ASHRAE2011-86098

Advancing Development of Hybrid Rooftop Packaged Air Conditioners: Test Protocol and Performance Criteria for the Western Cooling Challenge

Jonathan Woolley
ASHRAE Member

Mark Modera
ASHRAE Member

ABSTRACT

The Western Cooling Challenge is a multiple-winner competition that invites manufacturers to develop and commercialize the next generation of rooftop packaged air conditioners appropriate for dry western United States climates. Certification centers on requirements for sensible energy efficiency at two separate test conditions that are representative of western climates. Criteria for minimum energy and water use efficiency were developed based on the estimated performance of market-available retrofit solutions for conventional rooftop package units; thus it is expected that comprehensive ground-up system designs should easily achieve the performance requirements. This paper outlines and discusses the development of the test protocol and performance criteria for the Challenge. The choice of laboratory test conditions is discussed. The rationale for and calculation of performance metrics including nominal cooling capacity and credited cooling capacity are presented. Additionally, the assumptions underlying requirements for minimum sensible energy efficiency are summarized, and key non-performance-based criteria for the program are explained.

INTRODUCTION

The Western Cooling Challenge (WCC), hosted by the Western Cooling Efficiency Center (WCEC) at the University of California Davis, is a multiple-winner competition that encourages HVAC manufacturers to develop and commercialize rooftop packaged air conditioning equipment for dry climates that will reduce electrical demand and energy use by at least 40% compared to DOE 2010 standards. The units in design, testing, and demonstration are all some variation of a hybrid system that couples indirect evaporative cooling with high efficiency vapor compression. In such a configuration, each component can operate either independently or in unison based upon ambient conditions and cooling demand. In addition to a number of non-performance-based requirements, WCC certification requires that equipment meet stringent criteria for sensible energy efficiency and water use. Such performance must be proven through WCEC-observed laboratory tests at two outdoor air conditions that were chosen as surrogates for peak-day design and average cooling-season conditions in hot-dry climates of the Western United States. The Challenge was developed in part by encouragement from large retailer affiliates of the WCEC who are aggressively pursuing energy efficiency in their buildings and who would install very high efficiency hybrid equipment en masse if the technology was well proven, commercially available, and cost effective.

The Western Cooling Challenge criteria were developed in such a way that incremental improvement to a conventional vapor compression cycle could not meet energy performance requirements. However, the Challenge was designed such that conventional HVAC equipment could qualify with the addition of commercially available add-on evaporative technologies. Although the intent was to encourage manufacturers to develop and commercialize hybrid units that integrate these efficiency-improving components into a single package, partnerships between manufacturers to submit high-efficiency conventional rooftop units with add-on evaporative components was allowed and encouraged because ground-up design requirements would discourage major manufacturers.

Jonathan Woolley is an Associate Research Engineer with the Western Cooling Efficiency Center at the University of California, Davis. Mark Modera is Professor Civil and Environmental Engineering and Director Western Cooling Efficiency Center at the University of California, Davis

As of August 2010, one entry had been laboratory tested for the Challenge by the National Renewable Energy Laboratory (NREL). The system, referred to herein as a WCC Type 1 Hybrid, uses a Maisotsenko cycle indirect-evaporative heat exchanger in series with a vapor compression system. The system includes a number of energy-efficient components and control strategies, and demonstrated performance well beyond the Challenge requirements. Evaluation of the laboratory results indicate that at the WCC annual test conditions, the system can achieve a COP for sensible space cooling of more than three times that of conventional equipment meeting DOE 2010 efficiency standards. The sensible space cooling capacity at this level of performance is much lower than the nominal capacity, but even operating at full capacity under these conditions the WCC Type 1 Hybrid has a COP for sensible space cooling that is more twice that of standard equipment.

WESTERN COOLING CHALLENGE REQUIREMENTS, TEST POINTS, AND PERFORMANCE CRITERIA

Non-performance based requirements

The intent of the Western Cooling Challenge is to push beyond prototype high-efficiency cooling equipment by advancing the market introduction of fully-commercialized equipment. Thus, although the Challenge focuses on energy and water-use efficiency, it also includes a number of non-performance-based requirements. Most importantly, in order to qualify, a manufacturer must demonstrate the capacity to produce a minimum of 500 units per year. In this way, participants are challenged to develop commercialized products. They must consider design factors such as cost-effectiveness, robustness, longevity, availability of replacement parts, accessibility for maintenance, and non-energy code compliance. Further, they must be prepared to provide marketing, documentation, warrantees and support for the products.

The Challenge also specifies that equipment must self-detect and communicate performance degradation, and must respond to line-voltage droop without increasing current draw on the electrical grid. These requirements were included to address specific customer and utility problems associated with air conditioners.

Many rooftop units consume more energy than they should merely because of poor maintenance. The root of degraded performance is often not easily identifiable and will generally go unnoticed by the customer, resulting in poor energy efficiency that may persist for the life of the equipment. An emerging solution to tackle this problem is the inclusion of some form of fault detection diagnostics on each rooftop unit. The appropriate method to effectively detect and report faults or poor energy performance is ambiguous, but a requirement to include such capabilities in all new rooftop package units is under consideration for the California Building Energy Standards and is included as criteria for the Challenge.

In response to concerns from California electric utilities about overloaded electrical grids, the Challenge requires that systems respond to voltage droop and power outages in a way that isn’t unduly aggravating to an already overdrawn grid. Fan motors and compressors should not draw additional current when line-voltage is low, and must have the ability to restart in a way that minimizes startup stress on the grid.

Other requirements that would improve overall energy efficiency were considered, such as criteria for fan energy use, but ultimately the performance criteria were limited in part to maintain simplicity, and to in part to allow standard packaged units to compete by focusing simply on retrofit evaporative components.

Laboratory Test Conditions

Western Cooling Challenge certification of a machine centers on steady-state sensible energy efficiency at full capacity operation, with 120 *cfm/nominal ton* (16.1 *L/s-nominal kW*) ventilation rate, [external resistance that would produce] 0.7 *Inches WC* (174 *Pa*) external static pressure [at 350 *cfm/nominal ton*], at two different outdoor psychrometric conditions. The laboratory test protocol, described in Table 1, was designed roughly around conditions in a large retail facility. The two outdoor conditions were chosen to represent peak-day design conditions and average cooling-season conditions for cooling intensive regions in the Western United States. For both tests, the equipment must provide a minimum outside air ventilation rate of 120 *cfm/nominal ton* (16.1 *L/s-nominal kW*). This ratio was derived from two rough metrics for air conditioner sizing:

1. An outside air flow of 0.2 *cfm/ft²* (1.02 *L/s-m²*)– the California Energy Code (Title 24) required ventilation rate for retail stores
2. An installed cooling capacity of 600 *ft²/nominal ton* – an approximate design point for large retail facilities in CA Climate Zone 12 (Sacramento CA). Note that normalized cooling capacity varies significantly by climate zone and building type between 300 *ft²/nominal ton* (7.92 *m²/nominal kW*) and 800 *ft²/nominal ton* (21.1 *m²/nominal kW*)

~~Requirements for the Challenge also specify a full capacity test at AHRI 340/360 standard rating conditions for units that can operate with zero percent outside air. There are no WCC minimum energy performance criteria for this test, but it is used to determine the nominal system capacity. The protocol for evaluating the nominal capacity of systems that cannot operate at 0% outside air, such as the certified WCC Type-1 Hybrid, is described in a later section.~~

Table 1. Western Cooling Challenge Laboratory Test Conditions

	~~AHRI 340/360 Conditions~~	WCC Peak Conditions	WCC Annual Conditions
Outside Air Condition *Tdb°F/Twb°F (°C)*	~~95/75 (35/23.9)~~	105/73 (40.6/22.8)	90/64 (32.2/17.8)
Return Air Condition *Tdb°F/Twb°F(°C)*	~~78/67 (25.6/19.4)~~	78/64 (25.6/17.8)	78/64 (25.6/17.8)
Outdoor Ventilation *cfm/nominal-ton (L/s-kW)*	~~0~~	120 (16.1)	120 (16.1)
External Static *In WC (Pa)*	~~0.2-0.75 (50-187)~~	0.7 (174)	0.7 (174)

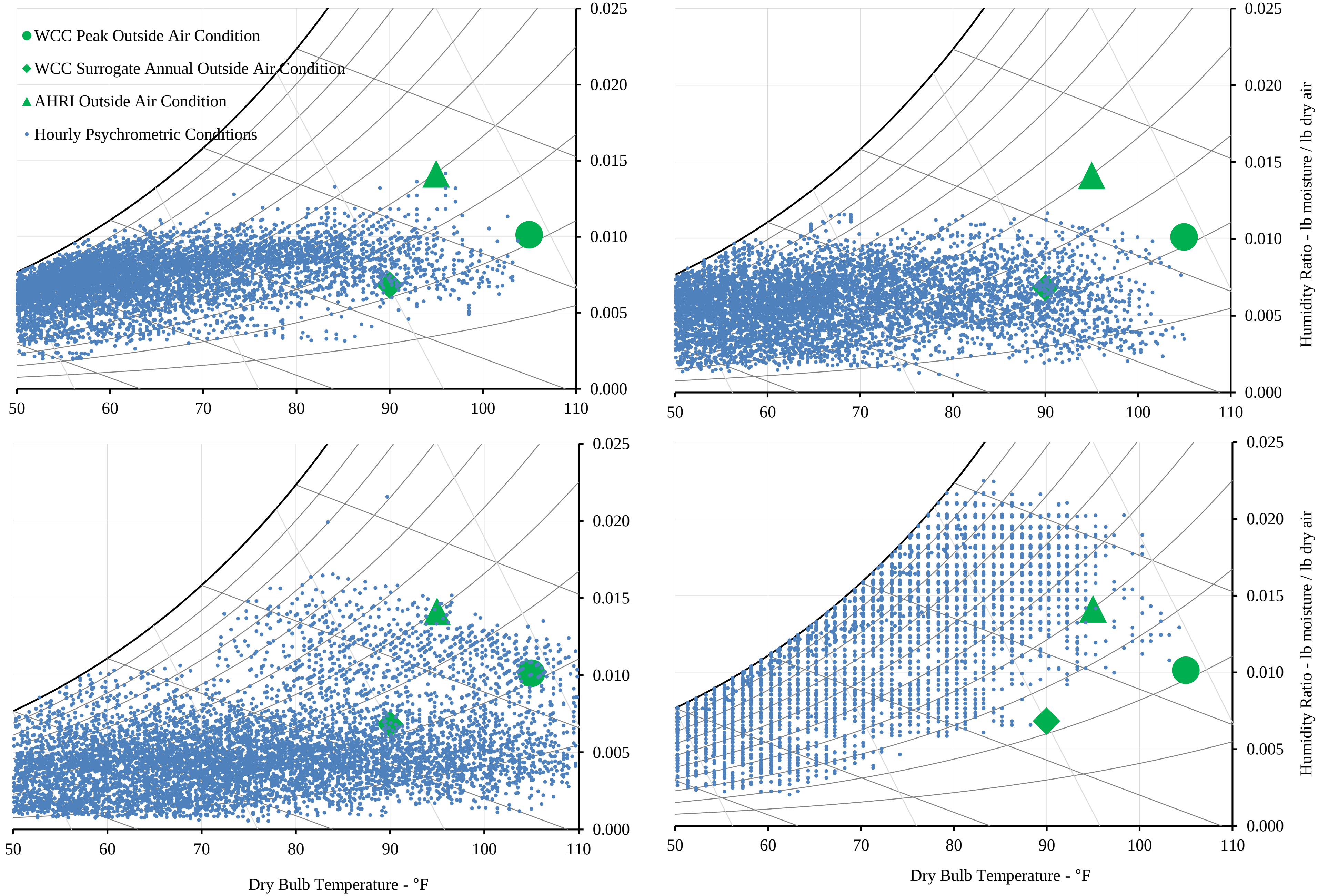
Figures 1–3 each plot the ~~three~~ [Cooling Challenge] outdoor-air test conditions, [and the conventional AHRI outdoor-air test condition] alongside a scatter-plot of the hourly psychrometric conditions from typical meteorological years in three different California Climate Zones. For comparison, Figure 4 plots the same for Baton-Rouge Louisiana. It is worth noting that the WCC peak conditions are generally more demanding on evaporative equipment than the 0.4%-occurrence design conditions for most western climates. Locations with design conditions at or above 105 *°F* (40.6 *°C*) Tdb typically have mean coincident wet-bulb temperatures much lower than the WCC peak condition; locations with design conditions at or above 73 *°F* (22.8 *°C*) Twb have significantly lower mean coincident dry bulb temperature. It's also clear from Figures 1-4 that AHRI 340/360 standard rating conditions are generally not representative of the cooling-intensive California climates.

Determining Credited Cooling Capacity

The test protocol for the Challenge was designed to evaluate system performance while operating with 120 *cfm/nominal ton* (16.1 *L/s-nominal kW*) outside air. For systems that have a minimum outside air fraction that exceeds 120 *cfm/nominal ton* (16.1 *L/s-nominal kW*), the WCC calculates a credited cooling capacity that does not count the cooling and dehumidification of additional outside air to return air conditions. This is important because it allows capacity and energy efficiency to be compared fairly between units even if they operate at different ventilation rates. If the correction were not made, the sensible capacity and energy efficiency of a system operating with 100% outside air would be misrepresented since it would include cooling of excess ventilation air. The following equations describe calculation of several metrics used to characterize WCC equipment:

$$\dot{H}_{space} = \dot{V}_{SA} \cdot \rho_{SA} \cdot (h_{RA} - h_{SA})$$

$$\dot{H}_{ventilation} = \dot{V}_{SA} \cdot \rho_{SA} \cdot \big((OAF \cdot h_{OA} + (1 - OAF) \cdot h_{RA}) - h_{RA}\big)$$



Figures 1-4 *Western Cooling Challenge Outside Air Test Conditions and Typical Meteorological Conditions for (from upper left to bottom right) California Climate Zones 12, 11, 15, and Baton Rouge Louisiana*

$$\dot{H}_{credited\ ventilation} = \dot{V}_{SA} \cdot \rho_{SA} \cdot \left(\left(\frac{120 \cdot nominal\ capacity}{\dot{V}_{SA}} \cdot h_{OA} + \left(1 - \frac{120 \cdot nominal\ capacity}{\dot{V}_{SA}} \right) \cdot h_{RA} \right) - h_{RA} \right)$$

$$\dot{H}_{system} = \dot{H}_{space} + \dot{H}_{ventilation}$$

$$\dot{H}_{credited} = \dot{H}_{space} + \dot{H}_{credited\ ventilation}$$

Figure 5 shows the various metrics for describing system capacity. It is important to note that $\dot{V}_{SA}$ is used as the normalizing flow rate for both the figure and for the proceeding equations. Thus the ventilation cooling and credited ventilation cooling are calculated using specific enthalpy differences between theoretical mixed-air conditions and return-air conditions, not between outdoor air conditions and return air conditions. Also, note that the minimum energy efficiency criteria for the Challenge are based only on the sensible component of the credited cooling capacity described here.

Determining nominal capacity

Nominal capacity of a system is typically determined at AHRI standard rating conditions. For the Challenge this nominal value is used to determine the credited ventilation cooling, the sensible credited cooling capacity, and thus the sensible credited EER by which a unit qualifies for certification. However, since the AHRI test occurs with 0% outside air and some hybrid equipment will have a non-zero minimum outside air fraction, the Cooling Challenge [uses] ~~includes~~ an alternate method to determine nominal capacity that uses measured performance from full-capacity operation under WCC peak conditions. This alternate nominal capacity is determined by:

$$\dot{H}_{nominal} = \dot{V}_{SA} \cdot \rho_{SA} \cdot (31.5 - h_{SA})$$

where 31.5 is the specific enthalpy of return air for AHRI nominal capacity tests. This metric is plotted for reference purposes in Figure 5. The method uses the enthalpy difference between return air and supply air to discount the capacity for cooling ventilation air and count only the space cooling delivered. This effectively scales the capacity measured under WCC peak conditions to a value that represents operation with 0% outdoor air, as in an AHRI test scenario. However, it does not represent space cooling capacity under AHRI outdoor air conditions, nor does it represent an actual space cooling capacity that would be achieved under any particular condition since the measurements are taken during full capacity operation at WCC peak conditions and the results are mingled post factum with the enthalpy value of AHRI return air.

The space cooling capacity of WCC equipment tested at AHRI outdoor air and return air conditions would be different than if tested at WCC peak conditions, and such a metric would not provide a fair basis for determination of what size conventional equipment could be replaced by a hybrid machine in western climates. For example, a conventional machine that has a nominal space cooling capacity of 60 *kbtu/h* (17.6 *kW*) at AHRI standard rating conditions might only have 43 *kbtu/h* (12.6 *kW*) sensible space cooling capacity, and this would slip to less than 30 *kbtu/h* (8.8 *kW*) with 30% outdoor air at WCC peak conditions. On the contrary, hybrid equipment could have a higher sensible space cooling capacity at WCC peak conditions than at AHRI standard rating conditions. Laboratory results indicate that under WCC peak conditions, the WCC Type 1 Hybrid equipment provides as much sensible space cooling as a conventional unit that has a significantly higher capacity at AHRI test conditions. Thus, using a nominal capacity determined at AHRI outside air conditions would misrepresent the effective cooling capacity for hybrid equipment in western climates. The lower nominal capacity would also result in a lower credited ventilation rate that would confound comparison of WCC equipment at the 120 *cfm/nominal-ton* (16.1 *L/s-nominal kW*) operating point.

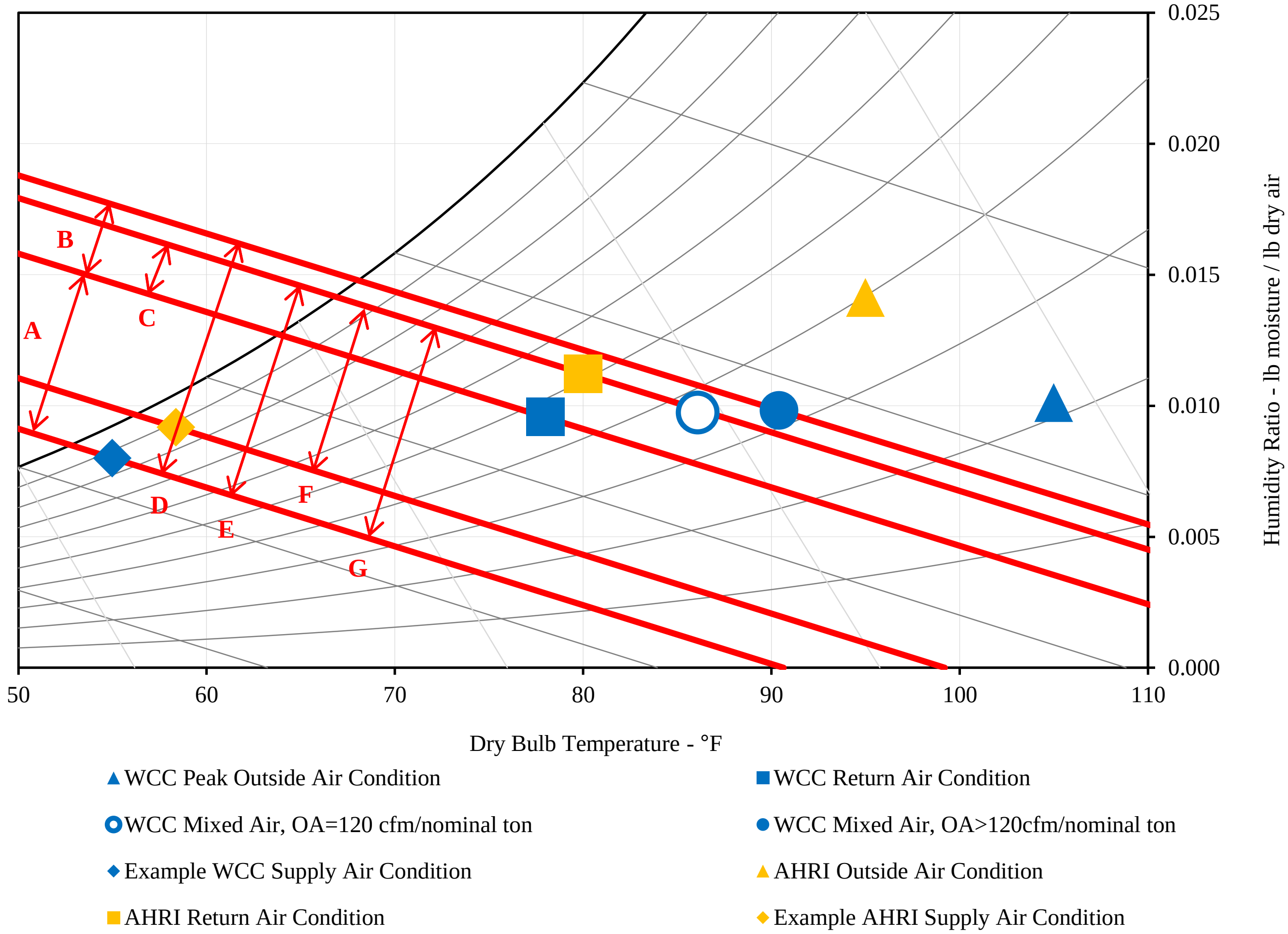


Figure 5 *Psychrometric chart illustrating the capacity metrics used to evaluate performance of WCC entries.* $A=\Delta h_{space}$, $B=\Delta h_{ventilation}$, $C=\Delta h_{creditedventilation}$, $D=\Delta h_{system}$, $E=\Delta h_{credited}$, $F=\Delta h_{AHRI\text{-}nominal}$, $G=\Delta h_{WCC\text{-}nominal}$

Performance Criteria

The minimum sensible energy efficiency criteria for each test condition in the Challenge was developed by estimating the performance that should be achieved for a 20-*ton* high-efficiency conventional rooftop unit that was retrofitted to be a Type-2 Hybrid by means of two additions:

1. Evaporative pre cooling of the condenser air, and
2. Indirect evaporative cooling of the ventilation air using the sump water from the condenser pre-cooler, by pumping the water through a water-air heat exchanger.

Estimates for the electrical demands of compressors, condenser fans, indoor blower, and auxiliaries were developed using manufacturer's published data across a range of air flow rates and temperature conditions. It was assumed that direct evaporative pre cooling of condenser air achieved 85% wet bulb effectiveness, that both the condenser air and sump water were cooled to 85% of the wet-bulb depression, that the water-air heat exchanger had a 60% heat transfer effectiveness, that

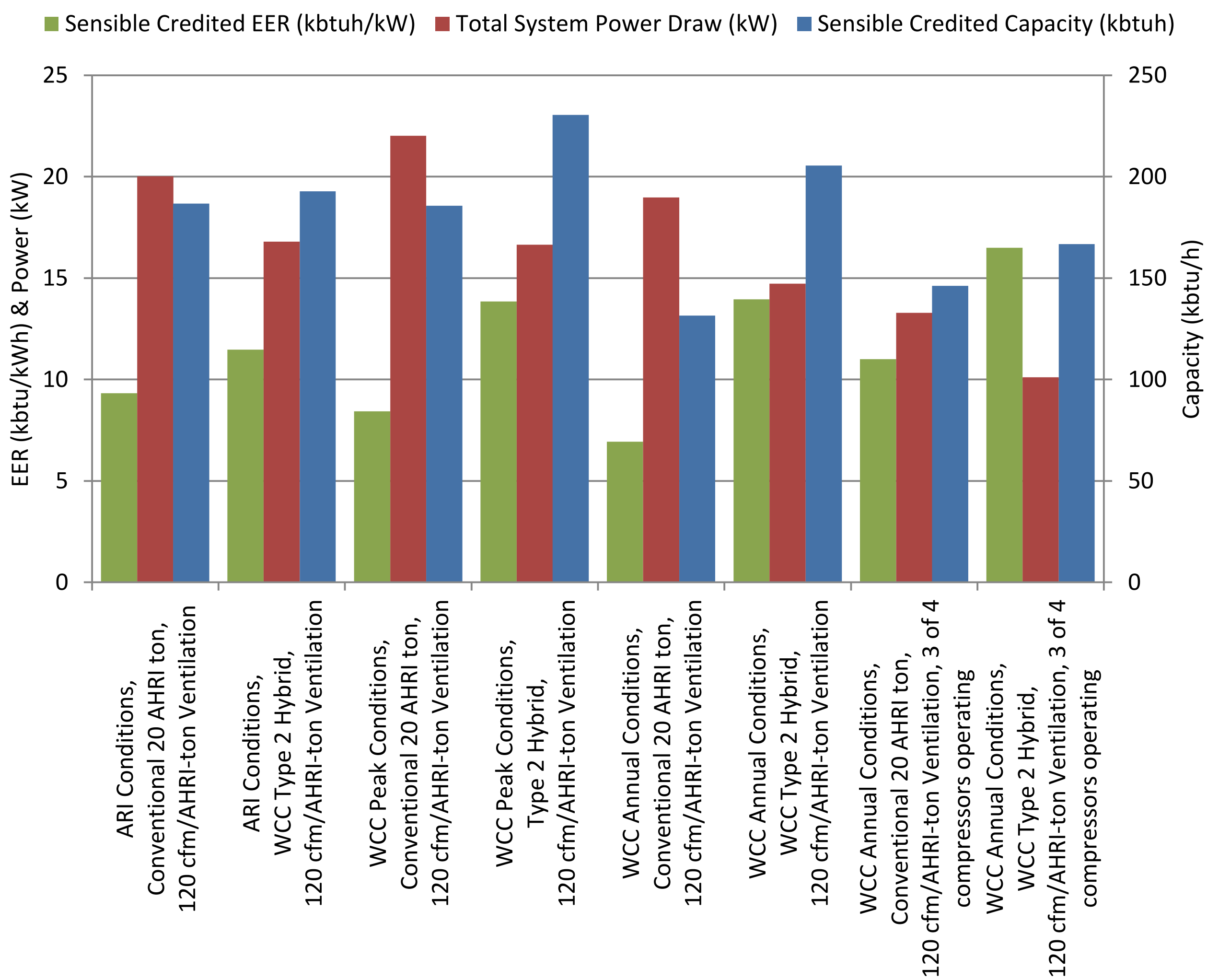


Figure 6 *Results of Estimates for Basis of Western Cooling Challenge Energy Performance Criteria*

the water-air heat exchanger in the indirect air stream increased the external static pressure seen by the indoor blower by 0.1 *in WC* (25 *Pa*), and that the pump for circulating water though the indirect coil consumed 0.2 *kW*. The key results from this analysis are presented in Figure 6

Table 2. Minimum Performance Criteria for Western Cooling Challenge

	Western Cooling Challenge Peak	**Western Cooling Challenge Annual**
Outside Air Condition *Tdb°F/Twb°F (°C)*	105/73 (40.6/22.8)	90/64 (32.2/17.8)
Return Air Condition *Tdb°F/Twb°F (°C)*	78/64 (25.6/17.8)	78/64 (25.6/17.8)
Outdoor Ventilation *cfm/nominal-ton (L/s-kW)*	120 (16.1)	120 (16.1)
External Static *In WC* (*Pa*)	.7 (174)	.7 (174)
Minimum Sensible Credited Capacity *% of nominal*	95%	80%
Minimum Sensible Credited EER *kbtu/kWh* (COP)	14 (4.1)	17 (5.0)
Maximum Water Use *gal/nominal-ton-hr* (*L/kJ*)	NA	4 (.24)
Maximum Supply Air Humidity *lb/lb* or *g/g*	.0092	.0092

CONCLUSION

The Western Cooling Challenge encourages manufacturers to reach for aggressive energy performance targets that would save at least 40% on energy and demand for cooling in western climates. Criteria for the program were developed in such a way that incremental improvement to a standard vapor-compression system would likely not suffice. However, the minimum performance requirements were developed so that achieving the required sensible credited EER of 14 at WCC peak conditions (Tdb=105°F/Twb=73°F) and 17 at WCC annual conditions (Tdb=90°F /Twb=64°F) is technically achievable with the addition of commercialized retrofit components on standard package rooftop units. In many ways, the Challenge can be thought of as a program to overcome organizational hurdles related to commercialization of an appropriate product, more than as a contest to encourage technical innovation.

NOMENCLATURE

$\dot{H}$	=	Cooling capacity (*kbtu/hr*)
Δh	=	Specific cooling capacity (*btu/lb dry air*), where $\Delta h = \frac{\dot{H}}{\dot{V}_{SA} \cdot \rho_{SA}}$
$\dot{V}$	=	Volume flow rate (*Standard- ft^3/min*)
ρ	=	Density (*lb dry air/ ft^3*)
h	=	Specific enthalpy (*btu/lb dry air*), where $h = 0$ at 0°F
OAF	=	Outdoor air fraction (-)

SUBSCRIPTS

SA	=	Supply air
RA	=	Return air or indoor air
OA	=	Outside air
MA	=	Mixed air (*defined by the hypothetical psychrometric mixture of OA and RA flows used for SA, regardless of whether or not such mixture occurs*)

REFERENCES

ASHRAE. 2009. ASHRAE Handbook-Fundamentals. Atlanta: American Society of Heating Refrigeration and Air Conditioning Engineers, Inc.

Kozubal, E. Slayzak, S. Coolerado 5 Ton RTU Performance: Western Cooling Challenge Results. Technical Report NREL/TP-550-46524. National Renewable Energy Laboratory. September 2009.

Lennox. Engineering Data for Strategos Packaged Gas/Electric Rooftop Units. Bulletin No. 210491. June 2009.

York. Technical Guide for Predator ZH/ZJ Series Rooftop Units. Johnson Controls Unitary Products. 528150-YTG-E-0510. August 2010.