Field Testing of Commercial Rooftop Units Directed at Performance Verification

David Robison, Stellar Processes
Reid Hart, Portland Energy Conservation, Inc.
Will Price, Eugene Water & Electric Board
Howard Reichmuth, New Buildings Institute

ABSTRACT

In Northwest DSM planning, malfunctioning packaged roof top units (RTUs) are recognized as the largest retrofit commercial efficiency opportunity, after commercial lighting efficiency. Previous monitoring has demonstrated that tune-up adjustments to existing packaged systems may pass checkout procedures but fail to correct performance errors. In particular, economizer controls failed to operate when expected, even after proper adjustment procedures were followed. Results from two investigations sheds light on why outdoor air economizers do not work as expected.

The electronic economizer controller with the largest installed market share was tested in a set of environmental chambers. Testing showed that these dry-bulb sensors—in conjunction with the economizer controller module—fail to meet manufacturer's specifications, significantly reducing hours of economizer operation during late spring through early fall. A low-cost work-around solution is demonstrated.

Beyond sensor and controller accuracy issues, outdoor air sensor placement can significantly affect economizer operation. Several sensor mounting options were tested outdoors, including under-hood sensor insulation options and mast mounting with various low-cost shields. Data collected from the various sensor placements and treatments is analyzed to determine preferred treatments for accurate outside air measurement.

Understanding the actual operation of popular economizer controllers and the impacts of outdoor air sensor location can lead to an improved method for installing and retrofitting these controls today and can lead the industry toward providing better controllers in the next generation of rooftop units.

Introduction

Throughout the United States, 40% of commercial building space is served by unitary packaged rooftop HVAC units. In the Pacific Northwest, 117 MWa of potential conservation have been identified in commercial HVAC retrofits (NPCC 2005). The principal conservation benefit is from an economizer using cool outdoor air for space cooling instead of mechanical cooling when conditions permit. However, existing packaged unit controls have been found to be unreliable and ineffective, with a cross section of studies showing operational problems with 64% of outdoor-air economizers (Cowan 2004). These HVAC units are numerous in small commercial buildings, but conservation options have been difficult to justify due to the costs necessary to optimize these systems. Previous investigations have attempted to quantify the savings from repair of existing packaged HVAC units. Unfortunately, detailed monitoring has revealed that repairs to economizers, even if carried out according to manufacturers' procedures, are often ineffective (EMI 2004).

There are several requirements for effective economizer operation, including proper damper adjustment and movement, good damper seals, proper integration of the economizer with mechanical cooling, and correct changeover (Hart, Morehouse & Price 2006). The outdoor temperature at which the economizer is disabled is referred to as the nominal changeover temperature. Above this temperature, only mechanical cooling is used. If the economizer is disabled at too low a temperature, many hours of integrated economizer operation can be lost. If disabled at too high a temperature, then energy is wasted through cooling outdoor air that is warmer than return air. This paper focuses on changeover issues, especially as related to correct measurement and response to outdoor air temperature.

Changeover is, in fact, based on two temperatures. A maximum temperature switches operations to mechanical cooling and a minimum temperature "resets" the controls into economizing mode. If the deadband differential between these two is too wide, the outdoor temperature must drop significantly before the economizer is re-enabled. This control error is referred to here as control "hysteresis." Monitoring studies indicated that this hysteresis effect prevented economizing during warm summer months in mild climates because the nighttime temperatures were not low enough to re-enable economizing. That is, even though the outdoor temperature was below the nominal changeover temperature, the controller still did not use outdoor air for cooling when there was a call for cooling from the thermostat. The same problem was not observed in climates with a larger diurnal temperature swing and colder night temperatures. In 2004, a committee of experts developed an advanced rooftop unit (ARTU) specification and noted in Feature # 1-07 "Economizer controller will utilize a deadband between economizer enable/disable operation of no greater than 2°F in a dry-bulb temperature application" (AEC 2005). The rationale behind this recommendation is to minimize the energy wasted during the changeover interval.

In addition, an earlier study noted inaccuracies in outdoor air temperature measurement due to poor sensor placement (Hart, Morehouse & Price 2006). Incorrect outdoor air temperature measurement can reduce economizer savings by limiting economizer action when it would be beneficial or by allowing economizer operation when it results in increased cooling energy use. In this paper, we discuss two separate studies to identify procedures to improve controls and sensor placement within current field repair and economizer upgrade programs.

Economizer Control Issues

The purpose of the controls investigation was to test a typical controller system, identifying the extent to which hysteresis or poor sensor calibration might limit full operation, and to develop and test a "work-around" solution as part of the development of a field service protocol. This task has been limited to testing the controller apparatus within a set of controlled environmental chambers in order to quantify the problem and verify the potential solution. The observations are of dry-bulb economizer control operations as observed in an indoor test chamber. This type of economizer operation is important in the Pacific Northwest and Rocky Mountain areas where humidity is generally low.

A preliminary task in this study reviewed available field data to identify the most commonly used control items. Characteristics data collected as part of the Puget Sound Energy (PSE) Premium Service Rooftop program represented a fairly large set of data expected to be typical of installations in the Northwest. Out of 223 systems with economizers, the following characteristics were noted:

- 70% of the systems had the controller that we selected for testing
- 60% had at least one of the following problems:
    - 41% used enthalpy sensors with unknown drift and calibration, although only dry-bulb sensing is necessary in our climate.
    - 56% had only a single stage of cooling wired, which significantly curtailed economizer use.
- 73% used a single changeover point (one outdoor sensor and no return air sensor), 27% used a differential changeover strategy (both outdoor sensor and return air sensor installed).

One manufacturer has provided the basic controller used throughout the last several decades by most HVAC manufacturers –with about 70% market share. This is the controller unit selected for testing.

The bench testing was done in test chambers set up specifically for this purpose. The initial bench tests were intended to reveal the specific operation of the most common older control system and are not necessarily representative of newer and less common systems. Two controllers and four temperature sensors were purchased for testing purposes. Eugene Water & Electric Board (EWEB) staff also provided a number of used sensors from classroom demonstrators. The test equipment recorded the position of the economizer actuator arm and the status of an LED which indicates when outdoor air is suitable to provide cooling (based on nominal changeover temperature selected). Both are conditions that indicate the controller is operating in economizer mode. These conditions agreed closely with each other – typically the actuator arm moved within a few seconds of the indicator light. It must be mentioned that early measurements failed to provide sufficient time for sensors to equilibrate after a temperature change. We found that sensors take up to 12 minutes to equilibrate to a 1ºF change. We allowed a full hour for equilibrium to occur when recording the control point of a specific setting and sensor.[1]

The manufacturer's documentation of the expected performance is sparse. The manufacturer's cut sheet for sensors indicates that control operations were expected to follow a linear response to outdoor temperature. This manufacturer's specification is referred in this report as the "reference". Of course, the reference operation also depends on the installer-adjusted changeover control points (as indicated by A, B, C, D settings on the controller). Accordingly, an overall control test protocol was devised that treated the sensor/controller pair as a single component.

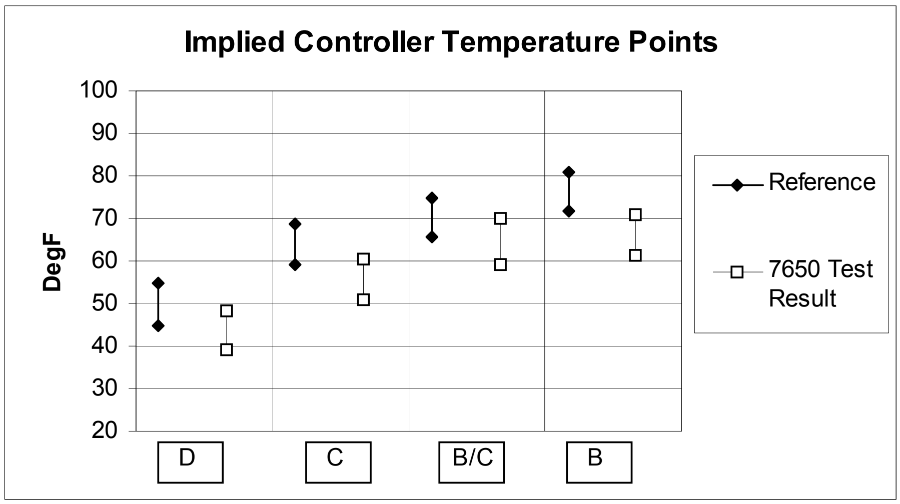
Figure 1 shows the response of one typical sensor at different controller setpoints. Notice that all the test results are biased lower than the specified reference. For example, at setting B/C, economizing is expected to occur within the range of 65 to 75ºF ambient temperature. In fact, the operation occurred within a range of 59 to 70ºF. The result is a

---

[1] The reference temperature was measured using calibrated Maxim/Dallas Semiconductor DS1920 digital sensors with specified accuracy is 0.9ºF (typical samples are much closer than that over normal air temperature ranges) and resolution of 0.03ºF. The practical precision limit is the control deadband inherent in control of the environmental chamber. This temperature averages within +/- 0.1ºF. The sensor readings reported here are the average of multiple trials with a typical standard error of 0.25ºF or 95% confidence limit of +/-0.8ºF.

constraint on economizing operation. Using this example at setting B/C, night temperatures will have to fall to below 59ºF so that economizing will take place the next day. Obviously, this rules out economizing during much of the summer in a mild climate. Thus, even such a small error can result in a serious reduction of economizing. The test results agree with previous field monitoring that showed ineffective economizing in locations with warm night temperatures. An evident difficulty is that the installer, relying on the manufacturer's reference documentation, will not be able to select an appropriate setpoint due to the undocumented bias of the components, which appears to be variable among sensors.

Figure 1. Test of Controller Settings



The controllers are typically shipped from the factory at setting D. Figure 1 demonstrates that this setting is likely to assure minimal economizing – only when outdoor air is quite cool. However, cooling loads are likely to be minimal under such conditions. A previous study based on simulation modeling estimated savings of about 0.5 kWh/sqft-yr due to changing the starting changeover of 55ºF to 65ºF (Davis, 2002). As a result, the repair programs have recommended that installers change the setting to B or C. Based on PSE program data, installers are following that recommendation and typically adjust the setting to midway between B and C. Accordingly, B/C was used as the typical setting for subsequent testing. Even so, Figure 1 demonstrates that this setting is far from ideal and will not necessarily provide optimal economizer operation. Optimal operation would require that economizing occurs whenever outdoor air is cool, without waiting for outdoor air to reach the minimum or "reset" temperature.

Figure 2 shows how several sensors performed at a B/C controller setting. Since the sensors are variable, it is difficult to suggest a compensating offset to the installation technician. Furthermore, such compensation would not solve the hysteresis problem. One observes relatively little difference between newly purchased and older sensors so calibration drift over time is not apparently a problem.

Figure 2. Comparison of Sensors

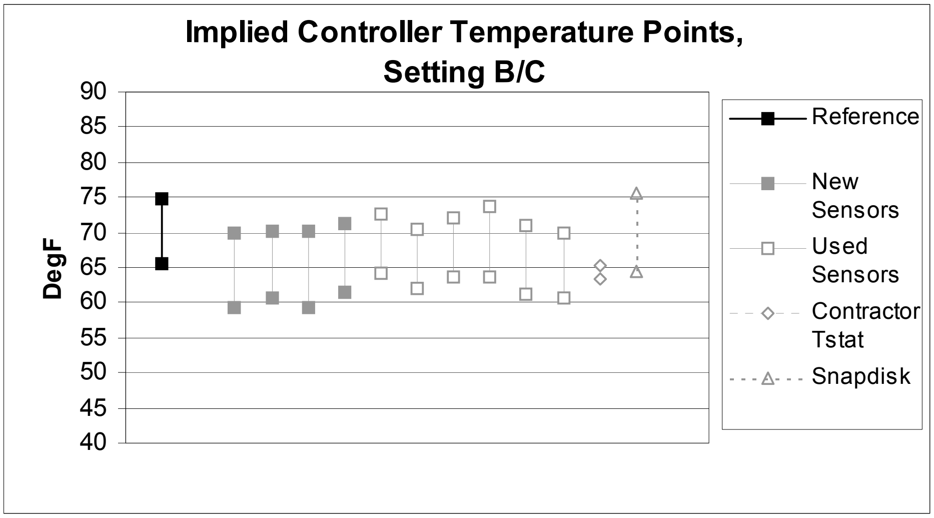


Figure 3. Alternative Thermostats

Given that the built-in hysteresis limits operation, one might ask if there is a "work-around" solution. The research team investigated the use of a simple thermostat (close-on-fall switch, cost <$10) to substitute for the outdoor temperature sensor. Two low-cost "contractor's thermostats" were tested and found to be equally accurate and repeatable. The thermostat will allow economizing whenever the temperature meets the range criteria without waiting for a "reset". Replacing the usual sensor with an on/off closure has the effect of providing a satisficing temperature input that overrides any control constraints. The closure switch is a possible workaround for the imprecision of the controller and sensors. Essentially, it bypasses the A/B/C/D settings and provides an on/off control instead. We tested another thermostat (snapdisk type, cost ~ $25) and found them to be highly repeatable and close to specifications. However, these are slightly more expensive and they still show a 10-degree deadband. Figure 2 shows the temperature control points for these options as well. Both the snapdisk and the contractor's thermostats provide a solution to the accuracy problem. But the best[2] choice is the contractor's thermostat that permits economizing when temperatures fall to 63ºF and below and continues until temperatures rise to 65ºF–the narrow deadband of this thermostat is preferred because it will increase the hours of economizing. Figure 3 shows these types of thermostats.

Outdoor Air Sensor Placement

An accurate outdoor air temperature measurement is important in proper economizer changeover. To evaluate options for sensor placement, a field test was conducted in Eugene, Oregon in the late summer of 2006 to determine the impact of various outdoor air sensor treatments using low cost shields or mounting techniques. Existing rooftop units with economizers and outdoor air hoods were retrofitted with calibrated sensors using different treatments. A reference aspirated outdoor air temperature was measured with a sensor installed on the same roof at about hood intake level inside a standard six-plate radiation shield with continuous fan aspiration. Eight different configurations of sensors were tested with additional treatments.[3] The sensor mountings tested are shown in Figure 4.

Tested Sensor Placement Configurations and Treatments

Sensors were tested placed both under hoods and in a mast configuration. Four mast configurations were tested and each of the masts had additional treatments added periodically during the test period. Once the foil was added to the mast configurations, it remained in place for the final two treatments. The under-hood sensors were tested with and without a foil wrap on two different packaged unit hoods serving offices in a utility equipment repair building. Configurations and treatments tested are shown in Table 1 with designations used in later tables.

To better match thermal lag and radiant characteristics of typical rooftop economizer sensors, calibrated[4] temperature probes were packaged in black plastic boxes of a similar size to typical commercial sensor packaging.

[2] While full discussion of various economizer configurations is beyond the scope of this paper, the "best" selection for sensor temperature range is configuration dependent. The nominal 60ºF or 65ºF thermostat is appropriate for an either/or changeover with a single-stage cooling thermostat. A two-stage cooling thermostat that allows economizer integration would benefit from a nominal 70ºF or 75ºF thermostat that allows more hours of economizer operation.

[3] For mast-mounted sensors, shields were fabricated from items purchased at a "dollar" store to emphasize the low cost concept.

[4] Temperature sensors provided with AEC micro data loggers were calibrated at a constant room temperature (72ºF) and in a water bath (51ºF). These temperatures represented the range of interest for economizer changeover. While all sensors were found to be within 0.8ºF of the selected reference sensor (closest to average), linear adjustment coefficients were developed for each sensor to match the reference exactly. Measured data were adjusted with the coefficients before analysis.

Figure 4: Sensor Mountings

Clockwise from left: Mast mounted sensors BH, BC, BV, BCS from left to right; Sensor mounting on PVC support; added white screen (inverted colander); under hood mounting from left to right: direct, air-gap, foam, bubble.

Table 1. Description of Sensor Placements and Treatments Tested

Designation	Description
Mast Configurations:	
BH	Mast-mount with a single bucket shield and a hole in the side of the bucket facing north.
BV	Mast-mounted with a single bucket shield and a top PVC vent, extracting air from a 'tee' in the PVC near the sensor (see "mounting on PVC support" photo in Figure 4).
BC	Mast-mounted with a top PVC vent and a 30-inch black ABS chimney to induce passive solar aspiration, extracting air from a 'tee' in the PVC near the sensor.
BCS	Mast-mounted with a top vent, black chimney, extracting air from a 'tee' in the PVC near the sensor with double nested white bucket shields.
Treatments added in successive order to mast sensor configurations (Foil is applied under hood also)	
+F	The black sensor case is wrapped in heavy-duty aluminum foil to reduce radiant heat effects. Applies to both mast and under-hood configurations.
+W	Solar gain is reduced adding a rigid white screen (inverted colander) over the bucket.
+B	Adding a black scrim (pet resistant insect screen) over the top of the white screen based on the theory that the heat absorbed by the black screen would induce a convection current, cooling the sensor.
Under-hood mounting configurations (All sensors mounted inside of the top of the outdoor air intake hood)	
direct	Sensor mounted directly to the inside of the top of the hood.
air-gap	Hood-mounted sensor with 3/8-inch standoffs to create an air gap between hood and sensor.
foam	Hood-mounted sensor with 1/2" R-2 foam insulation between sensor and hood.
bubble	Hood-mounted sensor with foil bubble insulation (advertised as R-4) between the sensor and hood.
Example designation of configuration with treatment	
BC+F+W	Mast-mounted with a top PVC vent and a 30-inch black ABS chimney with aluminum foil on sensor case and adding a white screen over the bucket top.

Testing Results and Observations

Testing results are shown for an August day for mast-mounted sensors (Figure 5) and hood-mounted sensors (Figure 6). The following observations can be made results for the mast-mounted sensors with the third treatment (foil wrap and white screen added) that have measured temperatures shown in Figure 5:

- Mast-mounted sensors had good agreement with each other and reported temperatures within 2.2ºF of the aspirated reference sensor when outside air is below 70ºF. In fact, mast sensor readings were so close; the lines are difficult to distinguish in Figure 5.
- The third treatment (foil wrap and white added screen) of mast-mounted sensors performed fairly well and similarly to each other.
- As the temperature rose above 75ºF, the sensors measured lower than the aspirated reference sensor. They were all located a few feet higher than the aspirated reference that was mounted at hood intake height. It is likely that the reference aspirated sensor was subject to a local elevated roof temperature effect due to stagnant air.
- The mast mounted sensors were all located on the top of a packaged unit and were exposed to condenser exhaust air. This is not recommended. Effects were removed from the statistical analysis by ignoring data when the condenser fan was on.

Figure 5. Mast-Mounted Sensors

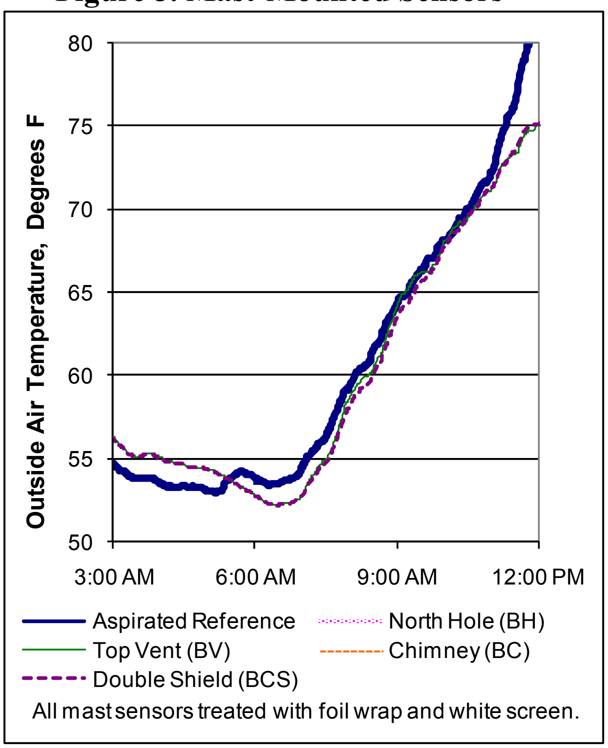
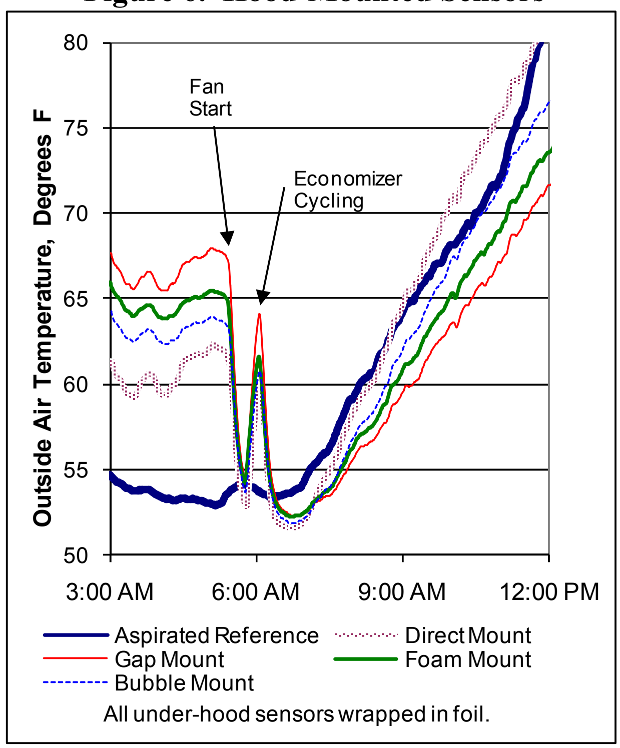


Figure 6. Hood-Mounted Sensors



On the same day, the foil-wrapped hood mounted sensors showed a much wider variation in readings, as seen in Figure 6. Multiple observations can be made from the hood-mounted sensor performance:

- Before the fan started at about 5:45 a.m. the temperature in the hood was several degrees higher than outdoor, probably due to air in the building exfiltrating through the unit at night. An important note is that the elevated temperature under the hood in the morning may lock out the economizer due to controller system hysteresis discussed earlier in this paper.
- The hood temperature drops several degrees as the damper opens, then increases several degrees as the damper closes. So, hood temperature is affected by the damper position.
- Once the damper re-opens, the direct-mount sensor is closer to the aspirated reference, but the air-gap-mount sensor provides a better measure of air temperature inside the hood.[5]
- Later in the morning, due to solar exposure, the direct mounted sensor registers higher than hood temperature and higher than the aspirated reference. The air-gap- and foam-mount sensors are closest to hood temperature, with the foam-mount being easier to install.
- The economizer operates during the entire period shown, even though air in the hood is too warm for effective cooling above 70ºF outdoor. The economizer was controlled by a DDC system, not the sensors being tested, and the OSA signal was from a remote sensor that was not impacted by solar loads; consequently the DDC OSA signal was about 5ºF to 10ºF lower than the rooftop air entering the economizer through the hood.
- The air in both hoods is generally measured at a lower temperature than both the aspirated reference and the mast sensors once the fan starts. This indicates the hood is getting cooled air drawn into it. On one unit, there is a power exhaust, and exhaust air will be drawn into the hood. On the other unit, there is no provision for exhaust or relief air. In both units, the lower temperatures inside the hood suggest that air cooled in the unit may be induced into the hood despite expected negative fan pressure, although further testing with flow measurement would be needed to verify this supposition.

Statistical Analysis

While the under-hood sensors are difficult to compare with the reference aspirated sensor due to the stagnant roof effect or cooled air being induced into the hood, the mast-mounted sensors can be compared directly to the aspirated reference at relatively cooler temperatures (48ºF to 72ºF) that are of interest in economizer change-over control. To eliminate the impact of condenser discharge, data are screened out when the cooling compressor is on. A small standard deviation and mean of the difference from aspirated reference to measured temperatures are good indicators of preferred treatment, as shown in Table 2. Based on these criteria, all configurations with the sensor wrapped in foil and a secondary white screen performed best.

[5] While a separate reference hood sensor was not installed, the better performance of the air-gap sensors can be inferred from the data, as this sensor has a higher temperature when the fan is off and warmer building is exfiltrating through the hood and has a lower temperature when the fan is on and there is solar gain on the hood.

Table 2. Comparison of Mast Treatment Temperature Differences to Aspirated Reference

Mean and Standard Deviation of degree F difference to aspirated reference for each configuration			Basic Configuration Without Treatment		*Added Treatments* Wrap Sensor Case in Foil (+F)		White Screen (+W)		Black Scrim (+B)	
Four configurations. Each has inverted bucket with:	Tag	Relative Cost	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
North Hole Vent	BH	$	2.4	5.0	**0.2**	2.3	**-0.6**	**1.6**	-2.0	2.4
PVC Top Vent	BV	$$	3.5	5.2	**0.7**	2.2	**0.3**	**1.5**	-1.3	2.4
Black Chimney	BC	$$$	2.6	4.7	**0.3**	1.9	**-0.3**	**1.3**	-1.5	2.4
Chimney + Shield	BCS	$$$$	1.4	4.2	**-0.2**	**1.5**	**-0.6**	**1.2**	-1.7	2.2
Number of readings per treatment, n			3960		641		2107		4423	
Average aspirated reference OSA, deg F			67.1		65.1		65.6		66.9	

Figure 7. Sensor Shield Configurations

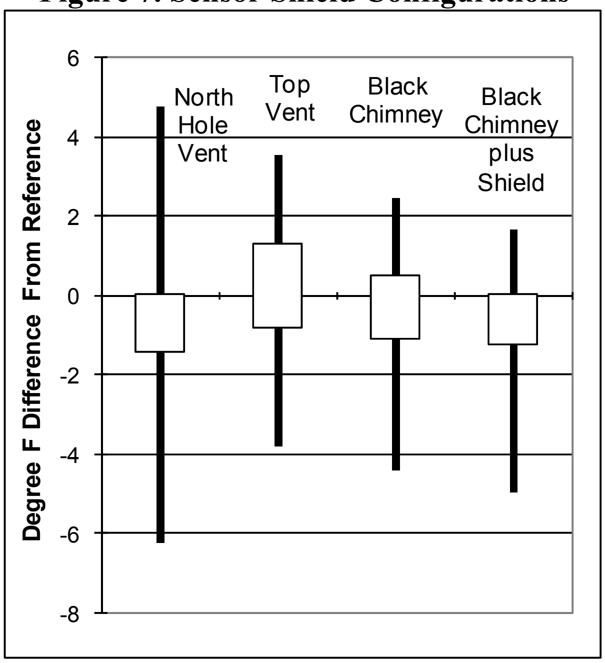
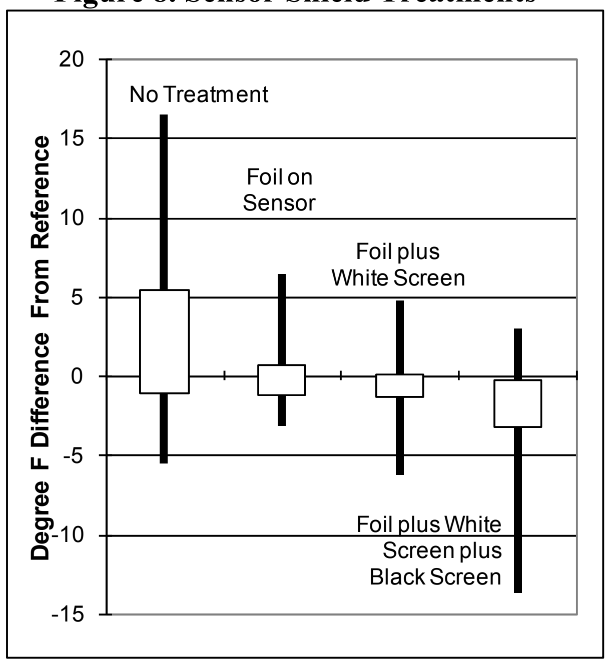


Figure 8. Sensor Shield Treatments



Note: Line indicates range of observations; box indicates middle two quartiles (50%) of observations. Observation is difference from six-plate shield aspirated sensor. Sensor shield configurations shown in Figure 7 are all with foil wrapped sensors and a white screen. Sensor treatments shown in Figure 8 are all for the basic configuration of inverted bucket with north hole vent.

The frequency and relative differences from the aspirated reference temperature for the different base configurations, all with foil and white screen treatments, are shown in Figure 7 with the difference between the screening treatments data shown in Figure 8. Wrapping the sensor package in foil significantly reduces the spread of differences to the aspirated reference temperature. A white screen added to the simplest bucket makes results acceptable without the complexity of adding a chimney. To verify differences between configurations and treatments, t-tests were completed on comparisons of interest with the following conclusions:

- For mast and under-hood sensor placements, the mean difference for foil covering compared to black sensor housings was found to be significantly different ($p<0.001$). The standard deviation was less for foil wrapping, indicating less variation.

- The four under-hood mountings with foil treatment on the unit without exhaust were compared with each other. They were all significantly different ($p<0.0001$).
- The mean differences between each of the four bare under-hood mountings was significantly different ($p<0.0001$) with the exception of the direct mount vs. the foiled bubble insulated ($p=0.24$).
- When all four treatments were compared on the same mast configuration, the mean difference to aspirated reference was significantly different ($p<0.0001$).
- The four mast configurations, all with foil and white screen were compared with each other. All were found significantly different ($p<0.01$), with the exception of the bucket with hole and the double shielded with chimney ($p<0.77$).

Sensor Placement Conclusions

The following conclusions about sensor placement can be made from this study:

- Under-hood sensor placement does not accurately measure the available outdoor air temperature, possibly due to inductions of cooled air into the hood. If measurement of the air inside the hood is desired, the sensor should be insulated from the hood surface to avoid solar effects. Insulation used in practice under hoods should be rated for use in ductwork, and duct lining material may be appropriate.
- Remote measured (DDC) outdoor air temperatures are inferior for economizer changeover control as they result in improper start or end of the economizer period.
- Superior control can be achieved with a separate sensor housing. A mast with a vented shield (inverted bucket) and a simple secondary screen can be used, but it must be placed to avoid condenser air discharge and avoid site damage. In actual production, UV resistant materials must be used for sensor shields.
- Sensor packages should be reflective or light colored rather than black to avoid radiant effects. A black sensor package results in excessive deviation from actual air temperature.

A simple hybrid of the tested items is a shielded and screened vented sensor mounted on the side of the hood. This will be simpler to install and will likely perform as well as mast options. It will not be subject to under-hood variations in temperature, but will measure the local temperature of air entering the hood, unlike a remote DDC sensor.

Conclusions

In the case of the economizer control system typical for older packaged rooftop units in the Pacific Northwest:

- Excessive control hysteresis inhibits proper economizer operation, even when the installer follows the recommended "tune-up" procedures. We have identified a low cost thermostat that may provide superior economizer operation and field tests will be conducted to verify the option.

- Improper sensor placement may interfere with operations, exacerbating the hysteresis problem. Improper placement may result in the sensor being artificially warmed by exfiltrating air or by solar radiation.

Acknowledgements

The design and set up of the testing chamber, testing of the components/systems, and initial data assessment was completed by Dennis Landwehr, P.E. Sensor placement data were analyzed by Travis Reeder, Eugene Water & Electric Board.

References

[AEC] Architectural Energy Corporation. 2005. "Project 4: Advanced Rooftop Unit Deliverable D4.3a – Final ARTU Product Definition Report." *Advanced Automated HVAC Fault Detection and Diagnostics Commercialization Program.* September 13, 2005. Sacramento, Calif.: California Energy Commission. www.newbuildings.org/mechanical.htm

Cowan, Alan. 2004. *Review of Recent Commercial Roof Top Unit Field Studies in The Pacific Northwest and California.* October 8, 2004. White Salmon, Wash.: New Buildings Institute.

Davis, R., Francisco, P., Kennedy, M. and Baylon, D. 2002. *Enhanced Maintenance for Small Package Rooftop HVAC Systems.* Prepared for Eugene Water & Electric Board. Seattle, Wash.: Ecotope Inc.

[EMI] Energy Market Innovations, Inc. 2004. *Small Commercial HVAC Pilot Program Market Progress Evaluation Report No. 1, 2004.* November 2004. Portland Oregon. Northwest Energy Efficiency Alliance. www.nwalliance.org/research/reports/135.pdf

Hart, R., D. Morehouse and W. Price. 2006. "A Premium Economizer – An Idea Whose Time Has Come." In *Proceedings of the ACEEE 2006 Summer Study on Energy Efficiency in Buildings*, 3:103-115. Washington, D.C.: American Council for an Energy-Efficient Economy.

[NPCC] Northwest Power and Conservation Council. 2005. *The Fifth Northwest Electric Power and Conservation Plan.* Portland, Oreg.: Northwest Power and Conservation Council. www.nwcouncil.org/energy/powerplan/plan/Default.htm