of 15 ft/s.

05 The Vena-Contracta pressure drop is the local pressure drop, a portion of which is recoverable. Users are cautioned that flashing or cavitation may occur if inadequate line pressure is present, which can void flow measurement. With proper system design and operation, an adequate pressure margin above HTF vapor pressure should be obtainable.

07 Minimal = Internal diagnostics only; Moderate = Calibration of secondary transmitter equipment; Significant = Moderate plus periodic inspection of internal components. See Instrument Notes below for details on calibration and inspection for each instrument type.

09 Upstream and downstream straight length, expressed as pipe diameters, required for an accurate measurement. The upstream length requirement can be reduced with flow-straightening vanes.

13 It is not the intent to provide a recommended technology but rather to screen all flow measurement technologies and provide users with some feasible options and the pros/cons of each. See Instrument Notes below on Insertion Turbine. The orifice plate/flow nozzle/Venturi differential pressure types generally have low turndown capabilities and have significant pressure drop (with the exception of Venturi, as shown above) and will likely not be acceptable for measurement at low DNI and/or high incident angles (i.e., for reliability testing). The low turndown capability will be an issue on the steam/feedwater side as well, where these technologies have traditionally been used in performance testing.

Instrument Notes

Orifice/Nozzle/Venturi: Although these technologies are the most mature and are well accepted in ASME PTCs, turndown ratio and pressure drop limitations may preclude their use, with the exception of the Venturi type. Within the Venturi family of meter types, low pressure drop options are available. Although these type of meters traditionally have accurate turndown ratios of 3:1 to 4:1, there are claims by certain manufacturers of $10{:}1^{+}$ with certain Venturi applications. Further investigation is warranted here. Periodic calibration of the external, secondary instruments (e.g., temperature, static P, delta P) is required.

Ultrasonic: Many products are temperature limited, with only a few meter manufacturers capable of meeting the application's temperature requirements and only one offering a clamp-on style that meets the temperature requirements and has reasonable accuracy. Ultrasonic (UT) meters are the mainstay in natural gas custody transfer applications that have high accuracy, reliability, and turndown requirements. UT meters have demonstrated, in other applications, as low as 0.15% accuracy at a 15:1 turndown ratio and much higher turndown ratios at reduced accuracy. Note that the superior maintainability of UT meters described in the KJOC report [17]Appendix R is due to the use of clamp-on type transducers; high accuracy UT meters are usually the insert type (e.g., wetted-transducer). Internal self-diagnostics can be performed on a UT transmitter while remaining online. Access to wetted transducers can only be obtained if fluid is evacuated from the meter section, which should be incorporated into the design (i.e., up/down stream isolation valves). The use of transducers (or more likely intervening materials due to high temperature) that are not flush with the pipe ID can theoretically erode (protruding type), or collect with sediment (cavity type), which can affect meter accuracy.

Insertion Vortex: Most products are temperature limited and KJOC Appendix R did report turndown issues. The internal devices need to be inspected periodically for fouling, which can be performed online (if appropriate hot-tap accessories are installed), though no measurement will be taken during inspection.

Insertion Turbine: Although published product literature theoretically would lend one to include an insertion turbine meter as an option (i.e., meets temperature, accuracy, and turndown requirements), the quote obtained for the specific application noted an accuracy range likely unacceptable for the testing purposes. There are inherent maintenance issues with moving parts, although the turbine can be inspected and/or repaired online with proper installation of hot-tap accessories.

[17] Cohen, G.; Kearney, D.; Kolb, G. "Final Report on the O&M Improvement Program for CSP Plants," Sandia National Lab Report SAND99-1290, June 1999.

5.5 Direct Normal Irradiance

Components of Solar Radiation

Radiation can be transmitted, absorbed, or scattered by an intervening medium in varying amounts, depending on the wavelength. Complex interactions of the Earth's atmosphere with solar radiation result in three fundamental broadband components of interest to CSP technologies (see Figure 5-2). These components are:

- Direct normal irradiance[18] (DNI)—Solar radiation available from the solar disk
- Diffuse horizontal irradiance (DHI)—Scattered solar radiation
- Global horizontal irradiance (GHI)—Geometric sum of the component of DNI normal to a horizontal plane and DHI (total hemispheric irradiance).

In a power tower solar field, each heliostat redirects DNI to the receiver.

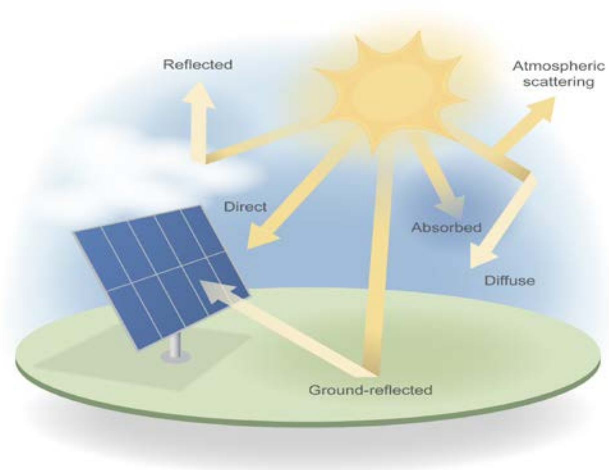


Figure 5-2. Components of solar radiation.
Illustration by Al Hicks, NREL

High accuracy is required for keeping the uncertainty low in the acceptance testing procedure. DNI is a very important input to the solar system performance model, and the heat input to the solar field is directly proportional to the DNI and the cosine of the angle of the sun's rays to the aperture of the collector.

Two conventional devices—the rotating shadowband radiometer (RSR) and the 2-axis tracking pyrheliometer—are available to measure DNI, the first indirectly and the second directly. The pyrheliometer option is highly preferred for Acceptance Test purposes because of its accuracy, despite its cost.

The data in Table 5-4 are from the report, T. Stoffel, et. al, CSP: Best Practices Handbook for the Collection and Use of Solar Resource Data, NREL/TP-550-47465, Sept 2010.

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[18] The terms "insolation" and "irradiance" are sometimes used interchangeably.

Table 5-4. Estimated Direct Normal Sub-Hourly Measurement Uncertainties (Percent)

Type A Error Source	U_{std} TP#	U_{std} Si^	Type B Error Source	U_{std} TP#	U_{std} Si^
Fossilized calibration error	0.615	0.615	Fossilized calibration error	0.665	0.665
Data logger precision (± 50 μV/10mV)*	0.5	0.5	Data logger precision (1.7 μV/10mV)*	0.02	0.02
Si detector cosine response	0	0.5	Si detector cosine response	0	1.5
Pyrheliometer detector temperature response (D20°C)	0.25	0.05	Detector temperature response	0.25	0.05
Pyrheliometer detector Linearity	0.10	0.10	Day-to-day temperature bias (10ºC)	0.125	0.10
Solar alignment variations (tracker or shade band) and pyranometer level for Si	0.2	0.1	Solar alignment variations (tracker or shade band) and pyranometer level for Si	0.125	0.10
Pyrheliometer window spectral transmittance	0.1	1.0	Pyrheliometer window spectral transmittance	0.5	1.0
Optical cleanliness (blockage)	0.2	0.1	Optical cleanliness (blockage)	0.25	0.1
Electromagnetic interference and Electromagnetic field	0.005	0.005	Electromagnetic interference and electromagnetic field	0.005	0.005
TOTAL Type A**	0.889	1.382	TOTAL Type B**	0.934	1.938

\# Thermopile detector used for a pyrheliometer.

^ Silicon diode pyranometer detector used for an RSR.

* Typical manufacturer specified accuracy: ± 0.05% of full-scale range (typically 50 mV) -25º to 50 ºC; assume 10 mV signal to ± 50 microvolts (μV)(0.5%) with 1.67 μV resolution (0.02%).

** Summed under quadrature.

As noted in the NREL report, the combined uncertainty can be determined from the standard uncertainties in the errors illustrated in Table 5-4 for each detector type by summing in quadrature. The resulting standard uncertainty is 1.3% for a pyrheliometer option and 2.4% for an RSR option. The expanded uncertainty, representing a 95% confidence interval as described in Section 6 of these Guidelines, is 2.6% and 4.8% for the pyrheliometer and RSR, respectively.

Maintenance considerations—which are simpler for the RSR device—figure into the choice of a unit for remote use, but are not a constraint or factor for the Acceptance Test application. Again, cost of the tracking pyrheliometer is high, but easily justified for this purpose.

For large heliostat fields (e.g., a 100-MWe power tower plant may have 1.0 to 1.2 million square meters of aperture area and occupy a land area about three times larger), multiple DNI instruments are advised, although this is primarily a matter of judgment and agreement between the test parties. Under clear skies, the DNI should be uniform over areas of this size. To put this in perspective, be advised that a single satellite measurement cell covers an area of about 10 km x 10 km, or 100 million square meters. Regarding solar field instrument placement, multiple instruments might be placed in discrete subsections of the solar field, which could translate to five or more instruments.

5.6 Working Fluid Physical Properties

The properties of density and specific heat of the working fluid are required to calculate the energy transferred out of the solar system into the heat-exchange train. In an indirect system, the parties to the test must agree whether to accept the manufacturer's table of properties for a newly purchased fluid, or to have random samples tested. Samples will typically be sent to authorized laboratories. Test costs are expected to be on the order of several hundred dollars per sample per property. Representative samples of the working fluid in the system during the performance test should be obtained using the methods described in ASTM D 4057 or ASTM D 5287. If working fluid properties could vary because of outside factors, such as a changing source of working fluid, a more rigorous sampling program will be required to ensure representative samples.

ASTM E-1269 is the standard typically used for specific heat measurements using digital scanning calorimetry (DSC). Multiple runs are required to reduce uncertainty in the measurements coming from a variety of contributors. It is also noted that working fluid properties are typically measured at lower temperatures, and properties at the solar system operating temperature may differ somewhat at the higher temperatures. The measurement of fluid density is more accurate, with measured values having accuracies well under 1%.

5.7 Mirror Reflectivity

D&S Field Portable Specular Reflectometer Model 15R-USB

Mirror reflectivity is an important input value to the solar system performance model. The primary instrument used at NREL and at many operating plants is the Device and Services (D&S) 15R-USB designed for field and laboratory measurements of flat or curved reflectors.

The D&S 15R is supplied with a high intensity red light emitting diode (LED) at 660 nm. The specular reflectance is measured at three customer selected instrument apertures chosen from 7-, 15-, 25-, and 46- milliradian (mrad) full-cone angle. NREL has one D&S with 7-, 15-, and 25-mrad and a second with apertures of 7, 25, & 46-mrad. The beam diameter is 10-mm, the beam divergence is 5-mm, and the incidence angle is 15°. The operating temperature range is 32-122°F (0 - 50°C). A 3½ digit LCD display indicates reflectance to 0.1%.

A USB port is provided for maintaining and downloading data sets and upgrading the firmware. According to the manufacturer and reports from solar field use a single operator can take reflectance readings at the rate on the order of 3-4 per minute and record the readings to data sets stored in the instrument. The data are stored in a comma-delimitated string and the instrument does not have the ability to annotate the data.

Uncertainty appears to be less than 1% with proper usage; though human error in taking readings, aperture size, and substrate roughness can be important factors. The manufacturer's specification sheet cites repeatability to +/- 0.002 reflectance units. Current detailed data from the operating plants are lacking. A study performed by PSA (Spain) found the resulting uncertainty was less than 1% for a D&S 15R reflectometer using the 25-mrad aperture, measuring 23 samples of back-silvered 4-mm glass mirrors of different qualities and taking 228 measurements with different operators and ambient conditions.[19]

[19] Personal communication with Eduardo Zarza, CIEMAT, September 2010.

6 Evaluation of Measurement Uncertainty

6.1 Measurement Uncertainty

Due to various influences, any test result will have an associated uncertainty. The uncertainty interval around a measured result describes our lack of knowledge about the true value of a measured quantity. Uncertainty can be reduced by many repeated measurements and in some instances can be further reduced through the use of redundant instruments.[20] The uncertainty of an interval about a measured value is usually expressed with a probability or level of confidence. Uncertainties arise from possibilities for error arising from or classified as: systematic errors, random errors, and human errors. It is very important in the measurements discussed here to quantify the uncertainty intervals to make judgments on the validity of the test results.[21]

Test uncertainty is an important element within any PTC. ASME in particular has placed critical importance on test uncertainty analyses of all measurements and calculations associated with PTCs. Therefore, significant attention has been paid to this aspect of the Guidelines. ASME *PTC 19.1 - Test Uncertainty* is devoted to this topic, and sections in some other codes address uncertainty analysis related to their respective topics.

Because of the resource variability and imperfections in control systems, variation in all of the measured parameters is inevitable. The frequency and period of data collection directly impacts the test uncertainty, and it is highly recommended that a pre-test uncertainty analysis be carried out prior to selection and subsequent installation of any instrumentation. A Power Test will typically consist of more than one test run (data collected during a period of time in which the measured parameters are relatively steady). Conducting more than one test in addition to a post-test uncertainty analysis is recommended to verify the repeatability of the test results and the validity of the pre-test uncertainty analysis.

The systematic error associated with a measurement of a single parameter can come from many sources, including the calibration process, instrument systematic errors, transducer errors, and fixed errors of method. The test engineer should be diligent in identifying all of these sources of error, although it is often the case that one or several will dominate within a particular measurement parameter.

Random errors can similarly be based on a manufacturer's specification. However, the random uncertainty for a given measurement can be reduced based on repeated measurements over the interval in which the system is considered to be in thermal equilibrium (defined by a minimal change in the DNI plus working fluid flow control over the test period, such that the effects of thermal exchange between the working fluid and the receiver hardware are negligible). For repeated measurements, the random standard uncertainty can be defined by

$$s_{\bar{X}} = S_X/\sqrt{N} \qquad \text{(Eqn. 6-1)}$$

[20] Redundant instruments are most readily used to reduce random errors associated with a measurement. To reduce systematic errors, the test engineer must calibrate the redundant instruments at different calibration laboratories to ensure that errors between the instruments are independent.

[21] In ASME PTCs, a great deal of attention is paid to uncertainty estimates. See, for example, *PTC 19-1 - Test Uncertainty* and *PTC 4-2008 - Fired Steam Generators*, Sec. 7.

where S_X is standard deviation of a series of sampled data and N is the number of data points collected over the test interval (e.g., 180 data points for a 30-minute test with data collected at 10-second intervals).

An example calculation is described below using the *PTC 19.1* principles and notation.[22] The purpose is to describe how the uncertainties in each of the measured variables X associated with an acceptance test propagate into the value of a calculated resulting quantity R.

Calculated results, such as the delivered power (Eqn. 3-1) and the solar thermal efficiency (Eqn. 3-2), are not typically measured directly, but rather, are based on parameters measured during the course of one or multiple tests. For this case, the result, R, is a function of individual or average values of these independent parameters as described by

$$R = f(\overline{X_1}, \overline{X_2}, \ldots, \overline{X_i}) \qquad \text{(Eqn. 6-2)}$$

where the subscript i describes the number of parameters used in the calculation of the result and $\bar{X}$ is either the value of a single measurement of the parameter or the average value of the parameter based on a number of N repeated measurements.

The expression for the combined standard measurement uncertainty of a calculated result based on multiple error sources can in many cases be calculated from the root-sum-square of the total uncertainty of the individual systematic and random error sources[23]

$$u_R = [(b_R)^2 + (S_R)^2]^{1/2} \qquad \text{(Eqn. 6-3)}$$

where b_R is the systematic standard uncertainty of a result and S_R is the standard random uncertainty of a result as calculated by

$$b_R = \left[\sum_{i=1}^{I}\left(\frac{\partial R}{\partial \bar{X}_i} b_{\overline{X_i}}\right)^2\right]^{1/2} \qquad \text{(Eqn. 6-4)}$$

$$S_R = \left[\sum_{i=1}^{I}\left(\frac{\partial R}{\partial \bar{X}_i} s_{\overline{X_i}}\right)^2\right]^{1/2} \qquad \text{(Eqn. 6-5)}$$

For the equations above, $b_{\bar{X}}$ is defined as the systematic standard uncertainty[24] of a component and $s_{\bar{X}}$ is the random standard uncertainty of the mean of N measurements. Definitions for the

[22] Although this section is consistent with the methodology and notation used in *PTC 19.1,* the reader can additionally refer to "Measurement Uncertainty: Methods and Applications" by Ronald H. Dieck, ISA, Fourth Edition. This book describes the ASME methodology (among others) and uses consistent notation to the information presented in this Guideline.

[23] See ASME *PTC 19.1* or Dieck for exceptions to this case.

[24] The test engineer should be careful in understanding what uncertainty may be represented by a manufacturer for a given measurement device. The standard uncertainty implies a 68% (one standard deviation) confidence level that the systematic error will fall within the uncertainty limits. The manufacturer may provide information that a 95% confidence (two standard deviations) level was chosen for the uncertainty. For this case, the test engineer should typically divide this value by 2 for use in this analysis. As a conservative estimate (for which the manufacturer does not state a confidence level), one should assume that the value provided is based on one standard deviation.

standard systematic and random uncertainty, as well as the methodology for calculating these values, are described in detail in *PTC 19.1* and Dieck.

The total standard measured uncertainty of the calculated result given by Eqn. 6-2 can be calculated using the methodology described above. It is important to note that this “standard” uncertainty implies that the calculated result will capture the true result within a 68% confidence level (one standard deviation). Typically, a confidence level of 95% (two standard deviations) is desired by the test engineer. For this case, the expanded uncertainty in the result is given by

$$U_{R,95} = 2u_R \qquad \text{(Eqn. 6-6)}$$

Example Calculation of Total Uncertainty for the Measurement of Solar Field Power

Applying Eqn. 6-4 to Eqn. 3-1 for the calculated solar field power (the C_p form is arbitrarily used in this example), we get the following equation for the standard systematic uncertainty of the result[25]:

$$b_R{}^2 = \left(\frac{\partial R}{\partial m} b_m\right)^2 + \left(\frac{\partial R}{\partial C_p} b_{C_p}\right)^2 + \left(\frac{\partial R}{\partial T_{hxin}} b_{T_{hxin}}\right)^2 + \left(\frac{\partial R}{\partial T_{hxout}} b_{T_{hxout}}\right)^2$$

$$= \left(C_p(T_{hxin} - T_{hxout})\right)^2 b_m{}^2 + \left(m(T_{hxin} - T_{hxout})\right)^2 b_{C_p}{}^2 + \left(mC_p\right)^2 b_{T_{hxin}}{}^2 + \left(mC_p\right)^2 b_{T_{hxout}}{}^2 \qquad \text{(Eqn. 6-7)}$$

Similarly, Eqn. 6-5 can be used to derive the equation for the absolute standard random uncertainty of the result.

$$S_R{}^2 = \left(C_p(T_{hxin} - T_{hxout})\right)^2 S_m{}^2 + \left(m(T_{hxin} - T_{hxout})\right)^2 S_{C_p}{}^2 + \left(mC_p\right)^2 S_{T_{hxin}}{}^2 + \left(mC_p\right)^2 S_{T_{hxout}}{}^2 \qquad \text{(Eqn. 6-8)}$$

Example Calculation of Total Uncertainty for the Measurement of Solar Field Efficiency

The above methodology can be applied identically to the equations for solar field efficiency to arrive at estimated uncertainties. The resulting equation for the standard systematic uncertainty associated with the solar field efficiency based on DNI is

[25] In actual practice, volumetric flow would likely be measured in lieu of mass flow resulting in a revised equation for power, $P = \rho V\overline{C}_p\left(T_{hx,in} - T_{hx,out}\right)$, where both ρ and $\overline{C}_p$ are a function of the working fluid temperature. A more detailed analysis of the uncertainties associated with the measurement of solar field power and efficiency would need to include these expanded terms.

$$b_R{}^2 = \left(\frac{C_p}{DNI \cdot A_{aperture}}(T_{hxin} - T_{hxout})\right)^2 b_m{}^2 + \left(\frac{m}{DNI \cdot A_{aperture}}(T_{hxin} - T_{hxout})\right)^2 b_{C_p}{}^2 + \left(\frac{mC_p}{DNI \cdot A_{aperture}}\right)^2 b_{T_{hxin}}{}^2 + \left(\frac{mC_p}{DNI \cdot A_{aperture}}\right)^2 b_{T_{hxout}}{}^2 + \left(\frac{mC_p(T_{hxin} - T_{hxout})}{DNI^2 \cdot A_{aperture}}\right)^2 b_{DNI}{}^2 + \left(\frac{mC_p(T_{hxin} - T_{hxout})}{DNI \cdot A_{aperture}{}^2}\right)^2 b_{A_{Aperture}}{}^2$$

(Eqn. 6-9)

and

$$S_R{}^2 = \left(\frac{C_p}{DNI \cdot \cos\theta \cdot A_{aperture}}(T_{hxin} - T_{hxout})\right)^2 S_m{}^2 + \left(\frac{m}{DNI \cdot A_{aperture}}(T_{hxin} - T_{hxout})\right)^2 S_{C_p}{}^2 + \left(\frac{mC_p}{DNI \cdot A_{aperture}}\right)^2 S_{T_{hxin}}{}^2 + \left(\frac{mC_p}{DNI \cdot A_{aperture}}\right)^2 S_{T_{hxout}}{}^2 + \left(\frac{mC_p(T_{hxin} - T_{hxout})}{DNI^2 \cdot A_{aperture}}\right)^2 S_{DNI}{}^2 + \left(\frac{mC_p(T_{hxin} - T_{hxout})}{DNI \cdot A_{aperture}{}^2}\right)^2 S_{A_{Aperture}}{}^2$$

(Eqn. 6-10)

Tables 6-1 through 6-4 summarize uncertainty data and results derived from the methodology described above as applied to the solar system power and efficiency calculations, and they can be considered an example of a pre-test uncertainty analysis. Although any such analysis must be undertaken with the specific system and instrumentation in mind, the systematic and random uncertainties of measurement parameters given in the tables represent what may occur in a typical field installation.[26]

[26] Uncertainties within this Guideline are estimates based on discussions with various experts. Actual uncertainties will depend on specific solar field instrumentation and calibration procedures associated with an acceptance test.

Table 6-1. Table of Data – Solar Field Power (100-MW Molten Salt Tower with 6 hrs TES)

Independent Parameters

Parameter Information (in Parameter Units)									Uncertainty Contribution of Parameters to the Result (in Results Units Squared)	
Symbol	Description	Units	Nominal Value	Standard Deviation	N_i	Absolute Systematic Standard Uncertainty $b_{\overline{X_i}}$	Absolute Random Standard Uncertainty $s_{\overline{X_i}}$	Absolute Sensitivity $\frac{\partial R}{\partial \bar{X}_i}$	Absolute Systematic Standard Uncertainty Contribution $\left[\frac{\partial R}{\partial \bar{X}_i} b_{\overline{X_i}}\right]^2$	Absolute Random Standard Uncertainty Contribution $\left[\frac{\partial R}{\partial \bar{X}_i} s_{\overline{X_i}}\right]^2$
m	Mass flow rate	kg/s	1180	15.5	120	11.8	1.4	429.0	25625829	367213
Cp	WF specific heat	kJ/kg-K	1.5	0.088	30	0.005	0.02	337480.0	2847319	29268329
Thxin	Hot WF temperature	ºC	574	1.5	120	1.0	0.14	1770.0	3132900	57942
Thxin	Cold WF temperature	ºC	288	1.5	120	1.0	0.14	1770.0	3132900	60425

Table 6-2. Summary of Data – Solar Field Power (100-MW Molten Salt Tower with 6 hrs TES)

Symbol	Description	Units	Calculated Value, R	Absolute Systematic Standard Uncertainty, b_R	Absolute Random Standard Uncertainty, S_R	Combined Standard Uncertainty, u_R	Expanded Uncertainty of the Result, $U_{R,95}$	Expanded Uncertainty of the Result, $U_{R,95}$ (%)
P	Solar Field Power	kJ/s	506,220	5894	5455	8031	16061	3.2%

Table 6-3. Table of Data – Solar Field Efficiency (100-MW Molten Salt Tower with 6 hrs TES)

Independent Parameters

Parameter Information (in Parameter Units)									Uncertainty Contribution of Parameters to the Result (in Results Units Squared)	
Symbol	**Description**	**Units**	**Nominal Value**	**Standard Deviation**	**N_i**	**Absolute Systematic Standard Uncertainty** $b_{\overline{X_i}}$	**Absolute Random Standard Uncertainty** $S_{\overline{X_i}}$	**Absolute Sensitivity** $\frac{\partial R}{\partial \overline{X}_i}$	**Absolute Systematic Standard Uncertainty Contribution** $\frac{\partial R}{\partial \overline{X}_i} b_{\overline{X_i}}{}^2$	**Absolute Random Standard Uncertainty Contribution** $\frac{\partial R}{\partial \overline{X}_i} S_{\overline{X_i}}{}^2$
m	Mass flow rate	kg/s	1180	15.5	120	11.8	1.4	0.0004	0.000028	0.0000004
Cp	WF specific heat	kJ/kg-K	1.5	0.088	30	0.005	0.0160	0.3505	0.000003	0.0000316
Thxin	Hot WF temperature	ºC	574	1.5	120	1.0	0.14	0.0018	0.000003	0.0000001
Thxin	Cold WF temperature	ºC	288	1.5	120	1.0	0.14	0.0018	0.000003	0.0000001
DNI	Direct Normal Insolation	J/s-m2	950	9.7	120	12.5	0.9	0.6	0.000048	0.0000002
$A_{Aperture}$	Collector Aperture SM=1	m2	1013655	--	--	--	--	--	--	--

Table 6-4. Summary of Data – Solar Field Efficiency (100-MW Molten Salt Tower with 6 hrs TES)

Symbol	**Description**	**Units**	**Calculated Value, R**	**Absolute Systematic Standard Uncertainty, b_R**	**Absolute Random Standard Uncertainty, S_R**	**Combined Standard Uncertainty, u_R**	**Expanded Uncertainty of the Result, $U_{R,95}$**	**Expanded Uncertainty of the Result, $U_{R,95}$ (%)**
η	Solar Field Efficiency	--	0.526	0.009	0.006	0.011	0.022	4.1%

7 Comments on Test Procedures and Plan

The Test Plan needs to be organized and developed according to the specific solar system design and to carefully consider both the previous discussion and ASME test code information to arrive at uncertainty results that are agreed upon by the test parties. For example, ASME *PTC 4-2008 – Fired Steam Generator* gives excellent guidance on preparations and guidance of performance testing. That code recommends that the preparation for testing include:

- Indisputable records on the equipment, test procedure, instrumentation characteristics locations, and calibrations
- Agreements on a wide number of issues that might later lead to misunderstandings
- Preliminary test runs to check out all aspects of the Power Test and Production Test procedures and data reduction
- Issues related to the conduct of the tests, e.g., preparation, starting and stopping, and readjustment of equipment or instruments during the test run periods
- Conduct of test and data collection.

Further recommendations cover instruments, operating conditions, and records.

7.1 Test Plan

The Test Plan in the example organization scenario of these Guidelines would be prepared by the EPC contractor, with comments by the technology provider and likely an independent engineer(s) representing the owner and debt providers. The plan translates guiding principles into a detailed program related to the specifics of the solar system being tested, based on the contractual agreements between the test parties. It is crucially important to cover all aspects of the testing and to document all agreements and methods. Instrumentation would typically be identified by instrument type and measurement, with location later verified visually in the field. More instrument details, such as serial numbers and calibration information, would be provided as they become available. Testing plans should be spelled out in detail as to purpose, duration, methods, data reduction, and pass/fail criteria. Test reports should be complete, with ample use of photographs and diagrams. For further information, see: *PTC 4-2008 – Fired Steam Generator; PTC 46 – Overall Plant Performance; PTC 50 - Performance Test Code for Fuel Cell Power Systems Performance; and PTC 19.1 - Test Uncertainty*.

To be clear, an independent Test Plan document must be written, based on these Guidelines and/or applicable ASME test codes, defining details of the performance acceptance testing. That document will become part of the contractual agreement between the party turning over the solar system and the party taking control of the solar system. Said differently, the Test Plan is a commercial agreement that will dictate the required testing for the transaction. The following bullet points and example outline in Section 0 are provided to show some elements of the use of the Guidelines in both the contract agreements and the Test Plan itself. In a general sense, the Guidelines (and eventually, an ASME PTC) provide the technical basis to produce a Test Plan that is specific to the project configuration, selected instrumentation, and other elements particular to the solar system under test.

7.1.1 Example of Contract Agreements Prior to Formulation of a Test Plan [27]

- Total plant performance guarantees are agreed to prior to signing of the EPC contract. Typically, only one or at most two system load points are guaranteed, usually at design capacity or near design capacity. Subsystem guarantees would typically be set at that time. Guarantees and requirements for the solar system may vary considerably between projects, EPC firms, and the solar system technology provider.
- To provide a wrap-around warranty, the usual EPC practice is to get back-to-back performance guarantees from major equipment suppliers. It is common to strive to pass through major equipment supplier terms, conditions, and exceptions to the contract.
- The performance test procedure is not developed prior to contract signing; however, the contract language typically includes "mutually agreed performance test procedure to be developed and approved by owner ~6 months prior to testing." The contract will also include major test-related principles so that no surprises occur when the test procedure is issued. Test procedures typically follow the appropriate ASME PTC, including sample calculations, correction curves (if any), and sometimes a calculation spreadsheet.
- A contract typically requires demonstration of minimum thresholds (perhaps 5% less than the guarantee level) prior to retirement of scheduled liquidated damages (substantial completion). This is known as "Minimum performance or minimum performance levels." Achievement of guarantees (or better) is to be performed prior to Final Completion. The duration typically allowed for Substantial Completion to Final Completion is about 6 months to 1 year.
- Contracts typically allow payment of performance-liquidated damages in lieu of achieving guarantee values, provided "minimum performance" criteria are achieved.

7.1.2 Some Elements of a Test Plan

- The guarantee values typically are included in the prime contract. Test specifics are usually covered in an Exhibit to the prime contract.
- The contract defines any commercial tolerance (which may or may not be linked to test uncertainty) allowed for past/fail criteria.
- Contract-defined tests are to follow appropriate ASME PTCs as possible. Because the ASME PTC on CSP systems (PTC 52) is currently under development and appears to be several years away from the issue date of these Guidelines, we recommend that these Guidelines and ASME PTCs such as those on uncertainty and instrumentation be among the sources used to formulate the Test Plan.
- Both the EPC contractor and owner nominate a person authorized to approve variations in test procedures, equipment/valve line-up, etc.
- The owner typically has an owner's engineer or third-party testing contractor acting on their behalf.

[27] Comments on these two pages extracted from personal communication with Marcus Weber, Fluor, December 2009, and David Ugolini, Bechtel Power Corp., July 2010.

- In practice, it is recommended that over test periods of several hours, or even days, per agreement between parties, data be taken continuously via the data acquisition system and processed in a post-test period through data reduction software. These data will not only document the Energy Test results, but will also serve to determine whether valid test run periods of 15 to 30 minutes can be identified in the Power Test. If desired, the data could be examined in real time using the same techniques to monitor progress through the test period.
- Preliminary test results/reports are typically required soon after test completion. The final test report is due later and includes laboratory analysis of fuel samples, test data, operator logs, and calculations. (A typical example list is in ASME *PTC 46 – Overall Plant Performance*.)

7.1.3 Sample Test Report Outline [28]

1. Scope and Objective
2. Definitions
3. Testing Methodology
   - Measured Parameters
   - Modeled Parameters
   - System Operation
   - Equipment in Service
   - DCS and Manual Data Collection
   - Description of Performance Model
   - Data Processing and Model Run
   - Responsibilities of Parties
4. Testing Procedure
   - Pre-test Plant Condition
   - Operation prior to Data Collection
   - Operation during Testing
   - Operation after Testing
5. Data Collection and Analysis
   - Calculation Procedures
   - Correction Factors
   - Uncertainty
   - Data and Results Distribution
   - Acceptance Criteria

[28] Based on input from M. Weber, Fluor and M. Henderson, R.W. Beck (now SAIC)

6. Appendices
    - Valve Positions
    - Instrument Data Points
    - Test Results
    - Performance Analysis
    - Representative Model Input/Output
    - Working Fluid Thermal Properties
    - Sample Calculation

7.2 Further Observations

7.2.1 General

In principle, the fundamental measured parameters and guiding equations for this Acceptance Test are straightforward, as shown in Section 0. The data required and computational methods for determining the performance of utility-scale solar thermal systems have been discussed in some detail in the previous sections, including data acquisition principles, instruments, and methods of measurement. Nevertheless, it is important to emphasize that there are many important considerations that must be addressed to ensure high-quality results. For this Acceptance Test, we reiterate a few important factors:

- Thermal equilibrium and stabilized conditions in the test runs for solar thermal power output and efficiency
- Acceptable measurement techniques for temperature, volumetric flow rate, and DNI, with all calibrations current
- Accurate working fluid property values over the entire operating range that are accepted by the principal parties involved in the testing
- Suitable locations for test measurements to ensure accurate results for a large solar system
- Acceptable uncertainty analyses throughout the test(s), with predetermination of systematic and random uncertainties
- Complete test logs and records of test data and data reduction methods
- Preliminary (practice) test runs to identify any problems or inconsistencies
- Pre-agreed-upon methods to deal with test anomalies and inconsistencies during testing.

Relevant ASME PTCs contain excellent, more detailed information about best practices for conducting performance acceptance tests. For example, they provide good guidance on measurement data reduction, including calibration corrections, handling test-point outliers, methods of averaging data, if required, and computations of random and systematic uncertainty. *PTC 46 – Overall Plant Performance* and *PTC 4-2008 – Fired Steam Generators* offer good examples. Complete records of test data and data reduction methods are critical. All instrument calibrations should be current.

There are other considerations that should be taken into account in writing the Test Plan. Various second-order effects on equipment not associated with the heliostat field and the receiver could affect solar performance measurements. Various potential examples postulated by the Advisory Committee for this report are provided in a lengthy footnote[29] below. These examples are ones that are likely to be difficult to incorporate into a performance model.

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- In a steam tower, the receiver is coupled to the turbine. If the condenser ejectors are slow in establishing the required condenser pressure to roll the turbine, the receiver will be waiting on the ejectors. If the performance model doesn't mimic "slow" ejectors, the measured receiver output will be lower than the theoretical value.
- In a salt tower, one of the upwind panel ovens might be slow to reach the salt fill temperature, i.e., the wind speed increased for a few minutes, but then decayed. This effect would be difficult to observe and to measure. If the fill is delayed, the measured daily receiver output will be less than the theoretical output.
- In a salt tower with storage, the storage capacity will reach 100% on a good summer afternoon. Some fraction of the heliostat field will need to be defocused, leading to a loss in the daily energy captured by the receiver. If the model shows the storage system is full at 3:05 p.m., but the storage is really full at 2:50, this will lead to an error in the performance calculation for the receiver.
- A loss of one of the circulating water pumps will cascade all the way back through the turbine to defocus some portion of the heliostat field on a good summer day. Does the performance model accurately predict the daily output of the condenser, the turbine, the steam generator, the storage system, and the receiver running at reduced equipment efficiencies?
- Aggressive operators may be prone to ignore the minimum superheat constraints on turbine startup, or the maximum allowable rate of temperature change in the metal of the salt steam generator.
- In salt steam generators, operating at low turbine loads will, unless various steps are taken, cause the salt to freeze at the outlet of the preheater. One method to keep the salt temperature high enough is to attemperate the salt temperature supplied to the superheater and the reheater. In effect, the salt temperature profile pivots about the evaporator pinch point. As the turbine load is increased, the attemperation is decreased. Granted, the turbine is not coupled to the receiver in a salt tower system. However, the cold salt temperature is a function of the steam generator performance, and the cold salt temperature influences both the startup time of the receiver and the daily receiver efficiency.
- In salt tower systems, cloud transients cause the temperature of the cold tank to rise. This, in turn, influences the receiver efficiency and the maximum power that can be absorbed. If the cloud transients are short and frequent, accurately modeling the effects on the daily receiver efficiency is likely to be difficult.
- For a direct steam system, a short-term power test would probably require drum blowdown to be isolated to get a good determination of the steam flow. This would put some constraints on just running the DAS and collecting data.

7.2.2 Summary of Agreements To Be Made Between Test Parties

The following list summarizes the various topics noted in these Guidelines that must be agreed to by the test parties:

- Complete procedures and Test Plan for Power and Production Tests
    - Structure of tests (see below)
    - Selection and placement of flow and temperature instrumentation
    - Pass/fail criteria for evaluation of test results
    - Schedule of mirror washing during tests, pattern of reflectivity measurements, and basis for cleanliness factor to be used in performance model
    - Test schedule(s)
    - Requirements for demonstration of rated solar thermal design power capacity and rated solar thermal design efficiency
    - Method of comparison between measured performance and model projected performance, and method of incorporation, or not, of test uncertainties into this comparison
    - Decision on measurements.
        - Working fluid properties (density; specific heat)
        - Multiple DNI locations
        - Single sensor or array of sensors at pipe measurement locations for flow and temperature measurements.
- Solar System performance model
    - Model selection (recommend model used for commercial *pro forma* performance projections)
    - Input data set to model (both fixed and per test values).
- Structure of short duration steady-state thermal Power Test
    - Steady-state test run duration
    - Repeated number of steady-state tests per day, number of test days, and duration of multi-day steady-state test period
    - Criteria that would cause a temporary interruption in the agreed-upon test period.
- Structure of multi-day continuous Production Test
    - Duration of test period.
- Uncertainty analysis
    - Random and systematic uncertainties for each parameter
    - Exact equations and methods to be used
    - Pre-test uncertainty analysis
    - Data collection
    - Post-test analyses
- Test report
    - Complete details and table of contents of test report
    - Data reduction procedures and equations
    - Schedule for completion.