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Airside Economizers and ASHRAE Standard 90.1-2013

Previous ENs discussed the benefit and operation of an airside economizer—a device used to conserve mechanical cooling energy and reduce operating costs.

This EN reviews the economizer requirements of ASHRAE Standard 90.1-2013, *Energy Standard for Buildings Except Low-Rise Residential Buildings*, the newest version of the popular energy standard, with a focus on airside economizers.

Standard 90.1-2013 includes similar prescriptive requirements for both comfort cooling and computer room applications (see sidebar p. 7). In this newsletter, we'll focus on airside economizer requirements in comfort cooling applications.

The standard requires airside or waterside economizers for "individual fan-cooling units" greater than 54,000 Btu/hr (4.5 tons, 15.8 kW) for all climate zones except 1A and 1B (very hot-humid and very hot-dry, respectively) where the benefit of airside economizing would be limited. It does not suggest which type of economizer to use, however, the airside economizer must be capable of providing up to 100 percent of the design supply airflow as outdoor air for cooling.

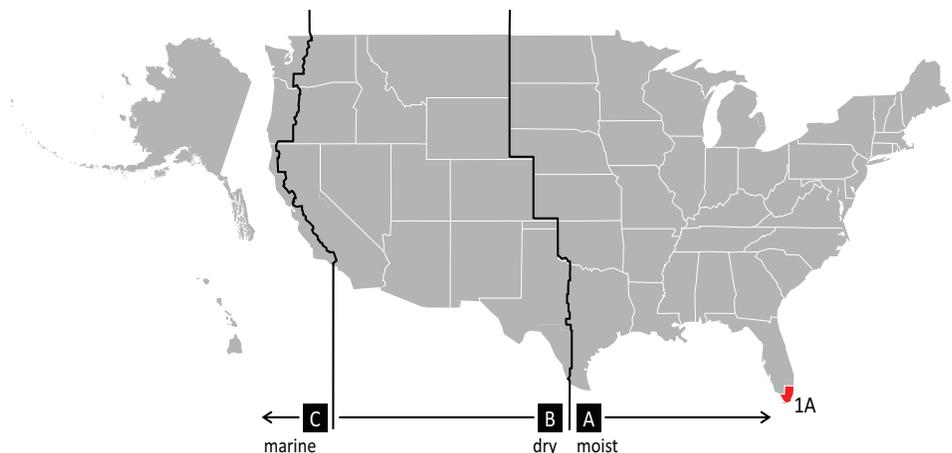
Figure 1 shows a map of the United States with climate zones requiring economizers in gray and the climate zone not requiring economizers in red (1A).

There are a number of exceptions to the economizer requirement (see sidebar p. 2). Standard 90.1 also describes allowable economizer control types and corresponding high-limit shutoff setpoints for various climate zones. Before we dive in, let's start with a definition.

What is a fan-cooling unit?

The standard uses the phrase *individual fan-cooling unit* to describe the type of system that should be evaluated to determine if an economizer is required. Put simply, an individual fan-cooling unit is a single cooling system that contains a fan. Examples of individual fan cooling units include air handlers, packaged rooftop units, water-source heat pumps, fan coils, and variable refrigerant flow (VRF) terminals. For distributed cooling systems, such as chilled-water fan coils or VRF, the Standard 90.1 *User's Manual* clarifies that the threshold applies to the individual fan coil or indoor VRF terminal, not to the total capacity of the central chiller plant or the outdoor VRF unit.

Figure 1. U.S. climate zones requiring economizers per ASHRAE Standard 90.1-2013



Economizer Exceptions.

Economizers are required for “each cooling system that has a fan,” however, there are a number of exceptions to this requirement. The following exceptions, for comfort cooling applications, are paraphrased from Standard 90.1-2013:

1. Individual fan-cooling units which have a cooling capacity less than 54,000 Btu/hr (4.5 tons, 16 kW).
2. Systems that require non-particulate air cleaning, such as ozone, based upon the requirements of Section 6.2.1 in ANSI/ASHRAE Standard 62.1.
3. Hospital and ambulatory surgery centers where more than 75 percent of the air supplied by the system is delivered to spaces that are required to be humidified to a dew-point temperature above 35°F (2°C). In all other buildings where more than 25 percent of the air is supplied to spaces that are designed to be humidified to a dew-point temperature above 35°F (2°C) to satisfy process needs.
4. Systems that include condenser heat recovery with a minimum capacity of:
 - a. 60 percent of the peak heat rejection load at design conditions, or
 - b. the amount needed to preheat the peak service hot-water draw to 85°F (29°C).
5. Systems that serve residential spaces where the system cooling capacity is less than 270,000 Btu/hr (22.5 tons, 79.1 kW).
6. Spaces where the cooling load is dominated by envelope loads. In these types of spaces, the cooling load decreases as the outdoor dry-bulb temperature decreases which reduces the need for cooling and limits the benefit of economizer cooling.
7. Systems that operate less than 20 hours per week.
8. Spaces where the use of outdoor air for cooling will affect open refrigeration cases, such as those found in supermarkets.
9. Systems where the cooling efficiency meets or exceeds efficiency improvement thresholds found in Table 6.5.1-3. See sidebar (p. 5).

Economizer Operation

Standard 90.1 does not allow the economizer control to be solely dictated by mixed-air temperature. It requires the economizer controller to use another variable, such as outdoor dry-bulb temperature, to sequence operation with the mechanical cooling equipment. New equipment operation-based requirements dictate that manufacturers and designers must comply with the following:

- **Damper sequencing.** The standard requires economizer dampers to be sequenced with the mechanical cooling equipment.
- **Integrated operation.** The standard now prohibits the use of controls that false-load the mechanical cooling system (such as hot gas bypass) which might limit or disable the economizer except at the lowest stage of mechanical cooling.
- **Interlocking.** Unit and economizer controls shall be interlocked to ensure 1) the outdoor air damper is fully open when mechanical cooling is on, and 2) that the outdoor air damper does not begin to close to prevent coil freezing until the leaving-air temperature is less than 45°F (7°C).

- **Cooling stages for direct expansion.**

There are new requirements regarding the minimum number of mechanical cooling stages for direct expansion (DX) units. Effective January 1, 2014, DX units rated at $\geq 75,000$ Btu/hr (6.3 tons, 22 kW) that control mechanical cooling capacity based upon occupied space temperature shall have a minimum of two stages of mechanical cooling capacity. This capacity threshold will drop from 75,000 Btu/hr to 65,000 Btu/hr (5.4 tons, 19 kW) on January 1, 2016.

All other DX units, including those that control space temperature by modulating airflow, need to comply with the following requirements (listed in Table 6.5.1.4):

- For units between 65,000 Btu/hr and 240,000 Btu/hr (5.4 tons to 20 tons, 19 kW to 70 kW), have at least three stages of mechanical cooling capacity and a minimum compressor displacement no more than 35 percent.
- For units larger than 240,000 Btu/hr (20 tons, 70 kW), have at least four mechanical cooling stages with a minimum compressor displacement of no more than 25 percent.

Table 1. Permissible economizer control types and high-limit shutoff setpoint conditions

Control type	Allowed in climate zone	Required high-limit shutoff setpoint
Fixed dry-bulb temperature	1B, 2B, 3B, 3C, 4B, 4C, 5B, 5C, 6B, 7, 8	$T_{OA} > 75^{\circ}\text{F}$ (24°C)
	5A, 6A	$T_{OA} > 70^{\circ}\text{F}$ (21°C)
	1A, 2A, 3A, 4A	$T_{OA} > 65^{\circ}\text{F}$ (18°C)
Differential dry-bulb temperature	1B, 2B, 3B, 3C, 4B, 4C, 5A, 5B, 5C, 6A, 6B, 7, 8	$T_{OA} > T_{RA}$
Fixed enthalpy with fixed dry-bulb temperature	All	$h_{OA} > 28$ Btu/lb (47 kJ/kg) or $T_{OA} > 75^{\circ}\text{F}$ (24°C)
Differential enthalpy with fixed dry-bulb temperature	All	$h_{OA} > h_{RA}$ or $T_{OA} > 75^{\circ}\text{F}$ (24°C)

Economizer Control Types

Standard 90.1 describes four allowable control types, but it doesn't specify which type of economizer control to use. System designers might wish to control economizer operation based on outdoor dry-bulb temperature, outdoor enthalpy, or a combination of these. The standard discourages certain control types in some climate zones. Table 1 shows the allowed control types by climate zone and the respective high-limit shutoff control setting required.

Fixed dry-bulb temperature control.

This is the simplest control type which compares the sensed outdoor dry-bulb temperature to a programmed high-limit shutoff temperature. When the outdoor dry-bulb temperature is above the high-limit shutoff temperature, the economizer must be disabled and mechanical cooling is used to satisfy the load.

Standard 90.1 provides three separate high-limit shutoff setpoints that vary with climate zone. Climates with hotter and more humid weather have a lower setpoint to minimize the introduction of humid outdoor air. The required setpoints are shown on a map of the United States in Figure 2.

Figure 3 illustrates a high-limit shutoff setpoint of 70°F (21°C) for climate zones 5A and 6A on a psychrometric chart. In this example, when the outdoor dry-bulb temperature is above this shutoff setpoint, or to the right of the vertical line, the economizer must be disabled.

Differential dry-bulb temperature control. This control type compares the outdoor dry-bulb temperature to the return dry-bulb temperature. When the outdoor temperature is greater than the return temperature, the economizer must be disabled. Figure 4 shows an example where the return air dry-bulb temperature is 78°F (26°C). When the outdoor dry-bulb temperature is above this temperature, or to the right of the vertical line, the economizer must be disabled. Conversely, when the outdoor

Figure 2. Required high-limit shutoff setpoints for an economizer with fixed dry-bulb temperature control

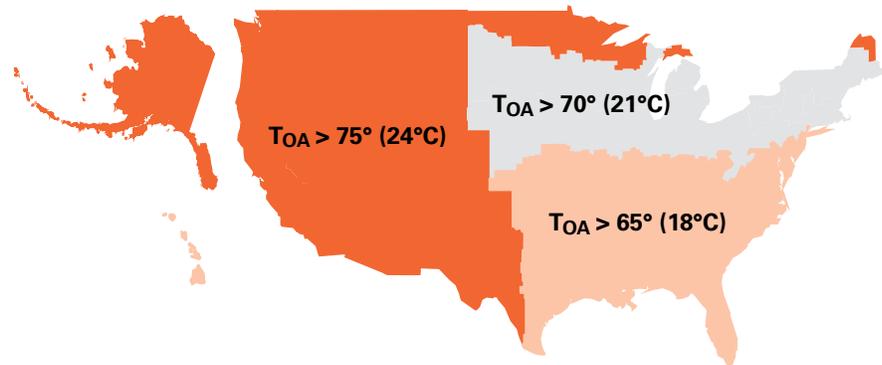


Figure 3. Fixed dry-bulb control with a high-limit shutoff setpoint of 70°F (21°C)

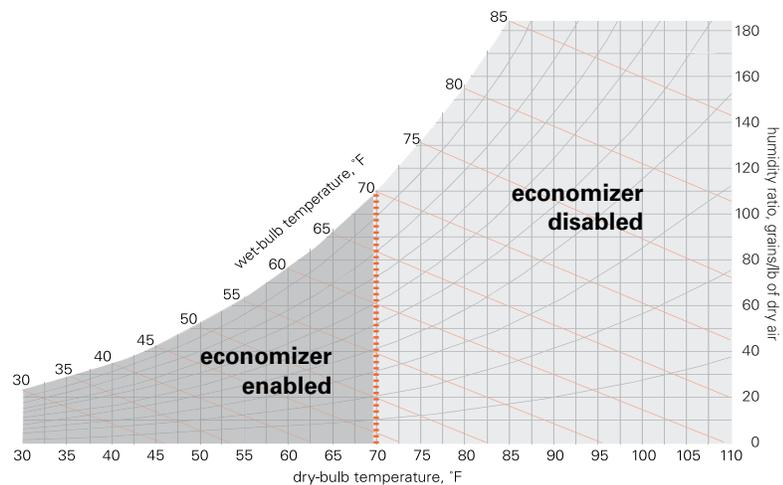
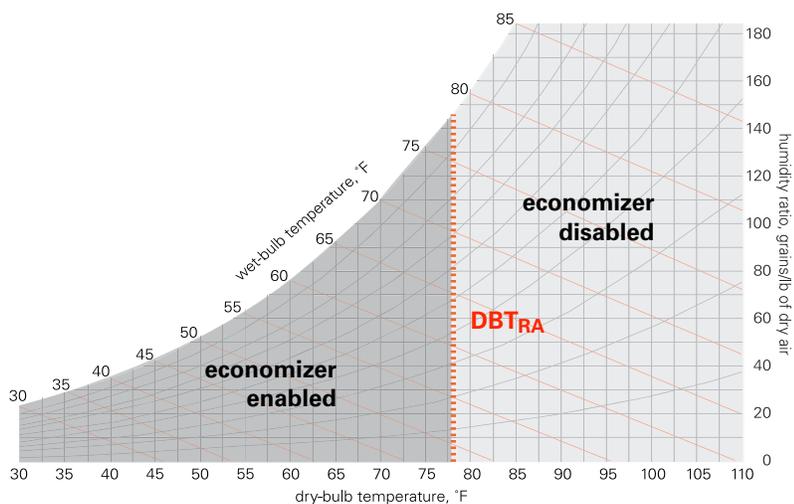


Figure 4. Differential dry-bulb control with return high-limit shutoff setpoint of 78°F (26°C)



temperature is less than the return temperature, the economizer must be enabled and “free” cooling can be used to satisfy the space loads. This prevents the airside economizer from operating when the outdoor temperature would increase the mixed-air temperature and increase the mechanical cooling load.

Both the fixed dry-bulb and differential dry-bulb temperature controls are easier to implement, but neither considers the moisture content of the outdoor air. In some instances, the dry-bulb temperature may be lower while the humidity ratio (or dew-point temperature) remains high. As a result, airside economizers that only consider dry-bulb temperature might introduce unwanted humid outdoor air.

Fixed enthalpy with fixed dry-bulb temperature control. This control type evaluates both enthalpy and dry-bulb temperature of the outdoor air (Figure 5). When either exceeds the high-limit shutoff, the economizer is disabled and mechanical cooling is used. The standard requires the airside economizer to be disabled when the outdoor dry-bulb temperature surpasses 75°F (24°C) or when the outdoor enthalpy is greater than 28 Btu/lb (47 kJ/kg). When both the outdoor dry-bulb temperature and enthalpy are below the high-limit shutoff conditions, the economizer is enabled.

Figure 5. Fixed enthalpy with fixed dry-bulb control with high-limit shut-off of $h_{OA} > 28$ Btu/lb (47 kJ/kg) or $T_{OA} > 75^\circ\text{F}$ (24°C)

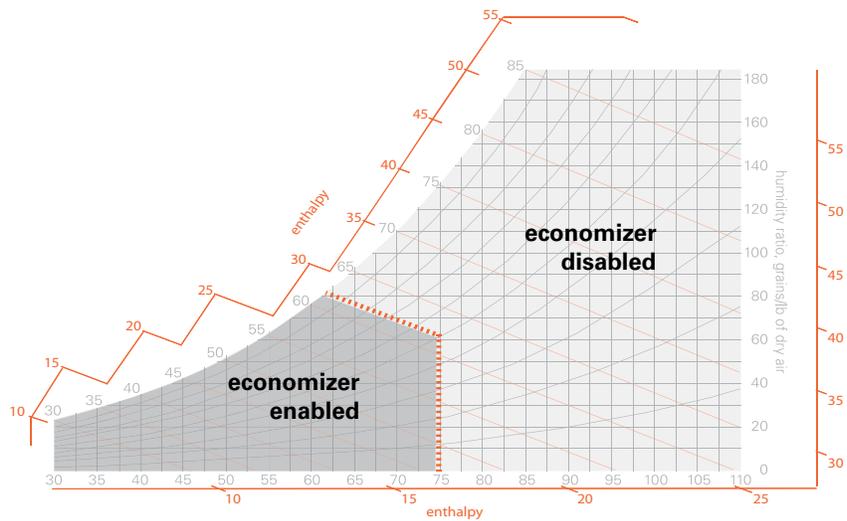
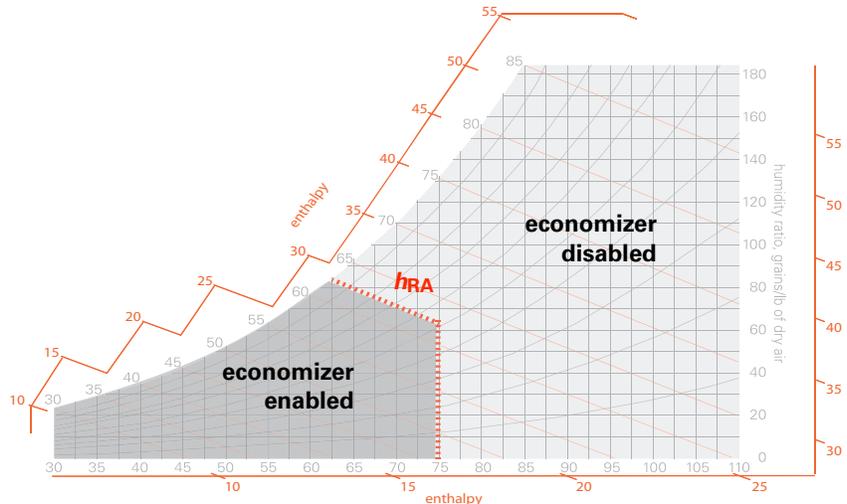


Figure 6. Differential enthalpy with fixed dry-bulb control with high-limit shut-off of $h_{OA} > h_{RA}$ or $T_{OA} = 75^\circ\text{F}$ (24°C)]



Differential enthalpy with fixed dry-bulb temperature control. The final permitted airside economizer control evaluates both the outdoor- and return-air enthalpy and the outdoor dry-bulb temperature to determine when economizing is required. Figure 6 illustrates this control with the return air enthalpy and fixed dry-bulb limit on a psychrometric chart. In this example, the return air enthalpy was computed to be 28.8 Btu/lb (49 kJ/kg) based upon a return air dry-bulb temperature of 78°F (26°C) and a dew point of 55°F (13°C). If the outdoor air enthalpy is higher than the return air enthalpy or the outdoor air dry-bulb temperature is higher than 75°F (24°C), the economizer is disabled.

90.1 allows several control types in most climate zones. For instance, a building located in Lexington, Massachusetts, which is in climate zone 5A (cool-humid), would be permitted to use either of the four allowable control types. Conversely, a building located in Charleston, South Carolina, which is in climate zone 3A (warm-humid), would be permitted to use all control types, except for differential dry-bulb temperature control.

Previous versions of the standard allowed the use of fixed enthalpy, electronic enthalpy, and differential enthalpy control. For the 2013 revision of the standard, these three controls

Enthalpy setpoints for cities at substantially different altitudes.

Footnote (a) in Table 6.5.1.1-3 of Standard 90.1-2013 requires the fixed enthalpy setpoint be adjusted for “altitudes substantially different than sea level.” The standard requires the high-limit shutoff setpoint to be determined at the city’s elevation and at the enthalpy which corresponds to a dry-bulb temperature of 75°F (24°C) and 50 percent relative humidity. For example, Colorado Springs, Colorado, sits at 6,035 feet (1,839 meters) and would require a setpoint of 31 Btu/lb (54 kJ/kg). This higher setpoint would allow more potential hours of economizer operation.

have been removed from the prescriptive table of allowable controls. The committee responsible for Standard 90.1 explained their reasoning in the foreword of Addendum DW to Standard 90.1-2010. They wrote, "Differential enthalpy sensors can have the worst performance of all devices because they have four sensors (return air dry-bulb and RH and outdoor air dry-bulb and RH) each of which can have error."

The committee also explained that electronic enthalpy economizer controls have been removed because they've been replaced with better-performing and lower-cost switches available in the market.

Designers can use other types of economizer control, even the aforementioned controls that are no longer listed, but this may require demonstrating Standard 90.1 compliance using the Energy Cost Budget (Section 11 of the standard).

Sensor Accuracy

Proper operation of the airside economizer is dependent upon accurate sensors that measure or compute outdoor dry-bulb temperature and enthalpy. As a result, a new section was added to the 2013 version of Standard 90.1 that addresses sensor accuracy. The standard prescriptively requires outdoor-air, return-air, mixed-air, and supply-air sensors to be calibrated to the following accuracies:

- For dry-bulb and wet-bulb sensors, the accuracy must be within $\pm 2^\circ\text{F}$ ($\pm 1.1^\circ\text{C}$) over the range of 40°F to 80°F (4.4°C to 27°C).
- For enthalpy sensors or sensors that compute a differential enthalpy, the accuracy must be within ± 3 Btu/lb (± 7 kJ/kg) over the range of 20 Btu/lb to 36 Btu/lb (29 kJ/kg to 66 kJ/kg)¹.
- For sensors measuring relative humidity, the accuracy must be within ± 5 percent relative humidity over the range of 20 percent to 80 percent.

¹ The specific enthalpy range and enthalpy difference values for enthalpy sensory accuracy in the SI-edition of Standard 90.1-2013 were incorrectly calculated from their I-P equivalents. The standing Standard Project Committee responsible for 90.1 intends to issue an erratum to correct the standard in 2015. The values printed in this newsletter are correct.

What if an economizer cannot be implemented?

Economizers are required in most climate zones in the United States (see Figure 1). However, there are some system types where neither an airside nor waterside economizer may be practical.

For example, in the case of a water-source heat pump system, adding a waterside economizer coil to each heat pump with a cooling capacity greater than 54,000 Btu/hr (4.5 tons, 15.8 kW) may be cost-prohibitive and will add additional airside pressure drop that must be overcome by the heat pump's fan. An individual heat pump would be exempt from the economizer requirement if the heat pump has a rated efficiency that exceeds the minimum required efficiency by the percentage listed in Table 6.5.1-3 of the standard (reprinted below as Table 2).

Table 2. Efficiency improvement for economizer elimination

Climate zone	Efficiency improvement
2A	17%
2B	21%
3A	27%
3B	32%
3C	65%
4A	42%
4B	49%
4C	64%
5A	49%
5B	59%
5C	74%
6A	56%
6B	65%
7	72%
8	77%

Using this table, designers can choose to increase the cooling efficiency to exempt the specific unit from the economizer requirement. For units that include both a full- and part-load efficiency requirement, this increase applies to the part-load efficiency value [see footnote (a) of Table 6.5.1-3]. Using the minimum efficiency requirement tables in Standard 90.1-2013 (Tables 6.8.1-1 through 6.8.1-10), system designers can identify the minimum full- and part-load efficiency required for a particular piece of equipment, and then increase the efficiency based upon the climate zone and corresponding percent improvement listed in the table. This new value becomes the minimum full- or part-load efficiency required in order to be exempt from the economizer requirement.

For example, a system designer is specifying a water-source heat pump system and the largest heat pump will be a 5 ton (60,000 Btu/hr, 17.6 kW) unit in Yorktown, Virginia. An economizer will be required because the building is located in climate zone 4A and the cooling capacity is greater than 54,000 Btu/hr (15.8 kW). Table 6.8.1-2 requires water-to-air electrically operated heat pumps of this size to have a full-load efficiency of at least 13.0 Energy Efficiency Ratio (EER). There is no part-load energy requirement for a heat pump of this capacity. To exempt this heat pump from the economizer requirement, the system designer must specify a unit that is 42 percent more efficient at full-load, or 18.5 EER ($13.0 \text{ EER} \times 1.42 = 18.5 \text{ EER}$).

To compute enthalpy, typically two properties of air are measured—dry-bulb temperature and relative humidity. The use of sensors with large errors can result in significantly inaccurate enthalpy values. There are different sensor types with different accuracies available on the market. Designers will now need to verify the accuracy of these sensors when using them to sense air conditions for economizer operation.

Selection of the economizer control strategy impacts both energy use and indoor humidity levels, and the best choice depends on building operation, HVAC system type, and climate. In the November 2010 issue of the *ASHRAE Journal*, Taylor and Cheng discussed concerns about sensor inaccuracy, and suggested that fixed dry-bulb control provides the best combination of energy savings, least risk of sensor error, and maintenance.

Building Pressure Relief

When a system transitions from its normal operating mode (minimum ventilation airflow) to airside economizer operation, the amount of outdoor air introduced into the building increases significantly. This can pose a challenge for building pressurization and relief—especially if the relief system is improperly designed or operated. Building overpressurization can cause exterior doors to stand open and whistling noises as air rushes through door openings. Section 6.5.1.1.5 requires a system be used “to relieve excess outdoor air during economizer operation to prevent overpressurizing the building.”

This section also requires the relief air outlet to be located far enough away from the outdoor air intake to prevent recirculation of this relief air. ASHRAE Standard 62.1-2013 provides a table of minimum distances between exhaust/relief outlets and outdoor air intakes based upon the classification of the air:

- Class 2 exhaust (e.g., retail sales areas, dance floors, health clubs), the minimum distance between outlet and inlet is 10 feet (3 meters).
- Class 3 exhaust (e.g., general manufacturing areas, refrigerating machinery rooms), the minimum distance is 15 feet (5 meters).
- Class 4 exhaust (e.g., paint spray booths, chemical storage rooms), the minimum distance is 30 feet (10 meters).

System designers can choose from several different methods to relieve excess outdoor air depending on the system configuration. If a system includes a supply and relief fan, building pressure can be controlled by varying the capacity of the central relief fan. If the system includes a supply and return fan, building pressure can be controlled by varying the position of the relief damper.

Damper Leakage

With the introduction of outdoor air for economizer cooling and possibly a damper to control the quantity of air leaving the building, it is important to use dampers that seal tightly with minimal leakage. As a result, Standard 90.1-2013 includes maximum damper leakage requirements that are based upon climate zone, building height, and type of damper.

The economizer section of Standard 90.1 refers to Section 6.4.3.4.3 and its corresponding table for return, exhaust, relief, and outdoor air dampers. When tested in accordance with AMCA Standard 500, dampers must not leak more air than what is specified within the table (reprinted below as Table 3).

Conclusion

ASHRAE Standard 90.1-2013 is now being adopted in model codes (see sidebar p. 7). Although there are new shutoff limits that designers need to be aware of, the standard provides enough flexibility to choose the best economizer control for a given project. A building energy model, created with software like Trane's TRACE™ 700 or EnergyPlus, can be used to evaluate different control types for the specific building in question to compare the potential energy and economic savings.

On the path toward lowering building energy use and energy cost, properly designed and operated airside economizers can offer the significant savings Standard 90.1-2013 strives to accomplish.

By Eric Sturm, Trane. You can find this and previous issues of the Engineers Newsletter at www.trane.com/engineersnewsletter. To comment, e-mail us at ENL@trane.com.

Table 3. Maximum damper leakage, cfm per ft² at 1.0 in. wc (L/s per m² at 250 Pa wc)

Climate Zone	Ventilation Air Intake		Exhaust/Relief	
	Non-motorized*	Motorized	Non-motorized*	Motorized
1, 2				
Any height	20 (100)	4 (20)	20 (100)	4 (20)
3				
Any height	20 (100)	10 (50)	20 (100)	10 (50)
4, 5B, 5C				
Fewer than three stories	Not allowed	10 (50)	20 (100)	10 (50)
Three or more stories	Not allowed	10 (50)	Not allowed	10 (50)
5A, 6, 7, 8				
Fewer than three stories	Not allowed	4 (20)	20 (100)	4 (20)
Three or more stories	Not allowed	4 (20)	Not allowed	4 (20)

*Unit dampers less than 24 inches (600 mm) in either dimension may have leakage of 40 cfm/ft² (200 L/s per m²).

Computer Room Economizers.

There are several important differences for using economizers in systems that serve computer rooms. Table 6.5.1-2 within Standard 90.1 defines which systems require economizers based upon climate zone and capacity. This table is reprinted below as Table 4.

Table 4. Minimum fan-cooling unit size for which an economizer is required for computer rooms

Climate zone	Cooling capacity when an economizer is required
1A, 1B, 2A, 3A, 4A	No requirement
2B, 5A, 6A, 7, 8	Systems \geq 135,000 Btu/hr (40 kW)
3B, 3C, 4B, 4C, 5B, 5C, 6B	Systems \geq 65,000 Btu/hr (19 kW)

Exception Number 10 of Section 6.5.1 exempts systems that serve computer rooms if either of the following is true:

- The total design cooling load of all computer rooms in the building is less than 3,000,000 Btu/hr (879 kW) and the building in which they are located is not served by a centralized chilled-water plant;
- The room total design cooling load is less than 600,000 Btu/hr (176 kW) and the building in which they are located is served by a centralized chilled-water plant;
- The local water authority does not allow cooling towers; or
- Less than 600,000 Btu/hr (176 kW) of computer-room cooling equipment capacity is being added to an existing building.

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Standard 90.1-2013 versus the 2015 IECC.

Standards, such as Standard 90.1-2013, are often incorporated into model codes, which typically are the basis of local codes. One popular model code, the International Energy Conservation Code (IECC) published by the International Code Council (ICC), has been adopted by numerous jurisdictions. The most recent version of this code, 2015 IECC, lists requirements that, in many cases, are very similar to the requirements of Standard 90.1-2013.

Section C403.3 *Economizers (Prescriptive)* details the requirements for airside and waterside economizer usage. Like Standard 90.1-2013, there are numerous exceptions including usage in climate zones 1A and 1B, where a humidification system would be negatively impacted, systems with limited weekly operation, where open supermarket refrigerated cases would be negatively affected, and where condenser heat recovery systems are used. Notable exception differences between 2015 IECC and Standard 90.1-2013 include:

- In the IECC, cooling units less than 54,000 Btu/hr (4.5 tons, 15.8 kW) are exempt only if one of the following is true:
 - The system has a direct expansion (DX) coil, or
 - The total chilled-water system capacity, less the capacity of fan units with air economizers, is less than the minimum specified in Table C403.3(1), printed below as Table 5. In addition, the total capacity of all fan-cooling units not provided with economizers shall not exceed 20 percent of the total capacity of all fan-cooling units in the building or 300,000 Btu/hr (88 kW), whichever is greater.

Table 5. Minimum chilled-water system capacity for economizer cooling requirements

Climate zone	Total chilled-water system capacity less capacity of cooling units with air economizers	
	Local water-cooled chilled-water systems	Air-cooled chilled-water systems or district chilled-water systems
1A	No economizer requirement	No economizer requirement
1B ² , 2A, 2B	960,000 Btu/hr (281 kW)	1,250,000 Btu/hr (366 kW)
3A, 3B, 3C, 4A, 4B, 4C	720,000 Btu/hr (211 kW)	940,000 Btu/hr (275 kW)
5A, 5B, 5C, 6A, 6B, 7, 8	1,320,000 Btu/hr (387 kW)	1,720,000 Btu/hr (516 kW)

- In the IECC, the system can be exempt if the cooling equipment efficiency meets or exceeds the minimum efficiency requirement by the percentage listed in Table C403.3(2), printed as Table 6.

Requirements for high-limit shutoff controls, outdoor air relief, economizer integration, and false loading are either the same or very similar between 2015 IECC and Standard 90.1-2013.

²This is printed with conflicting requirements for climate zone 1B. Please contact your local Authority Having Jurisdiction (AHJ) for clarification.

Table 6. Equipment efficiency performance improvement for economizer elimination

Climate zones	Cooling equipment performance improvement (EER or IPLV)
2B	10% efficiency improvement
3B	15% efficiency improvement
4B	20% efficiency improvement

References

- [1] ANSI/AMCA. *Standard 500-D-12 Laboratory Methods of Testing Dampers for Rating*. Arlington Heights: AMCA, 2012.
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- [3] ANSI/ASHRAE/IES. *Standard 90.1-2013 Energy Standard for Buildings Except Low-Rise Residential Buildings*. Atlanta: ASHRAE, 2013.
- [4] —. *Addendum DW to Standard 90.1-2010*. Atlanta: ASHRAE, 2013.
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- [6] International Code Council. *2015 International Energy Conservation Code*. 2014.
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- [10] —. "Managing the Ins and Outs of... Commercial Building Pressurization." *Engineers Newsletter* (2002).
- [11] Taylor, Steven and C. Hwakong Cheng. "Economizer High Limit Controls and Why Enthalpy Economizers Don't Work." *ASHRAE Journal* (2010).



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Central Geothermal Systems discusses proper design and control of central geothermal bidirectional cascade systems that use borefields. This manual covers central geothermal system piping, system design considerations, and airside considerations. (SYS-APM009-EN, February 2011)

Chilled-Water VAV Systems discusses the advantages and drawbacks of the system, reviews the various components that make up the system, proposes solutions to common design challenges, explores several system variations, and discusses system-level control. (SYS-APM008-EN, updated May 2012)

Water-Source and Ground-Source Heat Pump Systems examines chilled-water-system components, configurations, options, and control strategies. The goal is to provide system designers with options they can use to satisfy the building owners' desires. (SYS-APM010-EN, updated November 2013)



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