BSR/ASHRAE Standard 182-2008R

Public Review Draft

Method of Testing Absorption Water-Chilling and Water-Heating Packages

First Public Review (March 2020)
(Complete Draft for Full Review)

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FOREWORD

Insert foreword.

1. PURPOSE

The purpose of this standard is to prescribe a method of testing absorption water-chilling and water-heating packages to verify capacity and thermal energy input requirements at a specific set of operating conditions.

2. SCOPE

This standard applies to

a. absorption packages used to chill and/or heat water, as defined in Section 3, Definitions.
b. testing that will occur where proper instrumentation and load stability can be provided.
c. It is not the intent of this standard to provide for testing in typical field installations, where steady-state conditions are often difficult to achieve and adequate provisions for measurement are not made.

3. DEFINITIONS, ABBREVIATIONS, AND ACRONYMS

absorber: a heat and mass exchanger in which a concentrated solution absorbs refrigerant vapor and becomes dilute. This process is accompanied by the release of heat that is rejected to a liquid cooling stream.

absorption package: a factory-designed and pre-fabricated assembly used for chilling and/or heating water that consists of an evaporator, absorber, condenser, generator(s), and solution heat exchanger(s), with interconnections and accessories.

The package utilizes a mixture of at least two components. The more volatile component is the refrigerant, and the less volatile substance with high affinity for the refrigerant is the absorbent. Either single or multiple reconcentrations of an absorbent solution, known as *effects*, can be used. A single-effect package employs a one-step reconcentration of the absorbent in the generator. Refrigerant vapor is released when thermal energy is introduced into the generator.

The concentrated absorbent is returned to the absorber where it can absorb refrigerant vapor flashed off in the evaporator, and the cycle repeats.

A double-effect package employs a two-step reconcentration of the absorbent through the use of an additional high-temperature generator. The refrigerant released in the high-temperature generator (first effect) is used to drive release of additional refrigerant in the low-temperature generator (second effect).

Absorption packages can be further subdivided into the following two categories:

> ***direct-fired package:*** this type of package uses thermal energy derived from natural gas, LP gas, oil, or other fuel, combusted within the package.
>
> ***indirect-fired package:*** this type of package uses thermal energy from steam, hot water, hot heat-transfer fluids, or a hot gas stream not resulting from combustion within the package.

Absorption packages can be operated in several modes: a) cooling only mode, b) heating only mode, c) simultaneous heating/cooling mode, and d) heat pump mode. The first three modes are defined and described individually below. In heat pump mode, the useful product of the package is heated water (thermal output power) released at an intermediate temperature by the condenser and absorber. The heat is extracted from a lower temperature source through the evaporator. The cycle is driven by thermal power input from a higher temperature source through the generator. Measurement of performance during heat pump operation is not included in the current scope of this standard.

capacity: the rate at which heat (energy) is added to or removed from a liquid stream of an absorption package that is the useful product of an absorption package. Capacity can be either a gross heat transfer or a sensible heat transfer quantity.

> ***gross heating capacity:*** the capacity measured as the gross heat transfer of the liquid stream heated either in what is the evaporator in cooling mode (acting as a condenser in heating mode, two-pipe system) or in a separate hot water heat exchanger (four-pipe system). This value is used in calculation of the energy balance of a test.
>
> ***gross cooling capacity:*** the capacity measured as the gross heat transfer from the liquid to the refrigerant in the evaporator. This value is used in calculation of the energy balance of a test.
>
> ***net heating capacity:*** the capacity measured as the sensible heat transfer of water heated either in what is the evaporator in cooling mode (acting as a condenser in heating mode, two-pipe system) or in a separate hot water heat exchanger (four-pipe system) that is available for useful heating of the thermal load external to the absorption package.
>
> ***net cooling capacity:*** the capacity measured as the sensible heat transfer produced by the evaporator that is available for useful cooling of the thermal load external to the absorption package.

condenser: a *refrigerating system* component which condenses refrigerant from vapor state to liquid state by the removal of heat. De-superheating and sub-cooling of the refrigerant may occur as well.

> ***liquid-cooled condenser:*** a *condenser* that condenses refrigerant vapor by rejecting heat to *liquid* mechanically circulated over its heat transfer surface, causing a temperature rise in the *liquid*.

cooling-only mode: the operational mode of a direct-fired chiller/heater that supplies only chilled water.

design conditions: any set of operating conditions under which a single level of performance occurs and causes only that level of performance to occur.

direct-fired: a term applied to systems where the thermal energy input is the gross heating content of the fuel based on the higher heating value in MBH (kW).

efficiency: performance at specified operating conditions, expressed as the ratio of the *capacity* output and the *thermal power* of a process or a machine. Depending on the specific *efficiency* metric, the numerator and denominator may be switched, and the units of measure may be dimensionless or not. All efficiency metrics shall be stated in conjunction with a complete set of *operating conditions*.

> ***energy efficiency:*** any one of several metrics calculated as a ratio of two quantities, (1) thermal energy movement expressed as a rate and (2) required energy input to move that thermal energy. The numerator and denominator may be switched depending on the specific metric, and the units of measure may be dimensionless or not.
>
> ***cooling efficiency:*** a ratio of *net cooling capacity* and the *total input power*. The ratio may be inverted depending on the selected units of measure.

COP_R: coefficient of performance, the *cooling efficiency* expressed as a dimensionless ratio of *net refrigerating capacity* divided by the *total thermal input power*.

MBH/ton_R: thermal input power per unit capacity, the cooling efficiency expressed as a ratio of the thermal input power divided by the net cooling capacity. MBH/ton_R shall use the following units of measure: MBH for thermal input power and ton_R for net cooling capacity.

heating efficiency: a ratio of *net heating capacity* and the *thermal input power*.

COP_H: coefficient of performance, the *heating efficiency* expressed as a dimensionless ratio of *net heating capacity* divided by the *thermal input power*.

energy balance: a dimensionless ratio metric used to check for gross errors in measurement instrumentation and test results, defined as the difference between energy inputs and energy outputs to the liquid-chilling package, normalized to a percentage by dividing by the mean of the total input energy and the total output energy. For this standard, the energy inputs are generally limited to the *gross refrigerating capacity* and the *input power*, though other *auxiliary power* inputs are included when analysis demonstrates significance to the *energy balance*.

evaporator: component which boils refrigerant (water in the case of a water/lithium bromide absorption package) from liquid state to vapor state by the addition of heat. Superheating of the refrigerant may occur as well. For the purposes of this standard, the heat is exchanged from a liquid stream.

fouling factor: the thermal resistance due to fouling accumulated on the liquid side surface of a heat exchanger.

generator: a heat and mass exchanger in which heat is added to a dilute solution to drive off refrigerant vapor and re-concentrate the solution.

gross heat transfer: the heat transfer associated with the change in enthalpy of a liquid stream, where enthalpy is a function of both temperature and pressure. Gross heat transfer is calculated as the mass flow rate of a liquid stream multiplied by its enthalpy difference. Gross heat transfer accounts for both the sensible heat transfer associated with the change in temperature and the change in energy due to frictional losses associated with the liquid pressure drop.

heating-only mode: the operational mode of a direct-fired chiller/heater that supplies only hot water.

higher heating value (HHV): the amount of heat produced per unit of fuel when complete combustion takes place at constant pressure, the products of combustion are cooled to the initial temperature of the fuel and air, and the vapor formed during combustion is condensed. This value is expressed in Btu/lb (J/kg) or Btu/ft^3 (W/m^3) for gaseous fuel and in Btu/lb (J/kg) or Btu/gal for liquid fuel.

hot-water heating option: an option for providing hot water from an absorption chiller/heater through either of two circuits:

- Through the evaporator circuit (a two-pipe system), typically provided at temperatures up to 140°F (60.0°C) (standard-temperature hot water).
- Through a separate hot-water heat exchanger (a four-pipe system), typically provided at temperatures above 140°F (60.0°C) up to and including 175°F (79.4°C) and/or for simultaneous heating/cooling operation (high-temperature hot water).

indirect-fired: a term applied to systems where the thermal energy input is the heat consumed from the heat source in MBH (kW).

liquid: the fluid being cooled in the *evaporator* (cooler) or heated in the *condenser*, as distinguished from refrigerant in the liquid state. Examples of liquids are water, glycol mixture, or other heat transfer fluid.

liquid pressure drop: A measured value of the reduction in liquid pressure associated with the flow through a liquid- type heat exchanger.

operating condition tolerance: the maximum permissible variation between the time averaged measurement data observations and the specified (target) *operating conditions* as established in the test plan.

operating conditions: a unique set of system parameters resulting in a single level of performance.

percent load (%load): The part-load net capacity divided by the full-load net capacity at the full-load rating conditions, stated in decimal format. (e.g., 100% = 1.0).

power: the rate at which *energy* is transferred, used, or transformed.

> ***electrical power:*** *power* input to devices that are not integral to the operation of the vapor compression cycle, excluding power input to integrated pumps (if present) used for *liquid* in either the *evaporator* or the *condenser*. Including devices such as, but not limited to, oil pumps, refrigerant pumps, control panel, fans, and heaters. For reference, see also *thermal energy*.

sensible heat transfer: the heat transfer associated solely with the change in temperature of a liquid stream, ignoring the effect of liquid pressure drop. Sensible heat transfer is calculated as the mass flow rate of a liquid stream multiplied by its specific heat and temperature difference.

simultaneous heating/cooling mode: the operational mode of a direct-fired absorption chiller/heater whereby chilled water and hot (heating) water are produced at the same time.

steady state: a state or condition of a system or process that does not change in time, or a condition that changes only negligibly over a specified time interval.

temperature: measurement of warmth or coldness with respect to an arbitrary zero or to the absolute zero. Temperatures are indicated on defined scales, such as Kelvin and Rankine for absolute temperatures, and Celsius and Fahrenheit for ordinary temperatures.

> ***saturation temperature:***
>
> 1. The *temperature* where a substance changes between its liquid and its vapor phase. If the pressure in a system remains constant, a vapor at *saturation temperature* will begin to condense into its liquid phase as thermal energy is removed, and conversely, a liquid at *saturation temperature* will begin to evaporate as thermal energy is applied.
>
> 2. The equilibrium *temperature* of a pure refrigerant or an azeotropic refrigerant in a two-phase mixture of a vapor and liquid at a given absolute pressure.

thermal energy: the heat content of the fuel, steam, or hot heat-transfer fluid, excluding the electrical power.

total heat rejection: Heat rejected through the condenser and absorber.

4. CALCULATIONS AND CONVERSIONS

4.1 Liquid Properties

4.1.1 Water. One of the following two methods shall be used to determine the properties of water:

Method 1. Use a formulation of liquid water properties that is based on or consistent with IAPWS R7-97(2012), such as NIST's REFPROP (Lemmon et al., 2018), to calculate physical properties such as density, volume expansivity, specific heat, and enthalpy as a function of both pressure and temperature.

Method 2. Use the following polynomial equations to calculate density and specific heat of water as a function of temperature only.

$$\rho(T) = \rho_6\, T^6 + \rho_6\, T^5 + \rho_4\, T^4 + \rho_3 T^3 + \rho_2 T^2 + \rho_1 T + \rho_0 \tag{4-1}$$

$$1 - (T + T_0)\alpha_P(T) = \alpha_6 T^6 + \alpha_5 T^5 + \alpha_4 T^4 + \alpha_3 T^3 + \alpha_2 T^2 + \alpha_1 T + \alpha_0 \tag{4-2}$$

$$c_p(T) = c_{p7} T^7 + c_{p6} T^6 + c_{p5} T^5 + c_{p4} T^4 + c_{p3} T^3 + c_{p2} T^2 + c_{p1} T + c_{p0} \tag{4-3}$$

	IP (°F)	SI (°C)
T	32~400	0~204

IP	(lbm/ft³)
ρ_6	-2.37585E-15
ρ_5	3.5568E-12
ρ_4	-2.2802E-09
ρ_3	8.1558E-07
ρ_2	-2.1479E-04
ρ_1	1.3283E-02
ρ_0	62.2097

IP	(1/R)
T_0	459.67
α_6	3.44399E-16
α_5	-5.65895E-13
α_4	3.6293E-10
α_3	-1.2495E-07
α_2	2.3727E-05
α_1	-3.7465E-03
α_0	1.1166

IP	(Btu/lbm·R)
c_{p7}	-9.98516E-19
c_{p6}	1.76843E-15
c_{p5}	-1.29636E-12
c_{p4}	5.1114E-10
c_{p3}	-1.1556E-07
c_{p2}	1.5435E-05
c_{p1}	-1.1068E-03
c_{p0}	1.0306

SI	(kg/m³)
ρ_6	-1.30147E-12
ρ_5	9.42831E-10
ρ_4	-2.9486E-07
ρ_3	5.2282E-05
ρ_2	-7.7569E-03
ρ_1	5.0864E-02
ρ_0	1000.1809

SI	(1/K)
T_0	273.15
α_6	1.16999E-14
α_5	-9.43482E-12
α_4	2.9130E-09
α_3	-4.9003E-07
α_2	4.4645E-05
α_1	-4.6206E-03
α_0	1.0172

SI	(kJ/kg·K)
c_{p7}	-2.55521E-16
c_{p6}	2.19689E-13
c_{p5}	-7.73164E-11
c_{p4}	1.4481E-08
c_{p3}	-1.5199E-06
c_{p2}	9.6036E-05
c_{p1}	-3.1138E-03
c_{p0}	4.2161

Note: Density and specific heat polynomial equations are curve fits to values generated by NIST REFPROP v10 covering a temperature range of 32°F to 400°F [0°C to 204°C]. The applied pressure, $P_{applied}$, is taken as the larger of 100 psia [690 kPaa] and the saturation pressure corresponding to the temperature plus 60 psid [141 kPad]: $P_{applied}$(psia) = max(100, Psat(T)+60) or $P_{applied}$(kPaa) = max(690, Psat(T)+141). The 100 psia [690 kPaa] value was selected as representative of system pressures used in practice to allow for the calculation of water-side properties as a function of temperature only.

4.1.2 Other Liquids. Physical properties of the liquid versus temperature, and also by concentration for solutions or mixtures, shall be determined from published data sources such as manufacturer data sheets. Systems utilizing aqueous solutions or mixtures shall be tested to measure or determine the concentration of the liquid. Concentration test(s) shall be performed within two (2) weeks or less prior to the date of the chiller test(s), or within two (2) days after the test.

4.2 Steam Properties. The properties of steam shall be determined using a formulation that is based on or consistent with IAPWS R7-97(2012), such as NIST's REFPROP (Lemmon et al., 2018).

4.3 Gas Properties. The properties of hot gases used to indirectly fire an absorption chiller/heater shall be determined from properties of the constituent gas components. Bulk hot gas properties shall be calculated based on the mass fraction of the gas components. Gas makeup shall be determined by gas chromatograph or other comparable method.

4.4 Combustible Fuel Properties

4.4.1 The higher heating value (HHV) of the fuel used in direct-fired operation shall either be determined by analysis of the gas components or obtained from the supplying utility corresponding to the time period of the test. The properties of the exhaust gases that are needed for determination of combustion efficiency shall be determined as follows:

4.4.1.1 Flue gas temperature shall be determined by direct measurement of gas in the flue.

4.4.1.2 CO_2 or O_2 measurements shall be made as needed for determination of combustion efficiency. Measurement shall be provided by a combustion gas analyzer.

4.5 Data Collection

4.5.1 For determining chiller performance metrics, only data (measurements) collected during stable, steady-state operation of the chiller shall be used. Data shall be monitored and processed prior to collection to ensure operation is stable. The criteria for stability are given in Section 5.

4.6 Data Processing

4.6.1 Single-point instruments. Data point measurements collected during the duration of the testing period shall be processed to calculate the sample mean and sample standard deviation per the following equations where x_j represent the individual measurements collected over the time period for a total of J data points.

sample mean:

$$\bar{x} = \frac{1}{J}\sum_{j=1}^{J} x_j \tag{4-4}$$

sample standard deviation:

$$S_{\bar{x}} = \sqrt{\frac{1}{J-1}\sum_{j=1}^{J}\left(x_j - \bar{x}\right)^2} \tag{4-5}$$

4.6.2 Calculated quantities. Calculation of performance metrics (e.g., capacity, efficiency, energy balance, etc.), shall use the mean values of measured data.

4.7 Performance

4.7.1 Capacity, indirect thermal input power, or heat transfer rate. One of the following four methods shall be used depending on the available measurements and choice of enthalpy function. All capacities or heat transfer rates, whether representing energy transfer into the chiller/heater system (e.g., evaporator chilled water or regeneration energy from hot water or steam) or out of the chiller/heater system (e.g., absorber/condenser heat rejection or useful hot water), are computed as positive values. Direction of energy flows needs to be accounted for when computing the energy balance (see below).

4.7.1.1 Using measurements of **liquid volume flow rate**, inlet and outlet temperatures, and pressure loss; **not using a function for enthalpy**. The density shall be calculated at the temperature (and pressure) coincident with the volume flow rate meter. The specific heat shall be calculated at the mean of the entering and leaving liquid temperatures (and pressures).

4.7.1.1.1 Gross Capacity or heat transfer rate

$$Q' = |V\rho c_P \Delta T + V(1 - T_a \alpha_P)\Delta p| \tag{4-6}$$

4.7.1.1.2 Net Capacity or heat transfer rate

$$Q = |V\rho c_P \Delta T| \tag{4-7}$$

4.7.1.2 Using measurements of **liquid mass flow rate**, inlet and outlet temperatures, and pressure loss; **not using a function for enthalpy**. The density and specific heat shall be calculated at the mean of the entering and leaving liquid temperatures (and pressures).

4.7.1.2.1 Gross capacity or heat transfer rate

$$Q' = |mc_P \Delta T + m(1 - T_a \alpha_P)\Delta p/\rho| \tag{4-8}$$

4.7.1.2.2 Net Capacity or heat transfer rate

$$Q = |mc_P \Delta T| \tag{4-9}$$

4.7.1.3 Using measurements of **liquid volume flow rate**, inlet and outlet temperatures, and pressure loss; **using a function for enthalpy**.

4.7.1.3.1 Gross capacity or heat transfer rate

$$Q' = |V\rho \Delta h| \tag{4-10}$$

4.7.1.3.2 Net capacity or heat transfer rate

$$Q = |V\rho \Delta h - V(1 - T_a \alpha_P)\Delta p| \tag{4-11}$$

4.7.1.4 Using measurements of **liquid mass flow rate**, inlet and outlet temperatures, and pressure loss; **using a function for enthalpy**. The density shall be calculated at the temperature (and pressure) coincident with the volume flow rate meter.

4.7.1.4.1 Gross capacity or heat transfer rate

$$Q' = |m\Delta h| \tag{4-12}$$

4.7.1.4.2 Net capacity or heat transfer rate

$$Q = |m\Delta h - m(1 - T_a \alpha_P)\Delta p/\rho| \tag{4-13}$$

4.7.2 Temperature difference, Enthalpy difference, and Pressure difference

4.7.2.1 **Temperature difference** shall be computed as inlet temperature minus outlet temperature with the sign (positive or negative) carrying into the above equations.

$$\Delta T = T_{inlet} - T_{outlet} \tag{4-14}$$

4.7.2.2 **Enthalpy difference** shall be computed as inlet enthalpy minus outlet enthalpy with the sign (positive or negative) carrying into the above equations.

$$\Delta h = h(T_{inlet}, P_{inlet}) - h(T_{outlet}, P_{outlet}) \qquad (4\text{-}15)$$

4.7.2.3 Pressure difference or pressure loss shall be computed as inlet pressure minus outlet pressure. Pressure difference or pressure loss should always be a positive value.

For the case when energy is input into the system (i.e., heat into evaporator or generator, if hot water type)

$$\Delta P = P_{inlet} - P_{outlet} \qquad (4\text{-}16)$$

4.7.3 Direct *thermal input power* for direct-fired operation shall be computed based on the *higher heating value* (*HHV*) of the fuel being used. The *HHV* can be either volume-based or mass-based.

4.7.4 Gross direct *thermal power input* used in the calculation of efficiency or COP shall be computed as follows:

$$Q'_{direct} = V \cdot HHV_V \quad \text{or} \quad Q_{input} = V\rho \cdot HHV_m = m \cdot HHV_m \qquad (4\text{-}17)$$

4.7.5 Net direct *thermal power input* used in the calculation of the energy balance shall be computed as follows, where η_{cmb} is the combustion efficiency determined from measurements of the flue gas temperature and/or oxygen content.

$$Q_{direct} = \eta_{cmb}\, Q'_{direct} \qquad (4\text{-}18)$$

η_{cmb} shall be determined from the method provided in AHRI 1500, or other comparable method. The choice of use of a condensing versus a non-condensing method shall be determined by the type of combustion process applied. That is, for a non-condensing process, the non-condensing method is the correct one to apply.

4.7.6 Heat losses. Heat losses from uninsulated high temperature components that are insulated in the field shall be accounted for in the efficiency metric and in the energy balance.

4.7.7 Single-Effect Packages. In most cases for single effect absorption units, heat losses or heat gains caused by radiation, convection, etc., are relatively small and need not be considered in the overall heat balance because they are already compensated for in the heat balance closure allowance.

4.7.8 Double-Effect Packages. For double-effect machines, the heat losses from the high-stage generator and solution heat exchanger may be significant when the surfaces are uninsulated. Because this surface is normally insulated on the job site, the heat loss due to an uninsulated surface of a high-stage generator or a solution heat exchanger can be subtracted from the measured value. The heat loss shall be determined by using the heat-transfer calculations below. Alternatively, the heat loss can be determined by a method agreed upon by the customer.

4.7.9 Heat losses from uninsulated high temperature components that will be insulated in the field shall be estimated as described in this section. The measured heat input can be adjusted to account for that heat loss when calculating energy efficiency and energy balance.

$$Q_{loss} = 4.0\% \text{ of } Q_{input} \text{ for double effect} \qquad (4\text{-}19)$$

Alternatively, the loss can be calculated as follows:

$$L = \frac{Qloss}{Qinput} \qquad (4\text{-}20)$$

$$Qloss = Q0 - Q1 \qquad (4\text{-}21)$$

$$q_{uninsul} = (T_{uninsul} - T_{amb}) \cdot \alpha \cdot A_{s,uninsul} \tag{4-22}$$

$$q_{insul} = \frac{(T_{insul} - T_{amb}) \cdot A_{s,insul}}{\frac{1}{\alpha} + \chi/\lambda} \tag{4-23}$$

Where:

$\alpha = 6.7$ Btu/hr ft^2·F (0.0116 kW/m^2·K)

4.7.10 Auxiliary input power shall include the electrical power consumed by the refrigerant pump(s), solution pump(s), control panel, and any other electrically powered components, exclusive of the purge pump. The auxiliary power can be measured at one location upstream of these components or at multiple locations (e.g., individually). If measured at multiple locations, total auxiliary input power shall be computed as the summation of the multiple individual measurements,

$$W_{input} = \sum_i W_i \tag{4-24}$$

4.7.11 Energy *Efficiency.* Also known as Coefficient of Performance (COP). Determined as the ratio of the capacity to the thermal input power.

4.7.12 Cooling Efficiency The ratio of the *net cooling capacity* to the *thermal input power.*

4.7.12.1 Cooling Efficiency – indirect-fired operation. Ratio of the *net cooling capacity* determined as the heat transfer rate from the chilled water (evaporator), $Q_{ev}$to the *thermal input power*, Q_{input}, from the hot fluid, steam, or exhaust gas to the generator,

$$COP_R = \frac{Q_{Clg}}{Q'_{input} - Q_{loss}} \tag{4-25}$$

4.7.12.2 Cooling Efficiency – direct-fired operation Ratio of the *net cooling capacity* determined as the heat transfer rate from the chilled water (evaporator), Q_{ev}, to the gross *thermal input power*, Q'_{direct}, from the combusted fuel,

$$COP_R = \frac{Q_{Clg}}{Q'_{direct} - Q_{loss}} \tag{4-26}$$

4.7.13 Heating Efficiency The ratio of the *net heating capacity* to the *thermal input power.*

4.7.13.1 Heating Efficiency – direct-fired operation Ratio of the *net heating capacity* determined as the heat transfer rate from the heated water, either through the evaporator in a two-pipe system or the separate heating heat exchanger in a four-pipe system, Q_{Htg}, to the gross *thermal input power*, Q'_{direct}, from the combusted fuel,

$$COP_H = \frac{Q_{Htg}}{Q'_{direct} - Q_{loss}} \tag{4-27}$$

4.7.13.2 Simultaneous Cooling and Heating Efficiency The ratio of the sum of the *net cooling capacity* and the *net heating capacity* to the *thermal input power*,

$$COP_{SCH} = \frac{Q_{Clg} + Q_{Htg}}{Q'_{direct} - Q_{loss}} \tag{4-28}$$

4.7.14 Liquid Pressure Drop Correction. Measured liquid pressure drop values shall be adjusted to subtract static pressure drop due to piping external to the chiller connection points. Pressure drop in cross-over piping between the absorber and condenser is not considered as being external. The additional static pressure drop shall be the sum of all losses between the unit connections and the location of static pressure taps.

$$\Delta \mathrm{p_{adj}} = \mathrm{\rho g}\left[\sum_{\mathrm{i}} (\mathrm{h_f})_{\mathrm{i}} + \sum_{\mathrm{j}} (\mathrm{h_m})_{\mathrm{j}}\right]$$

where the $h_{f,i}$ are frictional head losses associated with lengths of pipe and the $h_{m,i}$ are head losses associated with elbows and expansions/contractions. The original measured static pressure drop value, the calculated adjustment value, and the final calculated result for unit liquid pressure drop shall all be recorded.

4.7.14.1 The static pressure drop adjustment shall not exceed 10% of the measured static pressure drop.

4.7.14.2 The general form of the adjustment equation utilizes the methods in the Crane Technical Paper No. 410.

4.7.14.3 Frictional head losses. Frictional head losses shall be calculated using the following equation,

$$h_f = \frac{1}{2g} v^2 \frac{f_D L}{d} = \frac{8}{\pi g} V^2 \frac{f_D L}{d^5} = \frac{8}{\pi g} \left(\frac{m}{\rho}\right)^2 \frac{f_D L}{d^5} \qquad \text{(4-29)}$$

depending on whether measurement of flow rate is volume based ($\dot{V}$) or mass based (m). The length of the pipe segment is given as L. The inside diameter of the pipe segment is given as d. The Darcy friction factor, f_D, is determined using the Swamee-Jain equation,

$$\mathrm{f} = \frac{0.25}{\left[log_{10}\left(\frac{\epsilon/d}{3.7} + \frac{5.74}{Re^{0.9}}\right)\right]^2}$$

Pipe roughness values, ϵ, shall be either actual measurements or approximations based on handbook values. If using handbook values, consideration shall be given and values adjusted accordingly to the actual conditions of the pipe interior surface, which may have higher roughness versus the clean conditions of new pipe. Typical pipe roughness handbook values for reference:

Commercial Pipe, New Condition	ϵ (rms)	
	(m)	(ft)
Steel	5.5×10^{-5}	1.8×10^{-4}
Plastic	1.8×10^{-6}	6.0×10^{-6}

4.7.14.4 Other head losses. Head losses due to elbows and expansions/contractions shall be calculated using the following equation where K is the loss coefficient for the given flow element,

$$h_m = \frac{1}{2g} K v^2 = \frac{8}{\pi g} K V^2 = \frac{8}{\pi g} K \left(\frac{m}{\rho}\right)^2 \qquad \text{(4-30)}$$

4.7.14.5 Loss coefficients shall be taken from Section 4.7.14.6, Section 4.7.14.7, the Crane Technical Publication 410, or ASHRAE Technical Report 1034-RP.

4.7.14.6 Loss coefficients for 90° elbow fittings (equivalent length formulation),

Table 1
K Factors for Elbow Fittings

Description	K Factor
Smooth elbow with r/d = 1	$20 \cdot f$
Smooth elbow with r/d= 1.5	$14 \cdot f$
Smooth elbow with r/d = 2	$12 \cdot f$
Smooth elbow with r/d = 3	$12 \cdot f$
Smooth elbow with r/d = 4	$14 \cdot f$
Segmented with 2·45° miters	$30 \cdot f$
Segmented with 3·30° miters	$24 \cdot f$
Segmented with 6·15° miters	$24 \cdot f$

4.7.14.7 Loss coefficients for expansion and contraction fittings. The determination of K expansion and contraction sections is a function of the diameter ratio, $\beta = d_1/d_2, d_1 < d_2$, as well as the angle θ of the expansion or contraction. For typical commercially available gradual expansion or contraction fittings, an equation has been developed for θ as a function of the smaller diameter d_1 that best represents the pressure drop results found in ASHRAE Technical Report 1034-RP. The equation is valid in the range of $10° < \theta < 45°$; use the table values for $\theta > 45°$.

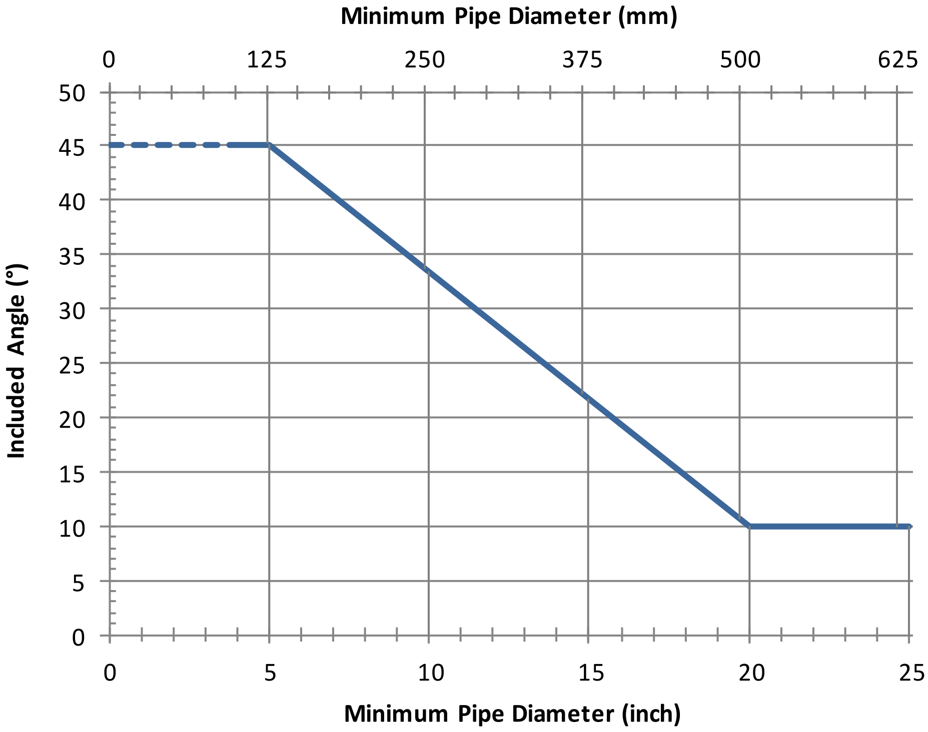

Figure 1 Included Angle Correlation for Gradual Expansion/Contraction Fittings

Table 2

	$d_1 \leq 127$ mm [$d_1 \leq 5$ inch]	127 mm < d_1 < 508 mm [5 inch < d_1 < 20 inch]	$d_1 \geq 508$ mm $d_1 \geq 20$ inch
gradual expander, gradual reducer	$\theta = 45°$	$\theta = \frac{170}{3} - \frac{84d_1}{914.4}$ $\left[\theta = \frac{170 - 7d_1}{3}\right]$	$\theta = 10°$
sudden expansion, sudden contraction	$45° < \theta < 180°$	$45° < \theta < 180°$	$45° < \theta < 180°$

Table 3

	$\theta \leq 45°$	$\theta > 45°$
Expansion	$K = \frac{2.6\sin\left(\frac{\theta}{2}\right)(1-\beta^2)^2}{\beta^4}$	$K = \frac{(1-\beta^2)^2}{\beta^4}$
Reduction	$K = \frac{0.8\sin\left(\frac{\theta}{2}\right)(1-\beta^2)^2}{\beta^4}$	$K = \frac{0.5\sqrt{\sin\left(\frac{\theta}{2}\right)}(1-\beta^2)}{\beta^4}$

Note: The values of the resistance coefficients (K) in the equations in the previous table are based on the velocity in the large pipe. To determine K values in terms of the smaller diameter, multiply equations by β^4.

4.8 Gravitational constant. The following values shall be used for the gravitational constant, *g*,

	SI	IP
gravitational constant	$g = 9.80665\ \mathrm{m/s^2}$	$g = 32.174\ \mathrm{ft/s^2}$
conversion factor	$1\ \mathrm{N} = 1\frac{\mathrm{kg{\cdot}m}}{\mathrm{s^2}}$	$1\ \mathrm{lb_f} = 32.174\frac{\mathrm{lb_m{\cdot}ft}}{\mathrm{s^2}}$

4.9 Validation. Test results are validated by checking the system *energy balance*. The equations to be used are listed in subsections to this section below. Requirements for the energy balance are given in Section 5.

4.10 Energy Balance. Based on the first law of thermodynamics, or the law of conservation of energy, an *energy balance* calculation evaluates all of the measured energy flow into and out of a control volume. If there is a non-zero difference between energy flow in and energy flow out, greater than the *energy balance* measurement uncertainty, then either (a) the system is not at steady state (lack of equilibrium), or (b) some significant heat gain or heat loss has been omitted from the calculation, or (c) there is a measurement error to be corrected. The control volume shall include the entire chiller package.

4.10.1 Gross capacity shall be used for *energy balance* calculations.

4.10.2 Sum all energy sources flowing into and out of the system through the control volume boundary, including losses that are significant,

$$E_{in} = \sum_i E_{in,i} \qquad E_{out} = \sum_i E_{out,i} \tag{4-31}$$

4.10.3 The general *energy balance* equation is expressed as the ratio of the difference between input and output energy to the mean of input and output energy

$$E_{bal} = 2\frac{E_{in} - E_{out}}{E_{in} + E_{out}} \quad (4\text{-}32)$$

Example: Consider a steam-driven single effect absorption package with negligible heat losses. Energy flows into the system include the steam heat source and the energy extracted from the chilled water by the evaporator,

$$E_{in} = Q'_{input} + Q'_{Clg} \quad (4\text{-}33)$$

where Q'_{input} could be computed by Equation (4-10) or (4-12) and Q'_{Clg} could be computed by one of Equations (4-6), (4-8), (4-10), or (4-12). Energy leaves the system as heat rejected by the absorber and condenser to the cooling water stream,

$$E_{out} = Q'_{a/c} \quad (4\text{-}34)$$

where $Q'_{a/c}$ could be computed by one of Equations (4-6), (4-8), (4-10), or (4-10).

Example: Consider a direct-fired double effect absorption package with heat losses from uninsulated higher temperature components. Energy flows into the system include the heat energy gained from the combusted fuel and the energy extracted from the chilled water by the evaporator,

$$E_{in} = (Q_{direct} - Q_{loss}) + Q'_{Clg} \quad (4\text{-}35)$$

where Q_{direct} is computed by Equation (4-18). Energy leaves the system as heat rejected by the absorber and condenser to the cooling water stream. In addition, the heat loss from the uninsulated high temperature components shall be included,

$$E_{out} = Q'_{a/c} + Q_{loss} \quad (4\text{-}36)$$

4.11 Conversions

4.11.1 All equations described in this standard assume consistent units. It is imperative that users of this standard ensure proper unit conversions in all calculations.

4.11.2 One ton of cooling, ton_R, is defined as $12000\ Btu_{IT}/h$.

4.11.3 $1\ Btu_{IT} = 1055.05585262\ J\ (exact\ conversion)$.

4.11.4 For all other unit conversions, refer to *NIST Special Publication 811, Guide for the Use of the International System of Units (SI)* or other authoritative source for appropriate unit conversions.

5. TEST REQUIREMENTS

5.1 Tests shall report measurement values and calculated results in accordance with methods and procedures described in this method of test.

5.2 From a test perspective, it is best to maintain heat transfer surfaces by cleaning or maintaining proper liquid treatment to avoid highly fouled conditions and the associated efficiency loss.

5.3 **Instrumentation.** This section defines requirements for each type of measurement (temperature, flow, pressure, power). Instruments shall be selected, installed, and operated according to the requirements of Table 4. Further details are provided in this section for each measurement type.

Table 4 Requirements for Test Instrumentation

Measurement	Measurement System Accuracy[2,3,4]	Display Resolution[5,6]	Selected, Installed, Operated, Maintained in Accordance With
Liquid Temperature	±0.11 Δ°C (±0.20 Δ°F)	0.005°C (0.01°F)	ANSI/ASHRAE Standard 41.1
Air Temperature	±0.3 Δ°C (±0.5 Δ°F)	0.05°C (0.1°F)	ANSI/ASHRAE Standard 41.1
Liquid Mass Flow Rate[1]	±1.0% RDG	4 significant figures	ANSI/ASHRAE Standard 41.8
Hot Gas Flow Rate	±1.0% RDG	4 significant figures	ANSI/ASHRAE Standard 41.7
Flue gas CO_2 concentration	±0.1%	0.1%	
Differential Pressure	±1.0% RDG	3 significant figures	ASME Power Test Code PTC 19.2
Electrical Power ≤ 600V	±1.0% FS, ±2.0% RDG	4 significant figures (V, A, kW, Hz)	ANSI/ASHRAE Standard 41.11
Atmospheric Pressure	±1.0 kPa (±0.15 psia)	0.1 kPa (0.01 psia)	ASME Power Test Code PTC 19.2
Steam condensate mass flow rate	±1.0% RDG	4 significant figures	
Steam pressure	±1.0% RDG	3 significant figures	
Fuel volumetric flow rate	±1.0% RDG	4 significant figures	
Fuel energy content	-	3 significant figures	Gas HHV shall be acquired by contacting the local authority and requesting a gas HHV report for the day of the test or measured on site using a gas calorimeter or gas chromatograph.

Notes:

1. Accuracy requirement also applies to volumetric type meters.
2. Measurement system accuracy shall apply over the range of use during testing, as indicated by the Turn Down Ratio determined during calibration, i.e., from full scale down to a value of full scale divided by the Turn Down Ratio. For many types of instruments and/or systems, this may require exceeding the accuracy requirement at full scale.
3. %RDG = percent of Reading, %FS = percent of Full Scale for the useable range of the measurement instrument or measurement system.
4. If dual requirements are shown in the table, FS, and RDG, then both requirements shall be met.
5. Display resolution shown is the minimum requirement (most coarse resolution allowable). Better (finer) resolution is acceptable for instrument or panel displays, or computer screen displays.
6. Significant figures (also known as significant digits) determined in accordance with Appendix D.

5.3.1 **Accuracy and Calibration.** All instruments and measurement systems shall be calibrated over a range that meets or exceeds the range of test readings. Data acquisition systems shall be either calibrated as a system, or all individual component calibrations shall be documented in a manner that demonstrates the measurement system meets the accuracy requirements specified in Table 4. Calibrations shall include no less than four (4) points compared to a calibration standard. Calibration standards shall be traceable to NIST or equivalent laboratories that participate in inter-laboratory audits.

Note: It is recommended that standards such as ISO 17025 be used by test facilities to improve processes for the development and maintenance of instrument systems to achieve desired accuracy and precision levels.

5.3.2 For each instrument device in a measurement system, the calibration process shall identify the range over which the required accuracy can be achieved (specified accuracy from Table 4). This range shall be documented in a readily accessible format for verification (such as a manual of calibration records, or instrument labeling system, or work instructions for test facility operators). Many types of instruments have a usable range or Turn Down Ratio of 10:1, though some types are quite different. Differential pressure type flow meters may be limited to 3:1 range of flow (due to a differential pressure measurement range of 10:1). Some types of instruments, such as electromagnetic and coriolis type flow meters, or current transformers with low burden, may be capable of wider ranges such as 20:1 or more.

5.3.3 To determine the range over which the calibration achieves the required accuracy, a linear regression analysis is performed on the calibration data. Table 5 and the equations that follow explain the method of calculating the prediction interval. The data is plotted to show the residual errors versus the calibration reference standard. The standard error of estimate shall be calculated for the measurement system indicated values (post calibration) versus the calibration reference standard, then using the equations in the following section, plot a 95% prediction interval (α=5%) on both sides of the curve fit. The point(s) at which the prediction interval curve exceeds the required accuracy shall be the limit(s) of the range. See example using sample data in Figures 2 and 3, in which the specified accuracy is ±1% of reading, and the useable range is from 100 to 13.4, or Turn Down Ratio of 7.5:1.

5.3.4 All test point readings (i.e., at any percent load, or at any operating test condition) shall be within the calibration range or Turn Down Ratio for each instrument device measurement. For a given type of measurement, multiple instruments may be required to cover a wide range of testing conditions for a given test facility, or a range of Liquid-Chilling or Liquid-Heating Package sizes. In the case of multiple instruments, procedures and protocols shall be established by the test facility for use by test operators regarding when and how to switch between instruments.

5.3.5 Accuracy of electrical measurements shall include all devices in the measurement system (i.e., power meter or power analyzer, potential transformers, current transformers, data acquisition signals). Liquid chilling or heating packages that utilize power-altering equipment, such as variable frequency drive or inverter, may require appropriate isolation and precautions to ensure that accurate power measurements are obtained. Chillers that utilize power-altering equipment may require the use of instrumentation that is capable of accurately measuring signals containing high frequency and/or high crest factors. In these cases, the instrumentation used shall have adequate bandwidth and/or crest factor specifications to ensure the electrical *input power* measurement errors are within the accuracy requirements of Table 4 for the quantity measured. Reference ASHRAE Standard 41.11 for examples of such measurements.

Table 5 Prediction Interval to Determine Range of Acceptable Accuracy

	Reference Standard Value ^{1} y_j j=1 to n	Corrected (As Left) Indicated Value ^{2} x_j j=1 to n	Absolute Prediction Interval of Indicated Value	Relative Prediction Interval of Indicated Value %RDG
Calibration Data	y_1	x_1	$x_1 - \hat{y} \pm PI(x_1)$	$\frac{x_1 - \hat{y} \pm PI(x_1)}{x_1}$
	y_2	x_2	$x_2 - \hat{y} \pm PI(x_2)$	$\frac{x_2 - \hat{y} \pm PI(x_2)}{x_2}$
	y_3	x_3	$x_3 - \hat{y} \pm PI(x_3)$	$\frac{x_3 - \hat{y} \pm PI(x_3)}{x_3}$
	…	…	…	…
	y_n	x_n	$x_n - \hat{y} \pm PI(x_n)$	$\frac{x_n - \hat{y} \pm PI(x_n)}{x_n}$
Regression Statistics	$\bar{x}$ SS_x	s_ε	continuous curve $\hat{x} - \hat{y} \pm PI(\hat{x})$ varying $\hat{x}$ from min to max values of x_j	continuous curve $\frac{\hat{x} - \hat{y} \pm PI(\hat{x})}{\hat{x}}$ varying $\hat{x}$ from min to max values of x_j

Notes:
1. Reference Standard Value is the actual value determined or measured by the calibration standard.
2. Corrected Indicated Value is the value of the measured quantity given directly by a measuring system on the basis of its calibration curve ("as left" when the calibration process has been completed, not "as found" at the beginning of the calibration process).

$$PI(\hat{x}) = s_\varepsilon \cdot t_{\frac{\alpha}{2},n-2} \cdot \sqrt{1 + \frac{1}{n} + \frac{(\hat{x} - \bar{x})^2}{SS_x}}$$

$$\overline{x} = \frac{1}{n}\sum_{j=1}^{n}\left(x_j\right)$$

$$SS_x = \sum_{j=1}^{n}\left(x_j - \overline{x}\right)^2$$

$$s_\varepsilon = \sqrt{\frac{\sum_{j=1}^{n}\left(y_j - mx_j - c\right)^2}{n-2}}$$

$$m = \frac{n\sum_{j=1}^{n}x_j y_j - \sum_{j=1}^{n}x_j\sum_{j=1}^{n}y_j}{n\sum_{j=1}^{n}\left(x_j\right)^2 - \left(\sum_{j=1}^{n}x_j\right)^2}$$

$$c = \frac{\sum_{j=1}^{n}\left(x_j^2\right)\sum_{j=1}^{n}y_j - \sum_{j=1}^{n}x_j\sum_{j=1}^{n}\left(x_j y_j\right)}{n\sum_{j=1}^{n}\left(x_j^2\right) - \left(\sum_{j=1}^{n}x_j\right)^2}$$

$$\hat{y} = m \cdot \hat{x} + c$$

α = 5%
95% = 1-α

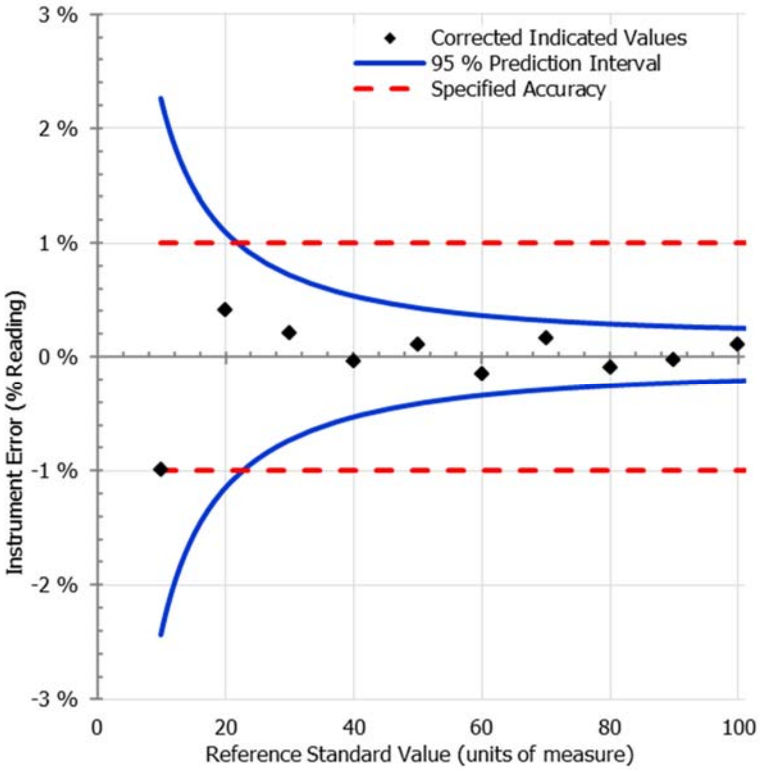

Figure 2 Sample of Relative Calibration Evaluation Data (Percent of Reading)

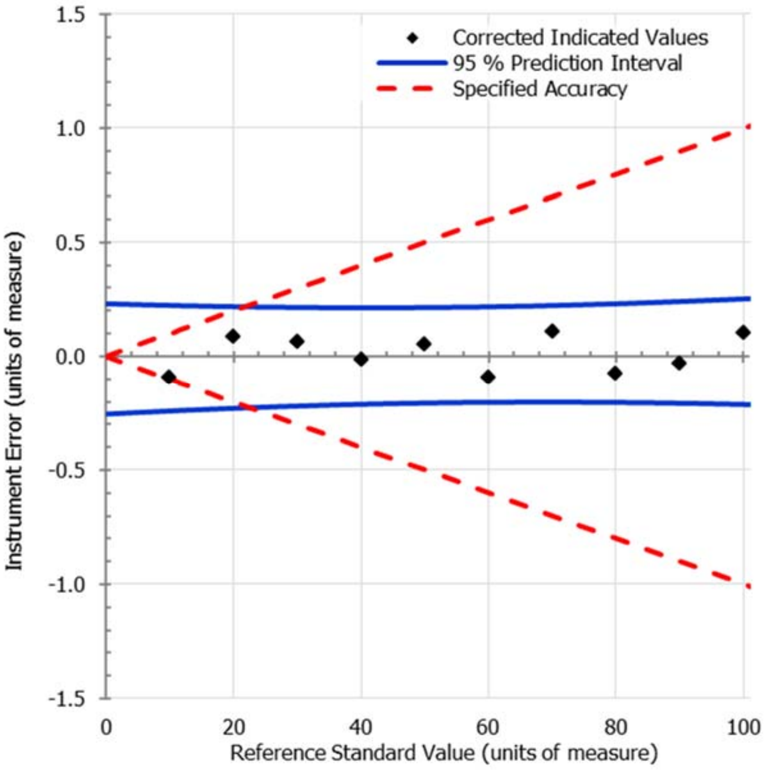

Figure 3 Sample of Absolute Calibration Evaluation Data

5.4 Temperature

5.4.1 Liquid. Measure entering and leaving liquid temperatures, °C (°F). Temperature sensor(s) shall be installed in a location that represents the average bulk fluid temperature.

Note*:* Non-mandatory but recommended practices to consider, especially if troubleshooting problems with energy balance. When deciding where to locate liquid temperature measurement sensors, consider the mixing effects of the piping configuration which may vary considerably across a range of flow rates. Check the spatial variation of temperature across a range of flow rates within a single plane perpendicular to the pipe, either with a movable (traversing) sensor or with multiple stationary sensors. If necessary, add flow conditioners or mixers.

5.4.2 Air. A representative air temperature in the test space shall be recorded.

5.5 Flow. Measure either liquid mass flow rate or volumetric flow rate and use the corresponding capacity calculation method in Section 4.7.1.

5.5.1 If using a volumetric flow meter, the capacity calculation in Section 4.7.1.1 shall use the density corresponding to either of the following locations: (1) the temperature of the liquid at the location of flow meter; or (2) the liquid temperature measurement, either entering or leaving, which best represents the temperature at the flow meter.

5.5.2 If the test plan specifies the target as a volumetric flow rate, the test plan shall reference whether the target volumetric flow rate applies at the inlet or outlet. If a volumetric measurement is made on the other connection location (opposite the test plan reference location), then the volumetric flow target at the measurement location shall be adjusted to have the same mass flow rate corresponding to the test plan target volumetric flow.

5.5.3 If evaporator or condenser liquid is used to add or remove heat to or from any other source(s) within the package, the flow measurement(s) shall be made at points so that the measurements reflect the Gross Capacity.

5.6 Pressure. This section prescribes a measurement method for Liquid Pressure Drop across the heat exchanger. The measurement method only applies to pipe of circular cross section.

5.6.1 Measurement Locations. Static pressure taps shall simultaneously meet all of the following requirements:

5.6.1.1 Static pressure taps may be in either the unit connections (i.e., nozzle) or in additional external piping provided for the purpose of test measurements.

5.6.1.2 If using additional external piping, the piping arrangement shall use rigid pipe and may include fittings such as elbows, reducers, or enlargers between the pressure tap locations and the unit connections. Flexible hose is prohibited between the unit connections and the pressure taps.

5.6.1.3 If using additional external piping, static pressure taps shall maintain the following lengths of cylindrical straight pipe in the flow path adjacent to each pressure tap location in Table 6.

Table 6 Straight Length in Flow Path

Unit Connection, Nominal Pipe Size	Straight Length in Flow Path	
	Upstream of Pressure Tap	Downstream of Pressure Tap
≤75 mm (≤3 inches)	Minimum 10 · d	Minimum 3 · d
100, 125, or 150 mm (4, 5, or 6 inches)	Minimum 6 · d	Minimum 2 · d
≥200 mm (≥8 inches)	Minimum 3 · d	Minimum 1 · d

D = The greatest pipe inside diameter dimension, using the nominal pipe size and pipe schedule nominal wall thickness, of the following locations:

- The pipe diameter at the pressure tap location
- The largest diameter of any reducer or enlarger fittings between the pressure tap location and unit connections
- The largest diameter of the first reducer or enlarger fitting between the pressure tap location and the test facility, if any

5.6.1.4 **Static Pressure Taps**. Static pressure taps will be in piezometer ring or piezometer manifold arrangement with a minimum of 3 taps located circumferentially around the pipe, all taps at equal angle spacing. To avoid introducing measurement errors from recirculating flow within the piezometer ring, each of the pipe tap holes shall have a flow resistance that is greater than or equal to 5 times the flow resistance of the piezometer ring piping connections between any pair of pressure taps. See Figure 4. A “Triple-Tee” manifold arrangement using 4 pipe tap holes is the preferred arrangement but not required if meeting the flow resistance requirement. See Figure 5.

5.6.1.5 For design or evaluation purposes, flow resistance may be estimated by resistance coefficient K factor calculation methods as found in Crane Technical Paper No. 410. Generally, manifold tubing or piping can be evaluated using the K factor, and pressure tap holes can be evaluated using orifice flow equations (refer to Section 5).

5.6.1.6 For more information about the design of piezometer rings, see paper by Blake in the Informative References, Appendix A.

5.6.1.7 Provisions shall be made to bleed air out of the lines connected to pressure measurement devices. These provisions shall take into consideration the orientation of pressure taps and manifold connections.

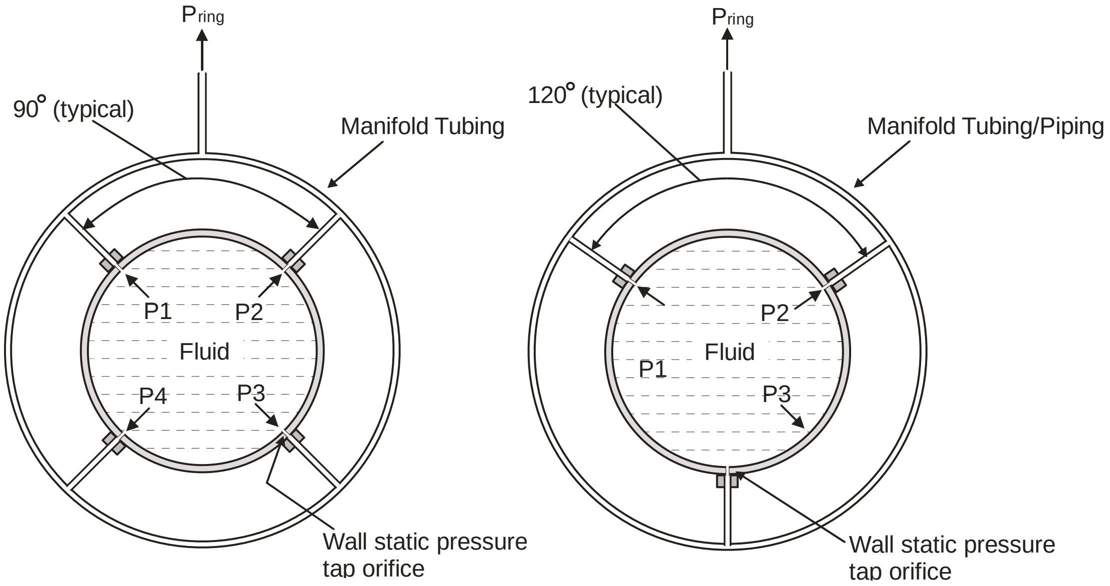

Figure 4 Examples of Piezometer Ring/Manifold

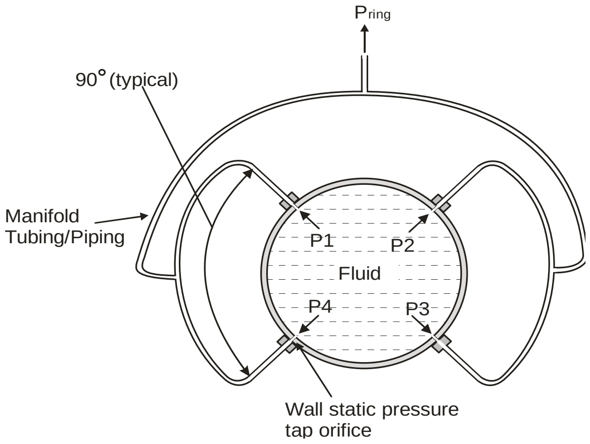

Figure 5 Example of Triple-Tee Piezometer Ring/Manifold

5.7 Power. Auxiliary power shall be measured by summation of measurements at one or more locations defined in the following sections.

Electrical measurements include voltage (for each phase), current (for each phase), power, and frequency (from a minimum of one phase).

5.7.1 Power Measurement Considerations for Energy Balance. Input power that enters the refrigerant/solution side of the circuit impacts the energy balance calculation. This includes the refrigerant and solution pumps.

5.7.2 The total input power for energy balance calculations shall be determined from steam at measured supply and exhaust conditions or fuel consumption.

5.8 Plan. A test plan shall document all requirements for conducting the test. This includes the operating mode(s), a list of the required full load and part load test points and associated operating conditions, including adjusted liquid temperature targets based on the rated Fouling Factor Allowance.

5.9 Operating Condition Tolerances. Operating condition tolerances are defined to control two characteristics. The first is deviation of the mean value relative to the target value. The second is the stability, which is defined in statistical terms and allows excursions from the target that are brief in time and/or small in magnitude. Over the time period of each test point, the operating conditions shall be controlled to maintain the mean and standard deviation within the tolerances defined in Table 7.

Table 7. Definition of Operating Condition Tolerances and Stability Criteria

Measurement or Calculation Result	Applicable Operating Mode(s)	Values Calculated from Data Samples		Operating Condition Tolerance Limits	Stability Criteria
		Mean	Std Dev		
Net Capacity, Q (Cooling or Heating)	Cooling, Heating	$\overline{Q}$	s_Q	Unit with Continuous Unloading: [1] Part Load test capacity shall be within 2% of the target part-load capacity [2] $\frac{\lvert\overline{Q}-Q_{target}\rvert}{Q_{100\%}} \le 2.000\%$	No requirement for s_Q
				Units with Discrete Capacity Steps: Part Load test points shall be taken as close as practical to the specified part-load rating points as stated in Table 3	
Cooling Mode Evaporator		$\overline{T}$	s_T		
Entering Water Temperature	Cooling, Heating			-	$s_T \le 0.10\ \Delta°C\ [0.18\ \Delta°F]$
Leaving Water Temperature				$\lvert\overline{T}-T_{target}\rvert \le 0.28\ \Delta°C\ [0.50\ \Delta°F]$ Exception for heating mode only: no requirement during defrost portion.	
Cooling Mode Heat Rejection Heat Exchanger (Condenser + absorber)		$\overline{T}$	s_T	$\lvert\overline{T}-T_{target}\rvert \le 0.28\ \Delta°C\ [0.50\ \Delta°F]$	$s_T \le 0.10\ \Delta°C\ [0.18\ \Delta°F]$
Entering Water Temperature	Cooling				
Leaving Water or Fluid Temperature	Heating				
Water Flow (Volumetric, Entering)	Cooling, Heating	$\overline{V}$	$S_{\dot{V}}$	$\frac{\lvert\bar{\dot{V}}-\dot{V}_{target}\rvert}{\dot{V}_{target}} \le 5.000\%$	$\frac{s_{\dot{V}}}{\bar{\dot{V}}} \le 0.750\%$
Voltage [5] (if multiphase, this is the average of all phases)	Cooling, Heating	$\overline{V}$	s_V	$\frac{\lvert\bar{\dot{V}}-\dot{V}_{target}\rvert}{\dot{V}_{target}} \le 10.00\%$	$\frac{s_{\dot{V}}}{\bar{\dot{V}}} \le 2.00\%$
Frequency [5]	Cooling, Heating	$\overline{\omega}$	s_V	$\frac{\lvert\overline{\omega}-\omega_{target}\rvert}{\omega_{target}} \le 1.000\%$	$\frac{s_{\omega}}{\overline{\omega}} \le 2.00\%$

5.10 Corrections. The following corrections shall be applied to test targets or test results when applicable.

5.10.1 Fouling Factor. Target liquid temperatures shall be adjusted per the test plan in consideration of fouling of heat transfer surfaces as prescribed in Appendix C of this standard.

5.10.2 Pressure Drop. The average measured Liquid Pressure Drop values during test shall be adjusted to subtract additional static pressure drop due to external piping. The additional static pressure drop shall be the sum of all losses between the unit connections and the location of static pressure taps. To account for measurement methods, the measured values of liquid pressure drop during testing shall be corrected per the methods defined in Section 5 prior to reporting the final test result for Liquid Pressure Drop.

5.11 Validation

5.11.1 Energy Balance. For the case of Liquid-cooled Condensers, measurement data shall be collected to calculate an *energy balance* (per Section 4.10) to substantiate the validity of each test point. Test validity tolerance for *energy balance* is found in Table 8. The energy balance (%) shall be within the allowable tolerance calculated per Table 8 for the applicable conditions.

If evaporator liquid is used to remove heat from any other source(s) within the package, the temperature, pressure drop, and flow measurements of chilled liquid shall be made at points so that the measurements reflect the Gross Refrigerating Capacity.

If condenser liquid is used for some other incidental function within the package, the temperature, pressure drop, and flow measurements of condenser liquid must be made at points such that the measurements reflect the Gross Heating Capacity.

Table 8 Definition of Validity Tolerances

Parameter	Limits	Related Tolerance Equations[3]
Energy Balance[1]	$\lvert E_{bal} \rvert \le Tol_4 \times 100\%$	IP: $Tol_4 = 0.074 - (0.049 \cdot \%Load) + \left(\frac{0.105}{\Delta T_{FL} \cdot \%Load}\right)$ SI: $Tol_4 = 0.074 - (0.049 \cdot \%Load) + \left(\frac{0.05833}{\Delta T_{FL} \cdot \%Load}\right)$

Notes:
1. Energy balance where applicable shall be calculated in accordance with Section 4.10.
2. %Load and Tol_4 are in decimal form.

The following figure is a graphical representation of the related tolerance equation for energy balance as noted in Table 8.

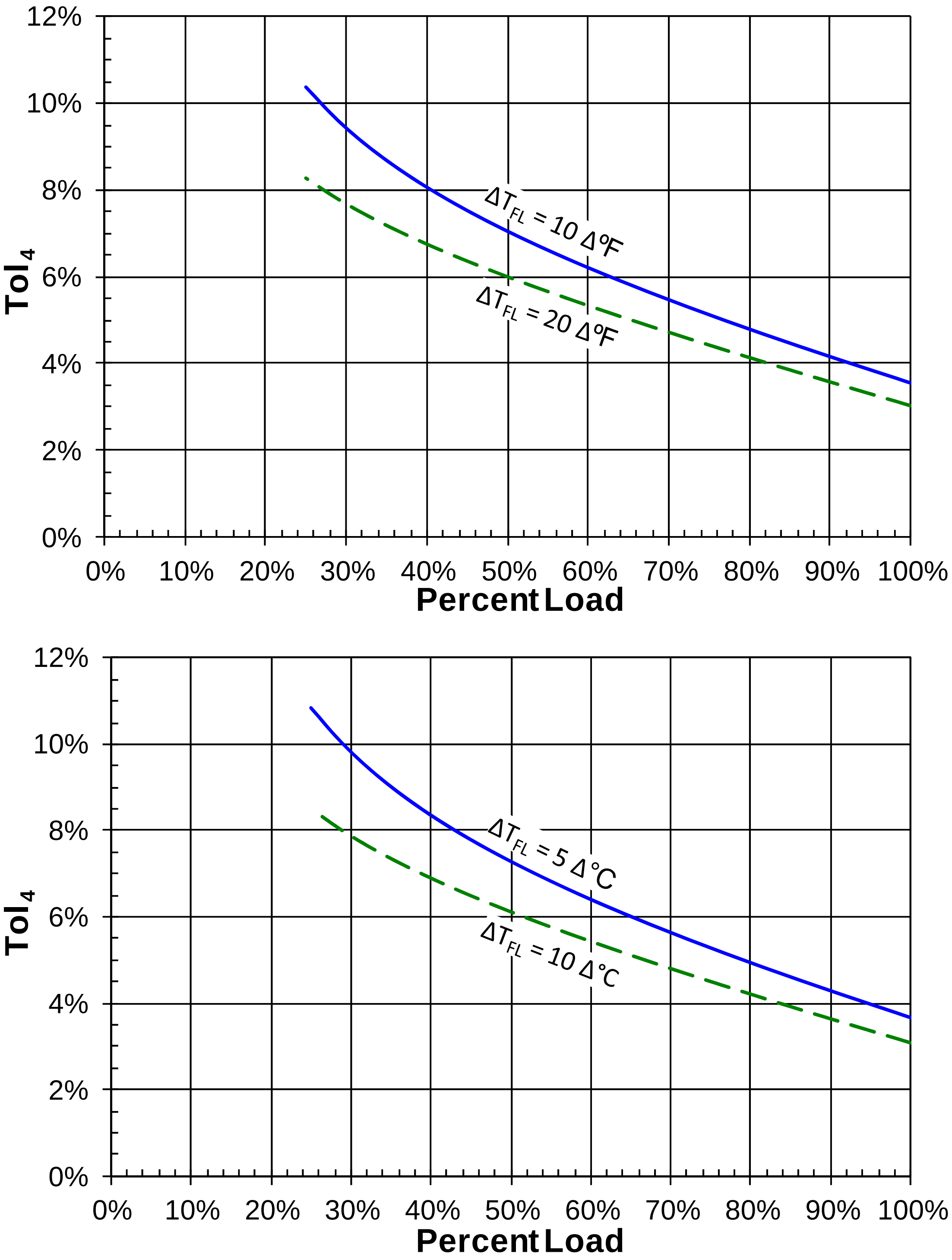

Figure 6 **Energy Balance Tolerance (Tol_4) Curve**

5.11.2 **Uncertainty Analysis**. This standard requires an uncertainty analysis for measurements and test results. Perform uncertainty analysis following the procedures in Appendix B of this standard. The energy balance uncertainty shall not exceed to allowable tolerance as prescribed in 5.11.1.

6. DATA TO BE RECORDED

6.1 Primary Data. Table 9 summarizes the data to be recorded during the test for each of the data point samples.

Table 9 Data to be Recorded During the Test

Type		Data Item
All Types	General	Time of day for each data point sample
		Atmospheric pressure
	Evaporator	T_{in}
		T_{out}
		$\dot{m}_w$ or $\dot{V}_w$
		Δp_{test}
	Absorber/Condenser	T_{in}
		T_{out}
		$\dot{m}_w$ or $\dot{V}_w$
		Δp_{test}
	General	Auxiliary power
Hot-water heating option (if tested)	Hot water heater	Flow rate of hot water, temperature of water entering and leaving water heater, hot water pressure drop.
Steam, Direct-fired, or hot water energy source	Generator	W_{input} (and W_{refrig} if needed)
		If Indirect (steam) Fired: Steam consumption Steam supply pressure Steam supply temperature Steam condensate temperature
		If Direct (gas) Fired: fuel consumption (natural gas or propane) HHV, Gas pressure and temperature entering gas train
		If Direct (oil) Fired Oil consumption, oil HHV, oil classification (e.g. class A heavy oil)
		If Indirect (hot water) fired: Hot water flow rate, Tin and Tout, hot water pressure drop
		If Indirect (hot gas) fired: Hot gas flow rate, hot gas entering and leaving temperature, hot gas specific heat at average hot gas temperature, hot gas pressure drop

6.2 Auxiliary Data. Table 10 summarizes the auxiliary data that shall be recorded for the test.

Table 10 Additional Information to be Recorded

Type	Data Item
All	Date, place, and time of test
	Names of test supervisor and witnessing personnel
	Ambient temperature at test site
	Nameplate data, including make, model, size, serial number, sufficient to completely identify the liquid chiller.

7. TEST PROCEDURES

7.1 Purpose. This section prescribes a method of testing for Liquid-chilling and Liquid-heating packages and to verify capacity and power requirements at a specific set of steady-state conditions.

Testing shall be conducted at a facility designed specifically for that purpose where instrumentation is in place and load stability can be obtained.

Testing shall not be conducted in field installations to the provisions of this standard. Steady-state conditions and requirements for consistent, reliable measurement are difficult to achieve in field installations.

7.2 Test Procedures. For each test point at a specific load and set of operating conditions, the test will measure capacity, thermal energy input, and liquid-side pressure drop. Capacity, a measurement of the heat added to or removed from the liquid as it passes through the heat exchanger, may be cooling or heating, according to the test plan. Net capacity is always required, and gross capacity is required when an energy balance requirement applies. Each test point will collect multiple data points versus time. The test shall use instrumentation meeting the requirements in Section 5 and calculations in Section 4.

7.3 Setup. The chiller package to be tested shall be setup at the test facility in accordance with the manufacturer's instructions, including, but not limited to support of installation mounting points, connections for liquid, connections for thermal energy input and auxiliary power supply, test instrumentation, charging of refrigerant and solution, etc. Non-condensable gases, if present, shall be removed from the system prior to the test commencement.

7.3.1 Condition of Heat Transfer Surfaces. The as tested Fouling Factors shall be assumed to be zero ($R_{foul} = 0.00\overline{0}\ m^2\cdot K/kW = 0.00\overline{0}\ h\cdot ft^2\cdot °F/Btu$). Tests conducted in accordance with this standard may require cleaning of the heat transfer surfaces (in accordance with manufacturer's instructions) prior to conducting the test.

7.4 Water temperatures for test are adjusted from the specified conditions to simulate the effect of fouling. The procedure for that adjustment is described in Appendix C.

7.5 Operation. After setup is complete, the chiller will be started and operated to attain the target conditions of the test point per the test plan. The chiller is not required to operate continuously between different test points; shut down and re-start between test points is allowable.

7.5.1 General Steady-state operating conditions and performance shall be maintained for a minimum test time period of 15 minutes, such that measurement parameters, associated standard deviations, and test results are within both the operating condition tolerances and test tolerances set forth in Section 5.9. If not within tolerance due to lack of stability, then continue testing until within tolerance. If not within tolerance but stability is acceptable, then stop testing to investigate and resolve instrumentation problems, then repeat the test. Resolving problems may require new calibration of instrumentation.

7.5.1.1 To minimize the effects of transient conditions, all measurement types should be taken as simultaneously as possible (flow, temperature, power, etc.). Software or other recording methods shall be used to capture time-stamped data points over the duration of the test time period. A minimum of 30 data point measurements shall be collected and recorded for each parameter at uniform time intervals. Intervals between time stamps shall not vary more than ±5% from the average time interval for all data points. Each data point measurement may represent either an individual reading from the measurement system, or a time averaged value from a larger number of data samples. In the case of using time averaging, whether in hardware or software, the time interval for averaging of data samples shall not exceed 1/60 of the total test time period. There is no limit on sampling rate, and various time averaging methods may be employed.

7.5.1.2 Measurement values include temperatures, flow rates, differential pressure, power, voltage, fuel or steam consumption, and atmospheric pressure. Calculate the average and standard deviation for each measurement value.

7.5.1.3 Test results include Net Capacity, Efficiency, and Liquid Pressure Drop (corresponding to certification program published rating values). Calculate test results using the mean of the test measurement values. Capacity may be calculated for each data point for purposes of test facility control, but the final result for capacity shall be calculated from the mean of all measurement values.

7.6 Adjustments

7.6.1 Controls Manual operation of chiller controls is allowed to avoid cycling and disruption of test stability.

7.6.2 Refrigerant. Refrigerant and solution charge may be adjusted during setup, prior to conducting the test, in accordance with manufacturer's instructions which may require operation of the chiller. Refrigerant and solution charge quantity shall be held constant for the duration of the test, including all test points in a series of full load and part load tests.

7.7 Liquid Pressure Drop Measurement Procedure

7.7.1 Purpose. The purpose of this section is to prescribe a measurement method for Liquid Pressure Drop and, when required, a correction method to compensate for friction losses associated with external piping measurement sections. The measurement method only applies to pipe of circular cross section.

7.7.2 Background. As a certified test point for the liquid to refrigerant heat exchangers, the liquid-side pressure drop needs to be determined by test with acceptable measurement uncertainty. In some cases, the measured Liquid Pressure Drop per this standard will be determined by using static pressure taps external to the unit in upstream and downstream piping. When using external piping, adjustment factors are allowed to compensate the reported pressure drop measurement. Numerous studies conclude that the determination of a calculated correction term for these external components may contain significant sources of error, and therefore, the use of external correction factors will be restricted to limit the magnitude of these potential errors. For units with small connection sizes, it is feasible that straight pipe sections be directly connected to the units with adequate length to obtain static pressure measurements with acceptable systematic errors due to instrument installation location. This is the preferred connection methodology. Units with larger size connections may have spatial limits in the upstream and downstream connection arrangement such that elbows or pipe diameter changes may be necessary to accommodate the available space at the test facility, or to provide mechanical support for piping weight loads. While this may increase the measurement uncertainty, it is a practical compromise considering capital costs of test facilities.

7.7.3 Correction Method. The average measured Liquid Pressure Drop values during test shall be adjusted to subtract additional static pressure drop due to external piping. The additional static pressure drop shall be the sum of all losses between the unit connections and the location of static pressure taps. Record the original measured value, the calculated adjustment value, and the final calculated corrected test result for Liquid Pressure Drop.

7.7.3.1 The adjustment shall not exceed 10% of the measured Liquid Pressure Drop.

7.7.3.2 Refer to Section 4.7.14 for the equations to be used.

8. REPORTING OF RESULTS

8.1 Reporting of results shall conform to the customer's request. The minimum list of items to report is presented below. This list is based on the minimum data requirements specified in AHRI Standard 560-2019.The report shall include the statement: "Tested in accordance with ANSI/ASHRAE Standard 182-2019."

8.1.1 The report shall list the following:

8.1.1.1 Name and address of the test facility.

8.1.1.2 Name of the client.

8.1.1.3 Report identification number and disclaimer (if such exists).

8.1.1.4 Description of test chiller, including Model and Serial numbers.

8.1.1.5 Solution type (e.g., lithium bromide – water).

8.1.1.6 Heat/energy input type (e.g., steam, hot water, direct-fired gas/oil, hot-gas, …).

8.1.1.7 Operating mode (e.g., cooling only, heating only, simultaneous heating and cooling).

8.1.1.8 Date and time of tests.

8.2 The test results report shall state the operating conditions and shall include the following items, rounded to the specified number of significant figures (sf) or decimal places (dp).

8.2.1 **Operation in Cooling-only Mode.**

8.2.1.1 Net refrigerating capacity and associated uncertainty (4 sf), tonR.

8.2.1.2 Total thermal energy input and associated uncertainty (4 sf), MBH.

8.2.1.3 **If steam-fired:**

8.2.1.3.1 Steam pressure and associated uncertainty (3 sf), psia or psig.

8.2.1.3.2 Condensate temperature and associated uncertainty (2 dp), °F.

8.2.1.3.3 Condensate flow rate and associated uncertainty (4 sf), gpm.

8.2.1.4 **If hot-water-fired:**

8.2.1.4.1 Hot water entering temperature, leaving temperature, and entering to leaving temperature difference and associated uncertainties (2 dp), °F/R.

8.2.1.4.2 Hot water flow rate (4 sf), gpm.

8.2.1.5 **If direct-fired:**

8.2.1.5.1 Fuel higher heating value (HHV) and associated uncertainty (4 sf); Btu/ft^3, Btu/gal.

8.2.1.5.2 Flue gas exiting temperature and associated uncertainty (2 dp), °F.

8.2.1.5.3 Combustion efficiency and associated uncertainty (4 sf).

8.2.1.6 Efficiency (4 sf) per Equation (4-25) or (4-26), COPR or MBH/tonR, and associated uncertainty.

8.2.1.7 Evaporator fouling factor (2 sf), hr-ft^2-R/Btu.

8.2.1.8 Application and as-tested (adjusted for fouling allowance) chilled (evaporator) water leaving temperatures and associated uncertainties (2 dp), °F.

8.2.1.9 Chilled (evaporator) water entering temperature and chilled (evaporator) water entering to leaving temperature difference and associated uncertainties (2 dp), °F/R.

8.2.1.10 Chilled (evaporator) water flow rate and associated uncertainty (4 sf), gpm.

8.2.1.11 Chilled (evaporator) water inlet to outlet pressure drop and associated uncertainty (3 sf), psid or ft H_2O.

8.2.1.12 Absorber/condenser fouling factor (2 sf), hr-ft^2-R/Btu.

8.2.1.13 Application and as-tested (adjusted for fouling allowance) cooling (absorber/condenser) water entering temperatures and associated uncertainties (2 dp), °F.

8.2.1.14 Cooling (absorber/condenser) water leaving temperature and cooling (absorber/condenser) water leaving to entering temperature difference and associated uncertainties (2 dp), °F/R.

8.2.1.15 Cooling (absorber/condenser) water flow rate and associated uncertainty (4 sf), gpm.

8.2.1.16 Cooling (absorber/condenser) water heat rejection and associated uncertainty (4 sf), Btu/hr

8.2.2 Operation in Heating-only Mode.

8.2.2.1 Net heating capacity and associated uncertainty (4 sf), Btu/hr.

8.2.2.2 Total thermal energy input and associated uncertainty (4 sf), MBH.

8.2.2.3 Fuel higher heating value (HHV) and associated uncertainty (4 sf); Btu/ft^3, Btu/gal.

8.2.2.4 Flue gas exiting temperature and associated uncertainty (2 dp), °F.

8.2.2.5 Combustion efficiency and associated uncertainty (4 sf).

8.2.2.6 Efficiency (4 sf) per Equation (4-27), COPH, and associated uncertainty.

8.2.2.7 Heated water fouling factor (2 sf), hr-ft^2-R/Btu.

8.2.2.8 Application and as-tested (adjusted for fouling allowance) heated water leaving temperatures and associated uncertainties (2 dp), °F.

8.2.2.9 Heated water entering temperature and heated water leaving to entering temperature difference and associated uncertainties (2 dp), °F/R.

8.2.2.10 Heated water flow rate and associated uncertainty (4 sf), gpm.

8.2.2.11 Heated water inlet to outlet pressure drop and associated uncertainty (3 sf), psid or ft H_2O.

8.2.3 Operation in Simultaneous Cooling and Heating Mode.

8.2.3.1 Report all items listed above under Cooling-only and Heating-only modes, except for efficiencies.

8.2.3.2 Report efficiency per Equation (4-28), COPSCH, (4 sf).

8.2.4 Additional items to report.

8.2.4.1 Ambient temperature of facility during the test (0 dp), °F.

8.2.4.2 Estimate of heat loss from generator (2 sf), Btu/hr.

8.2.4.3 Description of method used to calculate heat loss.

8.2.4.4 Energy balance closure per Equation (4-32) and associated uncertainty.

8.2.4.5 Auxiliary power consumption (3 sf), kW.

9. NOMENCLATURE

Some symbols use a subscript suffix; multiple subscripts are separated by a comma. Equations in this standard use the following units of measure for dimensional consistency. See Section 5.6 for converting to or from other units of measure.

			SI		**IP**	
Group	**Symbol**	**Description**	**Unit Name**	**Unit Symbol**	**Unit Name**	**Unit Symbol**
General						
	E	energy flow rate (thermal or electrical)	watt	W	British thermal unit (IT) per second	Btu/s
	E_{bal}	energy balance				
	HHV	higher heating value at a specified reference temperature	kilojoule per kilogram	kJ/kg	British thermal unit (IT) per pound	Btu/lb
	R_{foul}	fouling factor	meter squared Kelvin per kilowatt	$m^2\cdot K/kW$	hour, feet squared, degree Fahrenheit per British thermal unit	$h\cdot ft^2\cdot °F/Btu$
	Tol	tolerance	-	-	-	-
	$\alpha(T)$	volume expansivity as a function of temperature	-	1/K	-	1/°R
Electrical						
	A	amperage	amp	A	amp	A
	V	voltage	volt	V	volt	V
	ω	frequency (electrical)	hertz	Hz	hertz	Hz
Calibration and Uncertainty						
	B_x	sum of the fixed errors associated with variable x	-	-	-	-
	c	Intercept (offset) of the regression line	-	-	-	-
	j	Number of data points	-	-	-	-
	m	Slope of the regression line	-	-	-	-
	n	number of calibration data points	-	-	-	-
	PI ($\hat{x}$)	prediction interval at the value of $\hat{x}$	-	-	-	-
	S	standard deviation of a sample from a population	-	-	-	-

			SI		IP	
Group	**Symbol**	**Description**	**Unit Name**	**Unit Symbol**	**Unit Name**	**Unit Symbol**
	S_ε	Standard error of estimate, used to quantify the residual error of a measuring system after calibration against a reference calibration standard	-	-	-	-
	SS_x	Sum of squares of x value differences to the mean	-	-	-	-
	$t_{a/2,n-2}$	The critical value of Student's t distribution, at confidence level $\alpha/2$ and degrees of freedom n-2	-	-	-	-
	U_x	overall uncertainty in measured variable x				
	x	Variable representing any measurement value, such as temperature, flow rate, or power	-	-	-	-
	$\hat{x}$	any value of at which to evaluate the curve fit and prediction interval	-	-	-	-
	$\bar{x}$	sample mean (of a measurement)	-	-	-	-
	$\bar{y}$	mean of redundant measurement sample means	-	-	-	-
	$\hat{y}$	linear regression curve fit of the (x_j,y_j) calibration data used to compare indicated measurement values versus the calibration reference standard	-	-	-	-
	% FS	percent of full scale for the useable range of the measurement instrument or measurement system.	percent	%	percent	%
	% RDG	percent of reading for the useable range of the measurement instrument or measurement system.	percent	%	percent	%
	α	significance level used by this standard	percent	%	percent	%
Flow						
	$\dot{m}$	mass flow rate	kilogram per second	kg/s	pound per second	lb/s
	$\dot{V}$	volumetric flow rate	cubic meter per second	m^3/s	cubic foot per second	ft^3/s
	ρ	density	kilogram per cubic meter	kg/m^3	pound per cubic foot	lb/ft^3
Capacity						
	c_p	specific heat at constant pressure	kilojoule per kilogram kelvin	kJ/(kg·K)	British thermal unit per pound degree Fahrenheit	Btu/(lb·°F)

			SI		**IP**	
Group	**Symbol**	**Description**	**Unit Name**	**Unit Symbol**	**Unit Name**	**Unit Symbol**
	h	enthalpy	kilojoule per kilogram	kJ/kg	British thermal unit per pound	Btu/lb
	Δh	enthalpy differential	kilojoule per kilogram	kJ/kg	British thermal unit per pound	Btu/lb
	Q	net capacity, heat flow rate	watt	W	British thermal unit per hour	Btu/h
	Q'	gross capacity, heat flow rate	watt	W	British thermal unit per hour	Btu/h
	Q_{input}	thermal input power	watt	W	British thermal unit per hour	Btu/h
	T	temperature	degree Celsius	°C	degree Fahrenheit	°F
	ΔT	temperature differential (temperature interval)	degree Celsius	Δ°C	degree Fahrenheit	Δ°F
	%Load	percent load	percent	%	percent	%
Efficiency						
	COP	efficiency	watt per watt	W/W = 1	n/a	n/a
	MBH/ton_R	efficiency	n/a	n/a	Thousands of Btu per hour per ton	MBH/ton
	η	efficiency	watt per watt	W/W = 1	British thermal unit (IT) per watt hour	Btu/(W·h)
Heat Loss						
	A_s	surface area	meters squared	m^2	feet squared	ft^2
	A_w	water-side heat transfer surface area	meters squared	m^2	feet squared	ft^2
	L	ratio of heat loss to measured heat input	kilowatt per kilowatt	kW/kW = 1	British thermal unit (IT) per hour per British thermal unit (IT) per hour	Btu/h/(Btu/h) = 1
	q	heat transfer	kilowatt	kW	British thermal unit (IT) per hour	Btu/h
	α	heat transfer rate	kilowatt per meters squared Kelvin	$kW/(m^2 \cdot K)$	British thermal unit (IT) per hour per feet squared degree Fahrenheit	$Btu/h/(ft^2 \cdot °F)$
	χ	thickness of insulation	meters	m	feet	ft

Group	**Symbol**	**Description**	**SI**		**IP**	
			Unit Name	**Unit Symbol**	**Unit Name**	**Unit Symbol**
	λ	thermal conductivity of insulation	kilowatt per meters Kelvin	kW/(m·K)	British thermal unit (IT) per hour per feet degree Fahrenheit	Btu/h/(ft·°F)
Pressure Drop						
	d	pipe inside diameter dimension	millimeter	mm	inch	in
	f	Darcy friction factor	-	-	-	-
	g	standard gravitational term	meter per second squared	m/s^2	foot per second squared	ft/s^2
	h_f	frictional head loss in pipe (pressure drop, pressure differential)	meter	m	foot	ft
	h_m	minor head loss in fittings (pressure drop, pressure differential)	meter	m	foot	ft
	K	resistance coefficient	-	-	-	-
	L_p	length of the pipe segment	meter	m	foot	ft
	p	pressure	kilopascal	kPa	pound-force per	psia
	Δp	pressure differential	kilopascal	kPa	pound-force per	psid
	r	radius of the centerline of the elbow	millimeter	mm	inch	in
	Re	Reynolds number	-	-	-	-
	v	velocity, average across at the inlet cross section	meter per second	m/s	foot per second	ft/s
	β	diameter ratio	millimeter per millimeter	mm/mm = 1	inch per inch	in/in = 1
	ε	absolute roughness	meter	m	foot	ft
	θ	angle of fitting	degrees	°	degrees	°

Subscripts	**Description**
adj	adjusted
amb	ambient conditions of the test chamber
ca	Condenser and absorber
cmb	combustion
ev	evaporator
FL	full load, referring to rated capacity at design conditions
H	heating

i	index value
insul	insulated
ILMTD	incremental log mean temperature difference
in	inlet, entering, input
input	input
j	index value
LMTD	log mean temperature difference
loss	referring to heat leaving the chiller
out	outlet, leaving, output
Q	capacity
r	refrigerant
R	cooling or refrigerating
range	range
refrig	refrigerant
sat	saturation, referring to either saturation temperature, or the mean of dew point and bubble point temperatures
small,clean	small, clean
small	small, specified
T	temperature
target	target test condition
test	test, result from a test measurement
uninsul	not insulated
$\dot{V}$	volumetric flow rate
w	water
X%	denoting a value for X% part load capacity (i.e., 75%)
ω	frequency (electrical)

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INFORMATIVE APPENDIX A - INFORMATIVE REFERENCES

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INFORMATIVE APPENDIX B – UNCERTAINTY ANALYSIS

B1 DEFINITIONS

error: the difference between the true value of the quantity measured or calculated and the observed value. All errors in experimental data can be classified as one of two types: systematic (fixed) errors or random (precision) errors. The terms accuracy and precision are often used to distinguish between systematic and random errors. A measurement with small systematic errors is said to be unbiased. A measurement with small random errors is said to have high precision. A measurement that is unbiased and precise is said to be accurate.

fixed error: same as systematic error.

precision error: same as random error.

random error: an error that causes readings to take random values on either side of a mean value. The random error is quantified based on how well an instrument can reproduce subsequent readings for an unchanging input. Random errors cannot be corrected through calibration.

systematic error: an error that persists and cannot be considered as due entirely to chance. Systematic error can be corrected through calibration.

uncertainty: an estimated value for the error in a measurement or calculation, which may be the result of both systematic and random error.

B.2 METHODOLOGY FOR UNCERTAINTY ANALYSIS

B.2.1 Uncertainty analysis (also referred to as error analysis) is outlined in ASHRAE Guideline 2[B1]. The goal of the uncertainty analysis is to bound the reported test results such that the true values lie within the specified range with 95% confidence. The uncertainty of the reported results is found by propagation of error sources in the measurement system.

B.2.2 The error analysis applied in this standard is intended for steady state measurements taken from a single system over a time period long enough to encompass all system variations. The first step is to assign the uncertainty in each of the measured variables:

$$U_x = \sqrt{B_x^2 + (tS_x)^2} \qquad \text{(B-1)}$$

B.2.3 Fixed or *systematic error* associated with measured variables are those that do not vary randomly during operation of the facility. An example is errors introduced during calibration of the instrumentation. As a general practice, comparison against a known standard using the instrument in combination with the data acquisition system is the best way to estimate fixed errors. If this type of calibration is not possible, the manufacturer's specifications of uncertainty on instruments and data acquisition system shall be used at a minimum. The total fixed error is estimated from its individual contributors,

$$B_x^2 = \sum B_{x,j}^2 \qquad \text{(B-2)}$$

B.2.4 A sequence of measurements made over time of a particular quantity often exhibit some level of random variation or *random error*. The standard deviation in Eq (B-1) is a measure of the magnitude of the *random error* and is most meaningful if data is collected on a time scale longer than any naturally occurring variations in the system. The average and standard deviation for each measured variable is calculated from

$$\bar{x} = \frac{1}{J}\sum_{j=1}^{J} x_j \qquad \text{(B-3)}$$

$$S_{\bar{x}} = \left[\frac{1}{J-1}\sum_{j=1}^{J}\left(x_j - \bar{x}\right)^2\right]^{1/2} \qquad \text{(B-4)}$$

where x_j are the individual measurements made of variable *x* over time.

B.2.5 Quantities of interest are generally computed from the measured variables,

$$Y = Y(X_1, X_2, \ldots, X_i) \quad \text{where} \quad X = \bar{x} \qquad \text{(B-5)}$$

The uncertainty in the computed quantity *Y* can be estimated from

$$U_Y = \left[\left(\frac{\partial Y}{\partial X_1}U_{X_1}\right)^2 + \left(\frac{\partial Y}{\partial X_2}U_{X_2}\right)^2 + \cdots + \left(\frac{\partial Y}{\partial X_i}U_{X_i}\right)^2 + \cdots + \left(\frac{\partial Y}{\partial X_M}U_{X_M}\right)^2\right]^{1/2} \qquad \text{(B-6)}$$

where the partial derivatives represent the sensitivities of the computed quantity *Y* to variations in the individual (averaged) measurements X_i.

B.3 UNCERTAINTY CALCULATIONS – OVERVIEW

B.3.1 From 9.4.1 Test Result Reporting Requirements, the following quantities are required to be reported and shall therefore include an uncertainty:

- Net (& Gross) Refrigerating Capacity
- Net (& Gross) Heating Capacity (if applicable)
- Thermal Power Input
- Energy Efficiency or COP (cooling and heating)
- Energy Balance

B.3.2 The following assumptions are made:

- Tests will be conducted with water as the heat transfer fluid in both cooling and heating modes.
- Density and specific heat of liquid water are known perfectly (negligible uncertainty) when using formulations consistent with IAPWS-IF97[B2], such as the polynomial equations in Section 4 or REFPROP [B3]. The only uncertainty is in the input temperatures.
- Uncertainties in density and specific heat (with respect to uncertainties in their input temperatures) are negligible relative to uncertainties in the temperatures themselves and in their difference.
- The easiest way to visualize the uncertainty in enthalpy change Δ*h* for liquid streams is to use the approximation $\Delta h = c_p\Delta T + \Delta p(1\text{-}T\alpha_p)/\rho$, where $\alpha_p = \text{-}(1/\rho)(\partial\rho/\partial T)_p$ is the *volume expansivity* or *coefficient of thermal expansion* of the liquid.[B5]

B.3.3 Notes:

- Measured quantities are denoted by an underbar in the equations below. Example: $\underline{T}$ indicates a measured temperature. Each measurement has an associated uncertainty.
- θ_X denotes the partial derivative of the output quantity of interest (e.g., *Y*) with respect to one of its input quantities X_i, $\theta_X = \partial Y/\partial X_i$,, holding all other input quantities constant; see Eq (B-6).

- U_X denotes the absolute uncertainty of the measured input quantity *x* determined from Eq (B-1).

B.4 CALCULATION OF HEAT TRANSFER RATE AND ASSOCIATED UNCERTAINTY FOR LIQUID STREAMS

B.4.1 All liquid streams share the same general equations for calculation of heat transfer rate and the associated uncertainty. These streams include:

- gross refrigerating capacity: $Q_r' = Q$ with δ=1
- net refrigerating capacity: $Q_r = Q$ with δ=0
- gross heating capacity: $Q_h' = Q$ with δ=1
- net heating capacity: $Q_h = Q$ with δ=0
- gross cooling heat transfer rate: $Q_c' = Q$ with δ=1
- thermal power input: $Q_t' = Q$ with δ=1

B.4.2 The equations below allow for alternative measurement methods denoted within the braces {}. The liquid stream flow rate can be measured either by volume ($\underline{V}$) or by mass ($\underline{m}$). The liquid stream pressure drop can either be measured directly by a differential pressure meter (Δp) or as the difference between absolute pressures measured at the inlet and outlet ($\underline{p_i} - \underline{p_o}$).

$$Q = \left| \left\{ \begin{matrix} \underline{V} \cdot \rho\left(\underline{T_{meter}}\right) \\ \underline{m} \end{matrix} \right\} \cdot c_p(T_a) \cdot \left(\underline{T_i} - \underline{T_o}\right) + \delta \cdot \left\{ \begin{matrix} \underline{V} \\ \underline{m}/\rho \end{matrix} \right\} \cdot \left\{ \begin{matrix} \underline{\Delta p} \\ \left(\underline{p_i} - \underline{p_o}\right) \end{matrix} \right\} \cdot \left(1 - T_a' \alpha_p(T_a)\right) \right| \tag{B-7}$$

$$U_Q = \sqrt{ \left\{ \begin{matrix} (\theta_V U_V)^2 \\ (\theta_m U_m)^2 \end{matrix} \right\} + \left(\theta_{T_i} U_{T_i}\right)^2 + \left(\theta_{T_o} U_{T_o}\right)^2 + \delta \cdot \left\{ \begin{matrix} \left(\theta_{\Delta p} U_{\Delta p}\right)^2 \\ \left(\theta_{p_i} U_{p_i}\right)^2 + \left(\theta_{p_o} U_{p_o}\right)^2 \end{matrix} \right\} } \tag{B-8a}$$

$$U_Q = \sqrt{ \left\{ \begin{matrix} (\theta_V U_V)^2 \\ (\theta_m U_m)^2 \end{matrix} \right\} + 2(\theta_T U_T)^2 + \delta \cdot \left\{ \begin{matrix} \left(\theta_{\Delta p} U_{\Delta p}\right)^2 \\ 2\left(\theta_p U_p\right)^2 \end{matrix} \right\} } \quad \begin{matrix} \text{if the uncertainties in} \\ T_i \text{ and } T_o \text{ are the same} \\ \text{and } p_i \text{ and } p_o \text{ are the same} \end{matrix} \tag{B-8b}$$

$$\theta_V = \rho c_p \Delta T + \delta \cdot \left(1 - T_a' \alpha_p\right) \cdot \Delta p \tag{B-9a}$$

$$\theta_m = c_p \Delta T + \delta \cdot \left(1 - T_a' \alpha_p\right) \cdot \Delta p / \rho \tag{B-9b}$$

$$\left|\theta_{T_i}\right| = \left|\theta_{T_o}\right| = \left|\theta_T\right| = \left\{ \begin{matrix} V \rho c_p \\ m c_p \end{matrix} \right\} \tag{B-10}$$

$$\theta_{\Delta p} = \left|\theta_{p_i}\right| = \left|\theta_{p_o}\right| = \left\{ \begin{matrix} V \\ m/\rho \end{matrix} \right\} \tag{B-11}$$

where

$$\Delta T = \underline{T_i} - \underline{T_o} \quad \Delta p = \left\{ \begin{matrix} \underline{\Delta p} \\ \left(\underline{p_i} - \underline{p_o}\right) \end{matrix} \right\} \quad c_p = c_p(T_a)$$

$$\left\{ \begin{matrix} V = \underline{V} \\ m = \underline{m} \end{matrix} \right\} \qquad \rho = \rho\left(\underline{T_{meter}}\right) \quad \alpha_p = \alpha_p(T_a) \tag{B-12}$$

$$T_a = \tfrac{1}{2}\left(\underline{T_i} + \underline{T_o}\right) \quad \text{and} \quad \mathrm{T_a'} = \mathrm{T_a} \text{ in absolute temperature units (R or K)}$$

B.4.3 Values for the specific heat and density of water shall be derived using the polynomial equation for liquid water specific heat in Section 4 or by using another formulation consistent with IAPWS-

IF97^{B2}, such as REFPROP^{B3}. Values for the volume expansivity shall be derived using the method in Section 4.

B.5 CALCULATION OF HEAT TRANSFER RATE AND ASSOCIATED UNCERTAINTY FOR STEAM AS HEAT SOURCE

B.5.1 The thermal power input, Q_{input}, is calculated as follows when steam is used as the heat source, where it is assumed that the steam is in a superheated state upstream of the chiller and leaves as subcooled condensate. Flow rate of the condensate stream can be made on either a volume or mass basis.

$$Q_{input} = \left\{\begin{matrix}\underline{V}\cdot\rho\left(\underline{T_{meter}}\right)\\ \underline{m}\end{matrix}\right\}\cdot\left(h_v\left(\underline{T_i},\underline{p_i}\right)-h_l\left(\underline{T_o}\right)\right) \tag{B-13}$$

$$U_{Qinput} = \sqrt{\left\{\begin{matrix}(\theta_V U_V)^2\\ (\theta_m U_m)^2\end{matrix}\right\}+\left(\theta_{T_i}U_{T_i}\right)^2+\left(\theta_{p_i}U_p\right)^2+\left(\theta_{T_o}U_{T_o}\right)^2} \tag{B-14}$$

$$\theta_V = \rho\Delta h \qquad \theta_m = \Delta h \tag{B-15a,b}$$

$$\theta_{T_i} = \left\{\begin{matrix}\underline{V}\cdot\rho\left(\underline{T_{meter}}\right)\\ \underline{m}\end{matrix}\right\}\cdot\left(\frac{\partial h_v}{\partial T}\right)_{p_i} \tag{B-16}$$

$$\theta_{p_i} = \left\{\begin{matrix}\underline{V}\cdot\rho\left(\underline{T_{meter}}\right)\\ \underline{m}\end{matrix}\right\}\cdot\left(\frac{\partial h_v}{\partial p}\right)_{T_i} \tag{B-17}$$

$$\theta_{p_i} = -\left\{\begin{matrix}\underline{V}\cdot\rho\left(\underline{T_{meter}}\right)\\ \underline{m}\end{matrix}\right\}\cdot c_p\left(\underline{T_o}\right) \quad \text{where} \quad c_p = \left(\frac{\partial h_l}{\partial T}\right)_p \tag{B-18}$$

B.5.2 The sensitivities of the entering steam enthalpy to the uncertainties in its temperature and pressure, Eqs (B-16) and B-17), can be estimated from steam properties tables. However, it is most convenient to determine these using a software-based formulation of steam properties *via* numerical derivatives. As above for liquid water, such a formulation shall be consistent with IAPWS-IF97^{B2}, such as REFPROP^{B3}.

B.5.3 The sensitivity of the leaving condensate enthalpy to the uncertainties in its temperature, Eq (B-18), can be estimated using the polynomial equation for liquid water specific heat in Section 4 or by using a formulation consistent with IAPWS-IF97^{B2}, such as REFPROP^{B3}.

B.6 CALCULATION OF THERMAL POWER INPUT AND ASSOCIATED UNCERTAINTY FOR DIRECT-FIRED OPERATION

B.6.1 The thermal power input, Q_{input}, is calculated as follows under direct-fired operation. This requires measurement of volumetric flow rate of the fuel. The *HHV* of the fuel can be obtained from the utility supplying the fuel. Alternatively, *HHV* can be determined by analyzing a sample of the fuel for its composition.

$$Q_{input} = \underline{\dot{V}}\cdot\underline{HHV_v} \tag{B-19}$$

$$U_{Q_{input}} = \sqrt{(\theta_{\dot{V}}U_{\dot{V}})^2+(\theta_{HHV}U_{HHV})^2} \qquad \frac{U_{Q_{input}}}{Q_{input}} = \sqrt{\left(\frac{U_{\dot{V}}}{\dot{V}}\right)^2+\left(\frac{U_{HHV}}{HHV_v}\right)^2} \tag{B-20a,b}$$

$$\theta_{\dot{V}} = HHV_v \qquad \theta_{HHV} = \dot{V} \qquad \text{(B-21,22)}$$

B.6.2 The relative uncertainty in the direct-fired thermal power input shown in Eq (B-20b) is derived from the absolute metric in Eq (B-20a) combined with Eqs (B-21) and (B-22).

B.6.3 The uncertainty in *HHV* can be estimated from utility records of the variability of *HHV* over time. Alternatively, the uncertainty can be determined from the uncertainties in the composition measurement.

B.7 CALCULATION OF ENERGY EFFICIENCY OR COP AND ASSOCIATED UNCERTAINTY

B.7.1 The energy efficiency is defined as the ratio of the useful product to the thermal power input, Q_t. The useful product in cooling mode is the net refrigerating capacity, Q_r. The useful product in heating mode is the net heating capacity, Q_h.

$$\text{Cooling: } \eta_R = \frac{Q_r}{Q_t} \qquad \text{Heating: } \eta_H = \frac{Q_h}{Q_t} \qquad \text{(B-23a,b)}$$

$$U_{\eta_R} = \sqrt{\left(\theta_{Q_r} U_{Q_r}\right)^2 + \left(\theta_{Q_t} U_{Q_t}\right)^2} \qquad U_{\eta_H} = \sqrt{\left(\theta_{Q_h} U_{Q_h}\right)^2 + \left(\theta_{Q_t} U_{Q_t}\right)^2} \qquad \text{(B-24a,b)}$$

$$\theta_{Q_r} = 1/Q_t \qquad \theta_{Q_h} = 1/Q_t \qquad \text{(B-25a,b)}$$

$$\theta_{Q_t} = -\,Q_r/Q_t^2 \qquad \theta_{Q_t} = -\,Q_h/Q_t^2 \qquad \text{(B-26a,b)}$$

$$\frac{U_{\eta_R}}{\eta_R} = \sqrt{\left(\frac{U_{Q_r}}{Q_r}\right)^2 + \left(\frac{U_{Q_t}}{Q_t}\right)^2} \qquad \frac{U_{\eta_H}}{\eta_H} = \sqrt{\left(\frac{U_{Q_h}}{Q_h}\right)^2 + \left(\frac{U_{Q_t}}{Q_t}\right)^2} \qquad \text{(B-27a,b)}$$

B.7.2 The relative uncertainties in the energy efficiency metrics shown in Eqs (B-27) are derived from the absolute metrics in Eqs (B-24) combined with Eqs (B-25) and (B-26).

B.8 CALCULATION OF ENERGY BALANCE AND ASSOCIATED UNCERTAINTY

B.8.1 The energy balance (*EB*) in cooling mode is calculated by subtracting the gross cooling heat transfer rate (Q_c') from the sum of the gross refrigerating capacity (Q_r') and the thermal power input (Q_t'), Eq (B-28a).

B.8.2 A relative energy balance (EB^*) can be defined by comparing the absolute energy balance to the gross cooling heat transfer rate, Eq (B-28b).

$$EB = Q_r' + Q_t' - Q_c' \qquad EB^* = \frac{EB}{Q_c'} = \frac{Q_r'}{Q_c'} + \frac{Q_t'}{Q_c'} - 1 \qquad \text{(B-28a,b)}$$

$$U_{EB} = \sqrt{U_{Q_r'}^2 + U_{Q_t'}^2 + U_{Q_c'}^2} \qquad U_{EB^*} = \sqrt{\left(\frac{Q_r'}{Q_c'}\frac{U_{Q_r'}}{Q_r'}\right)^2 + \left(\frac{Q_t'}{Q_c'}\frac{U_{Q_t'}}{Q_t'}\right)^2 + \left(\frac{U_{Q_c'}}{Q_c'}\right)^2} \qquad \text{(B-29a,b)}$$

B.9 REFERENCES

[B1] ASHRAE. 2010. ASHRAE Guideline 2, Engineering Analysis of Experimental Data. Atlanta: ASHRAE.

[B2] IAPWS R7-97(2012) Revised Release on the IAPWS Industrial Formulation 1997 for the Thermodynamic Properties of Water and Steam, available from http://www.iapws.org/index.html.

[B3] Lemmon, E.W., Bell, I.H., Huber, M.L., McLinden, M.O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties – REFPROP, Version 10.0, National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2018.

[B4] Schultz, K. 2013. Method to compute the enthalpy difference of a liquid stream in the absence of an EoS-based function. ASHRAE Transactions 119(2).

NORMATIVE APPENDIX C - METHOD FOR SIMULATING FIELD FOULING ALLOWANCE AT FULL AND PART-LOAD CONDITIONS

C1 ***Calculations.*** The calculations in this section apply to evaporators and/or absorber/condensers using water, for full load and part load operating conditions. The resultant fouling factor correction, ΔTadj, is added or subtracted to the target test water temperature as appropriate to simulate the fouled condition.

$$\Delta T_{range} = |T_{out,w} - T_{in,w}| \quad C1$$

$$\Delta T_{small} = |T_{sat,r} - T_{out,w}| \quad C2$$

Where $T_{sat,r}$ is the saturated vapor temperature corresponding to refrigerant pressure.

Calculate the log mean temperature difference (ΔT_{LMTD}) for the evaporator and/or condenser using the following equation at the Fouling Factor Allowance (R_{foul}) specified by the rated performance, and the corresponding specified small temperature difference, ΔT_{small}.

$$\Delta T_{LMTD} = \frac{\Delta T_{range}}{\ln\left(1 + \frac{\Delta T_{range}}{\Delta T_{small}}\right)} \quad C3$$

Calculate the incremental log mean temperature difference (ΔT_{ILMTD}) using the following equation:

$$\Delta T_{ILMTD} = R_{foul}\left(\frac{Q}{A_w}\right) \quad C4$$

Where Q is the rated net Capacity and A_w is the water-side heat transfer surface area for the heat exchanger, which is inside or outside surface area depending on the heat exchanger design. In the case of the absorber/condenser, the area is the combined water-side area of those two components.

The water temperature adjustment needed to simulate the additional fouling, ΔT_{adj}, can now be calculated:

$$Z = \frac{\Delta T_{range}}{\Delta T_{LMTD} - \Delta T_{ILMTD}} \quad C5$$

$$\Delta T_{small,clean} = \frac{\Delta T_{range}}{e^Z - 1} \quad C6$$

$$\Delta T_{adj} = \Delta T_{small} - \Delta T_{small,clean} \quad C6$$

Where $\Delta T_{small,sp}$ is the small temperature difference as rated at a specified Fouling Factor Allowance, and $\Delta T_{small,clean}$ is the small temperature difference as rated in a clean condition with no fouling.

The calculation of ΔT_{adj} is used for both evaporator and condenser water temperature corrections. The correcting water temperature difference, ΔT_{adj}, is then added to the condenser entering water temperature or subtracted from the evaporator leaving water temperature to simulate the additional Fouling Factor.

C2 ***Special Consideration for Multiple Refrigerant Circuits.***

For units that have multiple refrigeration circuits for the evaporator and/or absorber/condensers, and the following items are known for each heat exchanger: refrigerant saturation temperatures, inlet and outlet water temperatures, and water flow rates; an adjustment temperature $\Delta T_{adj,i}$ shall be computed for each heat exchanger and then combined into a single water temperature adjustment. For series water circuits, the intermediate water temperatures are calculated when measurement is not practical. For this purpose, a weighted average for the $\Delta T_{adj,i}$ values shall be computed as follows:

$$\Delta T_{adj,weighted} = \frac{\Sigma(Q_i \cdot \Delta T_{adj,i})}{\Sigma(Q_i)} \qquad \text{C7}$$

For this purpose, the weighted temperature adjustment, $\Delta T_{adj,weighted}$, will be added to the condenser entering water temperature or subtracted from the evaporator leaving water temperature to simulate the additional fouling factor adjustment.

C3 *Example - Condenser Fouling Inside Tubes.*

Specified Fouling Factor Allowance, R_{foul} = 0.000250 h·ft^2·°F/Btu
Absorber/condenser load, Q_{ca} = 13,000 MBH
Specified absorber/condenser leaving water temp, $T_{out,w}$ = 101.00 °F
Specified absorber/condenser entering water temp, $T_{in,w}$ = 85.00 °F
Specified saturated condensing temperature with specified fouling, $T_{sat,r}$ = 106.00 °F
Inside tube surface area, A = 1500 ft^2 (since fouling is inside tubes in this example)

$$\Delta T_{range} = |T_{out,w} - T_{in,w}| = 101.00 - 85.00 = 16.00°F$$

$$\Delta T_{small} = |T_{sat,r} - T_{out,w}| = 106.00 - 101.00 = 5.00°F$$

$$\Delta T_{LMTD} = \frac{\Delta T_{range}}{\ln\left(1 + \frac{\Delta T_{range}}{\Delta T_{small}}\right)} = \frac{16.00}{\ln\left(1 + \frac{16.00}{5.00}\right)} = 11.14917°F$$

$$\Delta T_{ILMTD} = R_{foul}\left(\frac{Q_{cd}}{A_w}\right) = 0.000250 \cdot \left(\frac{13{,}000 \cdot 1{,}000}{1{,}500}\right) = 2.16667°F$$

$$Z = \frac{\Delta T_{range}}{\Delta T_{LMTD} - \Delta T_{ILMTD}} = \frac{16.00}{11.14917 - 2.16667} = 1.78124$$

$$\Delta T_{small,clean} = \frac{\Delta T_{range}}{e^Z - 1} = \frac{16.00}{e^{1.78124} - 1} = 3.24°F$$

$$\Delta T_{adj} = \Delta T_{small} - \Delta T_{small,clean} = 5.00 - 3.24 = 1.76°F$$

The entering condenser water temperature for testing is then raised 1.76°F to simulate the Fouling Factor Allowance of 0.000250 h·ft^2·°F/Btu. The entering condenser water temperature will be:

$$T_{in,adj} = 85.00 + 1.76 = 86.76\ °F$$

C4 *Derivation of LMTD.*

This derivation is included for reference only:

$$\Delta T_{LMTD} = \frac{(T_{sat,r} - T_{in,w}) - (T_{sat,r} - T_{out,w})}{\ln\left[\frac{T_{sat,r} - T_{in,w}}{T_{sat,r} - T_{out,w}}\right]} = \frac{(T_{out,w} - T_{in,w})}{\ln\left[\frac{(T_{sat,r} - T_{out,w}) + (T_{out,w} - T_{in,w})}{T_{sat,r} - T_{out,w}}\right]}$$

$$= \frac{(T_{out,w} - T_{in,w})}{\ln\left[1 + \frac{(T_{out,w} - T_{in,w})}{T_{sat,r} - T_{out,w}}\right]} = \frac{\Delta T_{range}}{\ln\left(1 + \frac{\Delta T_{range}}{\Delta T_{small}}\right)} \qquad \text{C8}$$

NORMATIVE APPENDIX D - ROUNDING AND SIGNIFICANT DIGITS

D.1 Calculations shall use measurement values with full numerical precision.

D.2 Numerical data are often obtained (or at least calculations can be made) with more digits than are justified by their accuracy or precision. In order not to be misleading, such data should be rounded to the number of figures consistent with the confidence that can be placed in them when reported in final form. However, more digits shall be retained at intermediate stages of calculation to avoid compounding of rounding errors; retain no less than two additional significant figures than the final reported value, or as many digits as possible. The number of significant figures is the number of digits remaining when the data are rounded.

D.3 Expanded uncertainty values on test reports shall be provided with two significant digits.

D.4 Calculations reporting values with expanded uncertainty shall be reported to the same level of significance as the expanded uncertainty.

D4.1. Consider an example result (prior to rounding) with value 10.573593 ± 0.097369424.

D4.2. Rounding the uncertainty to two significant digits yields ± 0.097.

D4.3. The final result shall be reported to the nearest 0.001 (the same significance as the uncertainty with two significant digits), yielding 10.574 ± 0.097.

D.5 The rules for identifying significant figures when writing or interpreting numbers are as follows:

D5.1. All non-zero digits are considered significant. For example, 91 has two significant figures (9 and 1), while 123.45 has five significant figures (1, 2, 3, 4 and 5).

D5.2. Zeroes appearing anywhere between two non-zero digits are significant. Example: 101.1203 has seven significant figures: 1, 0, 1, 1, 2, 0 and 3.

D5.3. Leading zeroes are not significant. For example, 0.00052 has two significant figures: 5 and 2.

D5.4. Trailing zeroes in a number containing a decimal point are significant. For example, 12.2300 has six significant figures: 1, 2, 2, 3, 0 and 0. The number 0.000122300 still has only six significant figures (the zeros before the 1 are not significant). In addition, 120.00 has five significant figures since it has three trailing zeros. This convention clarifies the precision of such numbers; for example, if a measurement precise to four decimal places (0.0001) is given as 12.23, then it might be misunderstood that only two decimal places of precision are available. Stating the result as 12.2300 makes clear that it is precise to four decimal places (in this case, six significant figures).

D5.5. The significance of trailing zeroes in a number not containing a decimal point can be ambiguous. For example, it may not always be clear if a number like 1300 is precise to the nearest unit (and just happens coincidentally to be an exact multiple of a hundred) or if it is only shown to the nearest hundred due to rounding or uncertainty. Various conventions exist to address this issue:

D5.5.1 A bar may be placed over the last significant figure; any trailing zeros following this are insignificant. For example, $13\overline{0}0$ has three significant figures (and hence indicates that the number is precise to the nearest ten).

D.5.5.2 The last significant figure of a number may be underlined; for example, "$2\underline{0}00$" has two significant figures.

D.5.5.3 A decimal point may be placed after the number; for example, "100." indicates specifically that three significant figures are meant.

D.5.5.4 In the combination of a number and a unit of measurement, the ambiguity can be avoided by choosing a suitable unit prefix. For example, the number of significant figures in a power measurement specified as 1300 W is ambiguous, while a power of 1.30 kW is not.

D.5.5.5 Ambiguity can also be avoided by use of scientific notation or exponential notation; for example, 1.30×10^3 W.

D.5.6 In multiplication and division, the operation with the least number of significant figures determines the numbers to be reported in the result. For example, the product 1256 x 12.2 = 15323.2 is reported as $15\overline{3}00$. In addition and subtraction, the least number of figures to either the right or the left of the decimal point determines the number of significant figures to be reported. Thus, the sum of 120.05 + 10.1 + 56.323 = 156.473 is reported as 156.5 because 10.1 defines the reporting level. In complex calculations involving multiplications and additions, for example, the operation is done serially, and the final result is rounded according to the least number of significant figures involved. Thus: (1256 x 12.2) + 125 = 15323.2 + 125 =$15\overline{4}00$.

D.5.7 The following rules shall be used in rounding values:

D.5.7.1. When the digit next beyond the one to be retained is less than five, the retained figure is kept unchanged. For example: 2.541 becomes 2.5 to two significant figures.

D.5.7.2. When the digit next beyond the one to be retained is greater than or equal to five, the retained figure is increased by one. For example; 2.453 becomes 2.5 to two significant figures.

D.5.7.3. When two or more figures are to the right of the last figure to be retained, they are to be considered as a group in rounding decisions. Thus in 2.4(501), the group (501) is considered to be >5 while for 2.5(499), (499) is considered to be <5.