Dew Point Evaporative Comfort Cooling Summary Report

Energy and Water Projects
Demonstration Plan SI-0821

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Link to Full Report

NOTICE

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ACRONYMS AND ABBREVIATIONS

AHU	air handling unit
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
Btu	British thermal units
cfm	cubic feet per minute
CT	current transducer
CoC	cycle of concentration
COP	coefficient of performance
CRAC	computer room air-conditioning
DAS	data acquisition system
DAT	discharge air temperature
DC-kW	direct-current kilowatt
DEC	direct evaporative cooler, direct evaporative cooling
DoD	U.S. Department of Defense
DX	direct expansion
EA	exhaust air
EAT	exhaust air temperature
ECM	electronically commutated motor
EER	energy efficiency ratio
eGrid	Emissions & Generation Resource Integrated Database
EISA	Energy Independence and Security Act of 2007
E.O.	Executive Order
ESTCP	Environmental Security Technology Certification Program
EUI	energy use intensity
HMX	heat mass exchanger
hp	horsepower
HVAC	heating, ventilating, and air-conditioning
IEC	indirect evaporative cooler, indirect evaporative cooling
IEER	integrated energy efficiency ratio
kW	kilowatt
kWh	kilowatt-hour
L	liter
MCDB	mean coincident dry bulb
MMBtu	million British thermal units
NERC	North American Reliability Corporation
NREL	National Renewable Energy Laboratory
NPV	net present value
OA	outside air
OAR	outside air ratio
OAT	outside air temperature
ppm	parts per million
RA	return air
RAT	return air temperature

RH	relative humidity
RMSE	root mean square error
RTU	rooftop unit
SA	supply air
SAT	supply air temperature
SHR	sensible heat ratio
SP	static pressure
SPP	simple payback
TDS	total dissolved solids
TTF	Thermal Test Facility
TMY	typical meteorological year
W	Watt

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EXECUTIVE SUMMARY

Air-conditioning is the single largest contributor to peak demand on U.S. electricity grids and is the primary cause of grid failures and blackouts.[1] Power generators and refrigeration-based air-conditioning units are least efficient at high ambient temperatures, when cooling demand is highest. This leads to increased pollution, excessive investment in standby generation capacity, and poor utilization of peaking assets. Air-conditioning accounts for approximately 15% of all source energy used for electricity production in the United States alone (nearly 4 quadrillion Btu), which results in the release of about 343 million tons of carbon dioxide into the atmosphere every year.[2] Evaporative air conditioners can mitigate the environmental impacts and help meet Energy Independence and Security Act (EISA) 2007 and U.S. Department of Defense (DoD) energy policy goals by eliminating energy waste and reducing electricity demand.

Researchers have developed a new multi-staged indirect evaporative cooling (IEC) technology known as the Coolerado Cooler. This technology uses a unique design that maximizes the effectiveness of the direct and indirect stages of its cooling process. The cycle works by cooling both the primary (or product) air and the secondary (or working) air in a 20-stage process. Each stage contributes to cooling by combining multiple direct stages with a single indirect stage. The cumulative result is a lower product air temperature than is possible with conventional evaporative cooling technologies, as the unit can achieve wet bulb effectiveness (WBE) of 90%–120%. The key difference between this and other direct/indirect processes is that the working air that accumulates moisture is exhausted at each stage, enabling the product air to be delivered at a lower dry bulb temperature. This thermodynamic cycle is referred to as the Maisotsenko Cycle (or M-Cycle).

The project objective was to demonstrate the capabilities of the high-performance multi-staged IEC technology and its ability to enhance energy efficiency and interior comfort in dry climates, while substantially reducing electric-peak demand. The project was designed to test 24 cooling units in five commercial building types at Fort Carson Army Base in Colorado Springs, Colorado, to provide an analysis of energy use, water use, energy performance, and interior thermal comfort. The five buildings selected for the demonstration included the training facility, event center, theater, jet aeration facility, and the digester facility. The event center, digester facility, and jet aeration facility did not have air-conditioning prior to the demonstration. The training center was using small spot coolers that did not have sufficient cooling capacity to meet the cooling load, and the theater had an antiquated heating, ventilation, and air-conditioning (HVAC) system that had insufficient capacity.

In addition to these buildings, a stand-alone unit was installed at the wastewater treatment plant to test the technology's ability to operate using gray water. Table 1 and Table 2 summarize the performance objectives, success criteria, and results.

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[1] Heat Wave Nearly Causes Rolling Blackouts in California, http://www.nytimes.com/2000/08/02/us/heat-wave-nearly-causes-rolling-blackouts-in-california.html

[2] Building Energy Databook 2011, http://buildingsdatabook.eren.doe.gov/

Table 1. Quantitative Performance Objectives

Performance Objective	Success Criteria	Results
Improve comfort provided by evaporative cooling *(Performance)*	< 1% outside ASHRAE summer comfort zone Supply air < 70°F	*Comfort Zone =* ***Pass*** *Supply air < 70°F =* ***Pass for 80% of units monitored***
Provide high-efficiency cooling *(Energy Efficiency)*	Peak power < 1 kW/ton Average power < 0.6 kW/ton	*Peak Power =* ***Pass*** *Average Power =* ***Pass***
Sustain high cooling performance *(Service Life)*	< 5% degradation of WBE over 3 years Negligible increase in supply air pressure drop	*WBE =* ***Pass*** *Negligible Increase pressure drop =* ***Pass***
Minimize water consumption *(Water Conservation)*	Demonstrate conservation approach consuming < 2.5 gal/ton·h	Water use = ***Fail***

Table 2. Qualitative Performance Objectives

Performance Objective	Success Criteria	Results
Maintainability *(Ease of use)*	A single facility technician able to effectively operate and maintain equipment with minimal training	***Pass***
Maintainability *(Cost)*	> 90% of units fall within nominal IEC maintenance schedule by project end	***Pass***
Maintainability *(Failure)*	No signs of biological growth, including gray-water unit No ruptured water lines	***Pass***

In general, the units met all performance objectives other than the supply air temperature limit for select units and the water draw requirement. The increased water draw was due to high water consumption settings in the Coolerado controls, which were modified near the end of the 2011 cooling season. These modifications reduced water consumption to levels that were slightly higher than the original performance metric and were around 3 gal/ton·h.

The Coolerado units demonstrated the ability to operate with an average seasonal efficiency as low as 0.157 kW/ton (energy efficiency ratio [EER] = 76.4) when calculated as a function of the total cooling provided by the unit and as low as 0.262 kW/ton (EER = 45.8) when calculated as a function of building cooling, which is considerably better than the specified performance metric.

The lessons learned during this demonstration project will aid in future implementation of the technology. The two primary lessons learned from the demonstration are that wastewater runoff should be diverted or collected for irrigation to use the water runoff and eliminate any potential water damage from pooling or freezing and the cycles of concentration (CoCs) setting (parts water evaporated to parts wastewater) has a significant impact on water consumption; the CoC should be set to 5 when the inlet water has low calcium carbonate concentrations and low Langlier indexes.

The total installed costs, seasonal energy efficiency, energy use, and projected water consumption of the Coolerado units were used to compare the economics and performance to a code-minimum packaged rooftop unit (RTU) with an integrated energy efficiency ratio (IEER) of 12. Given the measured performance of the Coolerado units during the 2011 cooling season, the annual energy savings were estimated at 63.3% compared to a code-minimum RTU. The estimated simple payback was 7.62–41.8 years, depending on the facility that the unit was installed in when the maintenance costs were assumed to be equivalent to a packaged RTU. The primary driver for the shorter paybacks was equipment runtime, the buildings with 24 hr per day cooling loads had better economics. The economics are sensitive to operations and maintenance (O&M) costs; any increase or decrease in O&M costs has a significant impact on the economics of the installation. For example, if the O&M costs are deemed to be substantially higher than those of an equivalent sized RTU, the O&M costs outweigh the energy cost savings. The O&M costs were estimated to be $39/year/unit more expensive than a standard air cooled RTU.

The performance of the Coolerado technology was also evaluated in a retrofit scenario using the energy simulation software tools eQuest and EnergyPlus in three building types across six applicable climate zones (Phoenix, Arizona; Las Vegas, Nevada; Los Angeles, California; Albuquerque, New Mexico; Colorado Springs, Colorado; Helena, Montana). Building types included a small classroom (400 ft^2), a data center (19,994 ft^2), and a quick-serve restaurant (2,500 ft^2). The performance of the Coolerado units was compared to common cooling technologies with respect to energy use, water consumption, and O&M costs. The technology was evaluated as a retrofit to existing air-conditioning systems or as a standalone zone cooler. The economics were calculated using the federal life cycle costing procedures outlined in the Federal Energy Management Program Building Life Cycle Costing.[3]

The Coolerado technology can reduce energy use by 57%–92% relative to standard air-cooled, refrigeration-based air-conditioning units, depending on facility type, location, baseline HVAC equipment, and technology application. The Coolerado technology has the best economics when applied to data centers, which had a positive NPV in all climate zones, with net present value (NPV) of $1.06–$1.66 million and simple paybacks (SPP) of 13–17.7 years. The data center application had the best economics because of the constant cooling load and need for air-conditioning throughout the year. If the data center cooling equipment is at the end of its useful life and needs to be replaced, the simple paybacks can be reduced to 3 to 4 years. The quick service restaurant had favorable economics in Phoenix (NPV = $1,999, and SPP = 9.9 years) and unfavorable economics in Colorado Springs (NPV = $-6,835, SPP = 61.8) and the SPP was better in both climate zones than the single-zone classroom. The single-zone classroom unit showed favorable economics in Phoenix and Las Vegas (SPP = 11 years, and SPP = 12.7 years, respectively), and unfavorable economics with payback periods of 52–345 years in Los Angeles, Albuquerque, Colorado Springs, and Helena.

The economic analysis indicates that the Coolerado technology has the best economics as a retrofit technology when it is competing against smaller air-cooled air-conditioning systems with EERs of 8–12. DoD should target facility types with high internal loads and/or high ventilation rates that require year-round cooling. A detailed description of applicable DoD bases, building types, and design guidelines is provided in the body of the report.

[3] FEMP BLCC, http://www1.eere.energy.gov/femp/information/download_blcc.html

1.0 INTRODUCTION

Evaporative cooling is an environmentally beneficial technology that is losing ground in parts of the country where it provides the greatest pollution reduction benefits and electricity grid congestion relief. The overall value proposition of evaporative coolers has failed to prevent over-reliance on electric-peaking mechanical air conditioning, largely because of perceptions of inferior comfort. Innovative, high-performance, multi-staged IEC units have been developed that surpass evaporative cooling paradigms for comfort-cooling applications and have demonstrated the ability to significantly reduce air-conditioning energy use.

1.1 BACKGROUND

Air-conditioning is the single largest contributor to peak demand on U.S. electricity grids and is a cause of grid failures and blackouts. Power generators and refrigeration-based air-conditioning units are least efficient at high ambient temperatures, when cooling demand is highest. This leads to increased pollution, excessive investment in standby generation capacity, and poor utilization of peaking assets. Evaporative air conditioners can help meet EISA 2007 and DoD energy policy goals by eliminating energy waste and reducing electricity demand.

A common misconception is that evaporative coolers do not supply cold enough air to meet accepted comfort standards. New dew point evaporative cooler configurations can provide colder supply air temperatures (SATs) and more comfortable indoor conditions than traditional evaporative cooling systems. This technology can lower air-conditioning energy consumption by 50%–90% relative to standard air-cooled, refrigeration-based air-conditioning units, and reduce the total peak demand of a base in arid western states. In California, for example air-conditioning energy use comprises 30% of the summer peak electricity demand[4].

In addition to the energy benefits the technology will also reduce inventories of ozone depleting refrigerants and enhance health, comfort, and productivity by providing ventilation rates in compliance with or exceeding ASHRAE Standard 62.1-2010 Ventilation for Acceptable Indoor Air Quality, Leadership in Engineering and Environmental Design 2009 v2.2 requirements.[5, 6]

1.2 OBJECTIVES OF THE DEMONSTRATION

The primary objective was to demonstrate the capabilities of a new high-performance, multi-staged IEC technology to enhance energy efficiency and interior comfort in dry climates, while substantially reducing electric peak demand. The project was designed to test 24 cooling units in five commercial building types to provide a side-by-side comparison of energy use, water use, energy performance, and interior thermal comfort. The objectives are provided below:

- Validate the performance of the units relative to predefined qualitative and quantitative performance metrics

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[4] Richard E. Brown, J.G.K., Electricity Use in California: Past Trends and Present Usage Patterns. Energy Policy, 2002. 31(9): p. 15.

[5] ASHRAE Standard 62.1-2010, http://www.techstreet.com/ashrae/standards/ashrae/62_1_2010?product_id=1720986

[6] LEED 2009, http://www.usgbc.org/DisplayPage.aspx?CategoryID=19

- Improve comfort provided by evaporative cooling
  - Provide high efficiency cooling
  - Sustain high cooling performance
  - Minimize water consumption
  - Increase maintainability – ease of use, cost, and failure mode

- Outline the advantages and disadvantages of the technology
- Create a detailed application guide for DoD energy managers and engineers
- Present a market analysis that compares the economic feasibility of IECs to standard direct expansion (DX) cooling units in different climate zones
- Create a new performance model of the IEC that can be used by design engineers and energy analysts to model the units in various building types and locations.

The performance of each unit was evaluated under different operational characteristics and the water consumption characteristics of the units were validated throughout the two-year demonstration.

1.3 REGULATORY DRIVERS

The DoD ESTCP program awarded this new technology demonstration project as a means to identify programmatic changes that could be applied to the design and construction of energy-efficient, evaporative-based air-conditioning equipment on new and existing facilities. A new high-performance, multi-staged IEC unit could be implemented throughout the western half of the United States to help the agency meet and exceed the requirements set forth in Executive Order (E.O.) 13423, Energy Policy Act of 2005, and the EISA 2007.

E.O. 13423 and E.O. 13514 list requirements for water conservation at federal facilities. E.O. 13514 expands on the requirements set by E.O. 13423, mandating federal agencies to reduce potable water consumption intensity 2% annually through FY 2020. This would result in a 26% reduction by the end of FY 2020, relative to a FY 2007 baseline. E.O. 13514 also mandates a reduction in industrial, landscaping, and agricultural water consumption by 2% annually, or 20% by the end of FY 2020, relative to a FY 2010 baseline.

The key features of EISA 2007 that pertain to this technology are outlined in section 431 and requires a reduction in energy use intensity (EUI) (kBtu/ft^2/yr) of federal buildings of 3%/year, from a 2003 baseline, resulting in a 30% EUI reduction by 2015. The EISA 2007 legislation has superseded all previous EUI reduction mandates.

The new multi-staged IEC unit will substantially reduce energy use and peak demand, which will help meet EISA 2007 requirements, but it also has the potential to increase potable water consumption, which will be detrimental to the E.O. 13514 requirements. Although the technology can increase onsite water use, it was shown to reduce regional water consumption. A detailed description of regional power plant water consumption characteristics is provided in Section 7.0. Each DoD installation is encouraged to try to identify alternative sources of water for the units and recapture excess water for reuse in irrigation systems, if this is permitted by local jurisdictions.

2.0 TECHNOLOGY DESCRIPTION

2.1 EVAPORATIVE COOLING

Direct evaporative coolers (DECs) cool air by directly evaporating water into an airstream. As the water changes phases from a liquid to a vapor through heat of vaporization principles, heat is drawn from the air and the air temperature is reduced. In low-humidity areas, evaporating water into the air provides a natural and energy-efficient means of cooling. DECs, also called swamp coolers, rely on this principle, cooling outdoor air (OA) by passing it over water-saturated pads, causing the water to evaporate into it. Unlike central air-conditioning systems that recirculate the same air, residential DECs provide a steady stream of fresh air into the house and require an exhaust air (EA) path through the house.

Conventional evaporative cooling has high potential for significant energy savings in dry climates. Evaporative systems have competitive first costs and significantly reduce operating energy use and peak loads. The primary concern with traditional evaporative cooling units is their ability to maintain comfortable interior conditions. DECs are typically rated with a supply air (SA) cfm, rather than a cooling capacity. The temperature of the SA that an evaporative cooling unit can provide is typically rated as a WBE with the following equation

$$\varepsilon = \frac{T_{DB} - T_{supply}}{T_{DB} - T_{WB}}$$

Where:

T_{DB} = dry bulb temperature of entering air

T_{supply} = supply air temperature

T_{WB} = wet bulb temperature of entering air

The efficiency of a DEC is a function of the following:

- *Evaporative pad effectiveness.* The typical residential swamp cooler will use an aspen pad that has a WBE of 65%–78%. The pads are typically made from aspen trees, plastic, or paper. A more efficient option for the evaporative pad is a rigid media cooler, which has more surface area per cubic volume and the medium is rigid, which prevents it from sagging over time and can achieve a WBE as high as 90%.[7] The WBE is also a function of pad thickness, the air velocity through the pad, and the effectiveness of the water distribution through the pad (Figure 1).

[7] Evaporative Cooling Design Guide, http://www.emnrd.state.nm.us/ecmd/multimedia/documents/EvapCoolingDesignManual.pdf

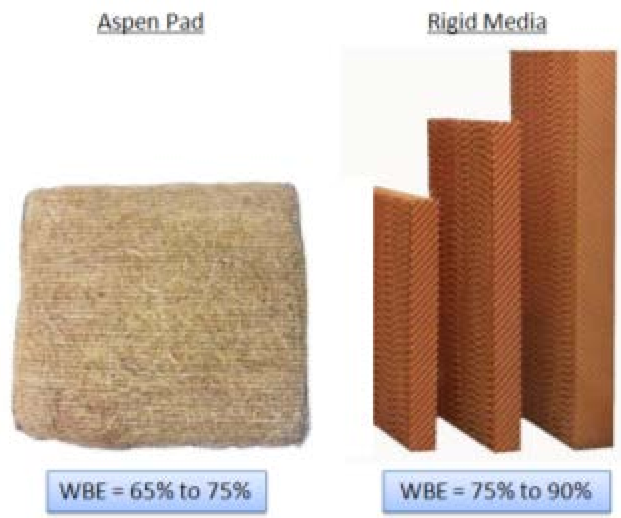


Figure 1. DEC media

(Source: Jesse Dean, NREL)

- *Supply fan and motor efficiency*. The efficiencies of the fan, motor, and belt/drive have a significant impact on unit efficiency. Typical DECs use a centrifugal fan, belt drive, and single-phase induction motor. The motors are typically one or two speed. Single-phase asynchronous induction motors are not subject to the same efficiency standards as three-phase motors and can have poor efficiencies, with electrical motor efficiencies as low as 50%. The most efficient designs use high-efficiency centrifugal fans, direct drive supply, and electronically commutated motors (ECMs). ECMs have significantly higher electrical efficiencies and allow for fully variable-speed operation.

The standard DEC also includes a circulation pump that will draw a small amount of power when it is circulating fluid through the direct evaporative pad.

There are number of commercially available residential and commercial evaporative cooling systems. Appendix D provides an overview of commercially available evaporative cooling technologies and their design characteristics.

2.2 TECHNOLOGY OVERVIEW

An internally manifolded IEC designed by Coolerado of Arvada, Colorado, has made dew point temperature—rather than wet bulb—the new low temperature limit for evaporative cooling. Wet bulb is the temperature at which air will cool when water is evaporated in unsaturated air. U.S. Department of Energy (DOE) laboratory testing has proven this cooler's ability to supply air at or below ambient wet bulb temperature (100%–120% WBE), surpassing state-of-the-art IECs (about 70% effective) and even swamp coolers (about 90% effective) without adding humidity to the SA. Accomplished by elegant use of multistage IEC, this approach is 2–4 times as energy efficient as conventional air-conditioning and significantly enhances occupant comfort and the climate range for non-compressive, non-refrigerant-based air conditioners. DEC uses about 1.37 gal per sensible ton·h of cooling to the SA (Note: DECs are adiabatic coolers, meaning that they do not significantly change the enthalpy of the cooled airstream.) However, DECs only work with 100% OA. If more OA is supplied than stipulated by ventilation requirements (ASHRAE 62.1-2010 and 62.2-2010), the instantaneous sensible cooling for airflow above minimum ventilation must be de-rated by the factor:

$$Derating\ ratio = \frac{RAT - SAT}{OAT - SAT}$$

The water evaporation rate (in gal/ton·h) must then be divided by this de-rating ratio.

The Coolerado cooler heat mass exchanger (HMX) have an evaporative water consumption rate of 2.5 gal/ton·h. These coolers may have the same issue if supplying more outdoor air than ventilation requirements, and thus require the same method of de-rating. However, these air conditioners can run down to 45% outdoor air ratio if return air (RA) is used, which will limit the amount of de-rated cooling. Thus, water consumption can be compared case-by-case only, using an annual simulation of building loads. At certain times during the season, a Coolerado Cooler can have a de-rating ratio that makes up for the difference in evaporation rate. During these hours, usually during high ambient wet bulb periods, the water evaporation by a Coolerado Cooler may be less than a DEC. In summary, in a climate like Colorado Springs a DEC will use roughly the same amount of water as the Coolerado Cooler, and the Coolerado Cooler will use less energy than a standard residential DEC with a standard, constant speed fan motor.

Scalable for residential or commercial application, the evaporative cores are made of plastic to separate the dry SA flows from the wet, EA flows, and can be mass produced by an automated assembly line. The wet exhaust flows serve as progressively colder heat sinks to produce the colder supply temperatures unique to this all-indirect technology. Fresh air is provided to the building at temperatures and relative humidities (RHs) that achieve indoor comfort in climates with design wet bulb temperatures below 70°F, which includes most of the western United States. Ambient dry bulb temperature is irrelevant, as the wet bulb temperature is the dominant factor in determining the SAT provided by the IEC.

2.2.1 How It Works

The Coolerado Cooler has a unique design that maximizes the effectiveness of the direct and indirect stages of its cooling process. The schematic in Figure 2 illustrates fluid movement through the patented HMX. The HMX is made of plastic HMX in a geometric design that cools both the product and working airstreams in an isolated heat exchange process.

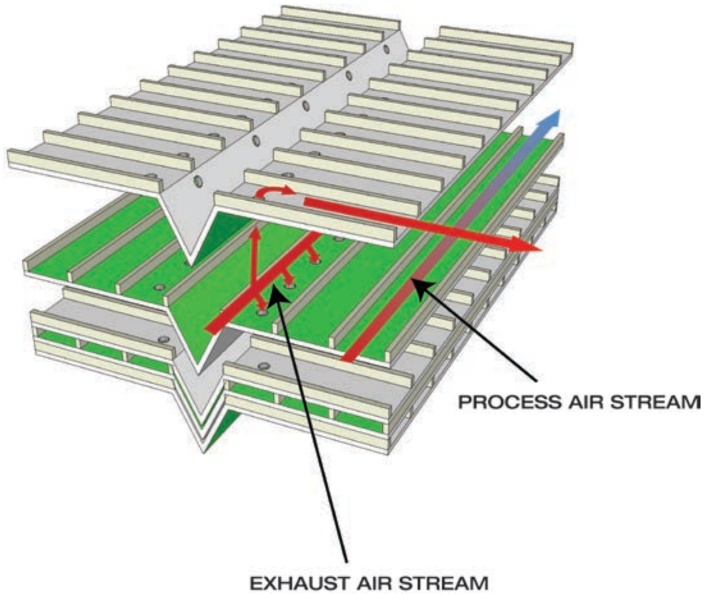


Figure 2. Internal HMX process airstream and EA stream airflow

(Source: NREL)

Figure 3 proivides a side view of the Coolerado Cooler and an illustration of the main components.

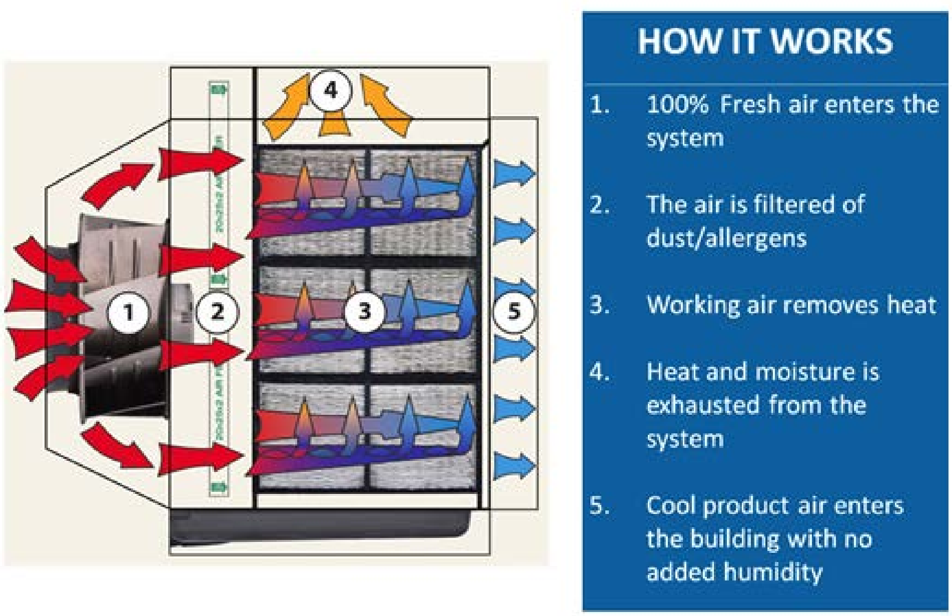


Figure 3. Side view of Coolerado airflow process

(Source: Coolerado)

Fan energy is the only form of electrical energy input into the system. The fan is driven by an ECM that is > 90% efficient and is variable down to a near 0% flow rate. The inlet air passes through a filter before it enters the unit. The top portion of the inlet air is supplied to the space as the primary/product air stream. The air that flows through the bottom part of the HMX is the seccondary/working air. The system of cascading incremental airflows creates a thermodynamic cycle called the Maisotsenko Cycle (or M-Cycle) (see Figure 2). The cycle works by cooling both the primary/product air and the secondary/working air in a 20-stage process. The cumulative result is a lower primary/product air temperature than is possible with conventional evaporative cooling technologies. The key difference between this and other direct/indirect processes is that the secondary/working air that is accumulating moisture is exhausted at each stage, enabling the primary/product air to be delivered at a lower dry bulb temperature.

The advantage of the M-Cycle is that the working air is purged repeatedly so the initial conditions are essentially reset, as lower dry bulb and wet bulb temperatures are established with each purge cycle. This allows the eventual SAT to be below what the original initial conditions would indicate possible—below the thermodynamic wet bulb temperature. This key staged-cooling process is essentially what sets the Coolerado Cooler apart from other IEC and DEC systems and enables greater cooling performance. During this process, no moisture is added to the primary/product air.

2.3 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

The primary advantage of dew point IEC is its ability to supply colder SATs than traditional evaporative cooling units, which extends the range of applicable climate zones and increases thermal comfort. The increased performance over traditional evaporative cooling units comes at a fraction of the energy use and energy cost of mechanical air-conditioning. An IEC may have diverse applications; it can be applied as a single-zone dedicated outside air system, as an OA pre-conditioner or mixed air (OA and RA) conditioner that feeds into an RTU or air handling unit (AHU). Additional benefits include improved ventilation rates versus traditional air-conditioning, reduced strain on and investment in power distribution grids, and reduction in harmful refrigerant gases. The energy savings improve energy security and reduce pollution. The Coolerado can provide up to 30% colder SATs than traditional DECs without adding moisture to the SA stream. The Coolerado can also reduce air-conditioning energy use by 57%–92% depending on facility type, location, baseline HVAC equipment efficiency, and application.

The target climates for the Coolerado are ASHRAE climate zones 2B, 3B, 4B, 5B, and 6B. The system should be installed as an OA pre-conditioner in climate zones 2B and 3B and can be applied as a zone cooler for climate zones 4B, 5B, and 6B. An ASHRAE climate zone map is provided in Figure 4.

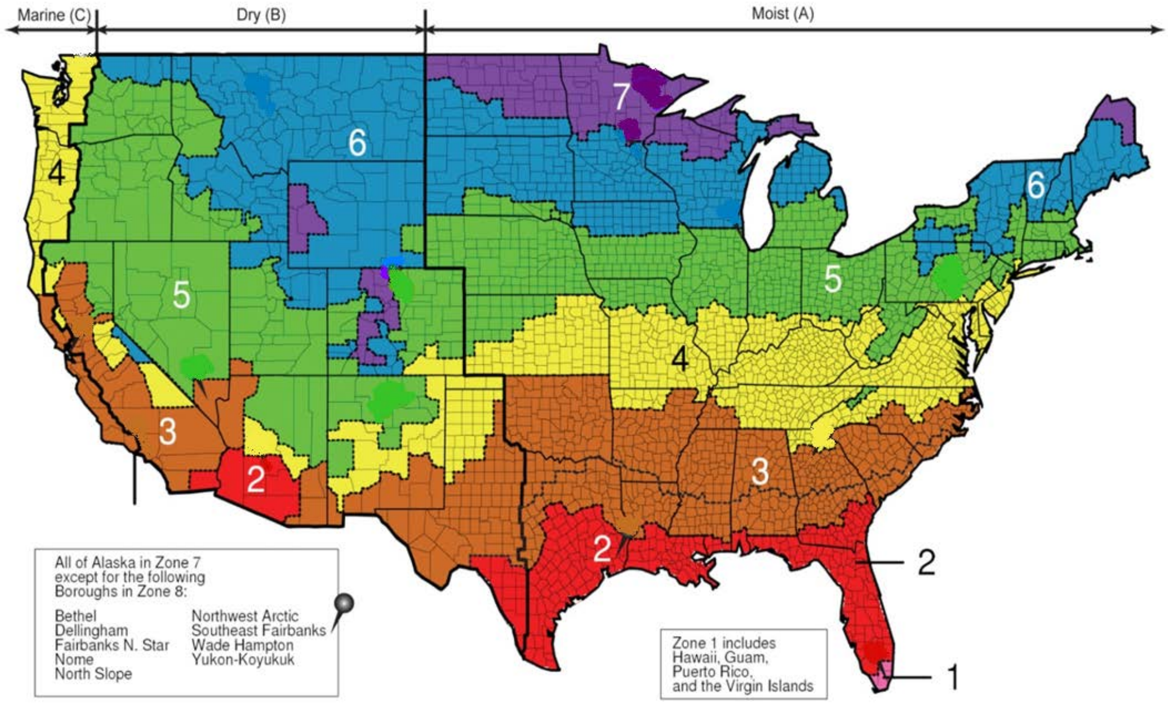


Figure 4. ASHRAE climate zone map

(Source: Joelynn Schroeder, NREL)

Although the technology can be installed in ASHRAE climate zones 1A–7A, the increased outdoor air humidity levels reduce the cooling capacity of the unit and the overall energy savings to the point that the technology cannot provide a favorable return on investment. Other limitations include increased onsite water consumption, inability to dehumidify, and sensitivity to inlet air conditions. Coolerado has developed a dew point IEC with mechanical air-conditioning to extend energy savings benefits to all climates. The 5-ton H 80 unit recently exceeded Western Cooling Efficiency Challenge goals; a description of the technology is provided in Appendix D.[8]

[8] Coolerado H80, http://www.nrel.gov/docs/fy11osti/46524.pdf

3.0 PERFORMANCE OBJECTIVES

Table 3 and Table 4 summarize the quantitative and qualitative performance objectives outlined for the evaluation of the Coolerado Cooler. The quantitative objectives include interior thermal comfort, energy efficiency, service life, and water use metrics; qualitative performance objectives include ease of use, cost, and failure, which address the maintainability of the system. Each performance objective is described in detail below. The results presented in Section 6 highlight how the Coolerado units in this demonstration project met or did not meet these performance objectives.

Table 3. Quantitative Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Improve comfort provided by evaporative cooling *(Performance)*	• Hours outside psychometric comfort zone • SAT	• Interior space temperature Indoor humidity • SAT	• < 1% outside ASHRAE summer comfort zone • SA < 70°F • OK to apply where design wet bulb ≤ 70°F
Provide high efficiency cooling *(Energy Efficiency)*	• kW/ton of building cooling	• SAT • Building EA temperature (EAT) • Coolerado power consumption • SA flow rate	• Peak power < 1 kW/ton • Average power < 0.6 kW/ton
Sustain high cooling performance *(Service Life)*	• WBE • SA pressure drop	• SAT • Outdoor air temperature • Core pressure drop • Outdoor air humidity	• < 5% degradation of WBE over 3 years • Negligible increase in SA pressure drop
Minimize water consumption *(Water Conservation)*	• Gal/ton·h of building cooling Site water quality (total dissolved solids [TDS])	• Water inlet flow • Water outlet flow • Water conductivity	• Demonstrate conservation approach consuming < 2.5 gal/ton·h

Table 4. Qualitative Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria
Maintainability *(Ease of Use)*	Ability of an HVAC technician to operate and maintain the technology	Standard form feedback from the HVAC technician on time required to maintain	A single facility technician able to effectively operate and maintain equipment with minimal training
Maintainability *(Cost)*	Service Frequency	Standard form feedback from the HVAC technician on time required to maintain	> 90% of units fall within nominal IEC maintenance schedule by project end
Maintainability *(Failure)*	Biological Fouling Freezing	Visual inspection	No signs of biological growth, including gray-water unit No ruptured water lines

4.0 FACILITY/SITE DESCRIPTION

For Carson Army Base is located in Colorado Springs, Colorado. The base sits atop a high plane at 5,835 ft against the foothills of the Rocky Mountains. The base covers more than 8.7 mi^2 and includes more than 11 million ft^2 of building area. Facilities include offices, headquarter buildings, commissaries (on-base grocery stores), a hospital, barracks, and retail spaces. Other spaces that do not fall into these categories include—but are not limited to—a training facility, auditorium, and event center. Table 5 summarizes the percentage of total facility square footage based on building type.

Table 5. Building Types at Fort Carson

Building type	Percent of Total
Other	41
Barracks	29
Headquarters	17
Offices	5.7
Hospital	4.6
Retail space	1.8
Commissaries	0.9

The OATs are typically 80°–90°F during the cooling season and are rarely above 100°F. The outside air (OA) wet bulb temperatures are low during the cooling season (50°–60°F), making Colorado Springs ideal for evaporative cooling technologies. One disadvantage is that the cooling season is relatively short, typically June–August, with fewer than 500 cooling degree days (base 65°F). Table 6 summarizes the Typical Meteorological Year 3 (TMY3) weather data for Colorado Springs and the maximum measured OA conditions at Fort Carson during July 2010.

Table 6. TMY3 and Measured Climate Data

Climate Data	TMY3 Data for Colorado Springs
Cooling design day (0.4%) Dry bulb	90.3°F
Cooling design day (0.4%) mean coincident wet bulb	58.8°F
Evaporative design day (0.4%) Wet bulb	63.3°F
Evaporative design day (0.4%) mean coincident dry bulb (MCDB)	78.3°F
Measured maximum dry bulb (July 2010)	97.8°F
Measured maximum mean coincident wet bulb (July 2010)	62.9°F
Maximum wet bulb (July 2010)	70.8°F
Number (percent) of hours above 0.4% design conditions	113 hours (1.3%)

The measured wet bulb temperature is significantly higher than the ASHRAE 0.4% design condition (70.8°F versus 63.3°F) and there were 113 hours above the 0.4% design condition. A similar trend was also monitored for the 2011 cooling season. The increased outdoor wet bulb temperatures made it more difficult for the Coolerado Cooler to meet the SAT and thermal comfort performance metrics.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Twenty-four Coolerado C60 units were installed across five facilities at Fort Carson, including a training center (classrooms), auditorium, events center, a digester facility, and a jet aeration facility. One additional Coolerado unit was installed as a standalone unit at the wastewater treatment facility to test its performance with wastewater. These facilities were selected based on their different end uses, occupant densities, cooling loads, schedules, and physical constraints. All the systems were set up as zone coolers with 100% OA. Most were installed as ground or stand mounted; a few were roof mounted.

4.2 FACILITY/SITE CONDITIONS

Many of the facilities selected for the demonstration used old HVAC systems that did not provide adequate cooling; therefore, installing the Coolerado units had the potential to save energy and improve occupant comfort. Additionally, all the selected facilities are of older vintages and had significant air leakage, so it was not necessary to install pressure relief dampers in conjunction with the Coolerado units, which saved installation costs.

5.0 TEST DESIGN

5.1 CONCEPTUAL TEST DESIGN

The conceptual test design consisted of a combination of controlled laboratory testing and field testing. NREL tested two units in the TTF before the installation and installed instrumentation and data acquisition equipment on 20 of the 24 Coolerado C60 units. The two units tested at the laboratory were used to pre-calibrate the field monitoring systems to improve the accuracy of field data. These two units were installed at the training center.

5.2 BASELINE CHARACTERIZATION

Because mechanical air-conditioning is a well-understood technology, baseline measurements were not required for individual sites to project energy savings relative to conventional equipment at various efficiency levels. Once cooling loads were established for each demonstration site, comparisons of Coolerado energy use versus energy needs of mechanical air-conditioning were straightforward. The efficiencies of competing cooling technologies, including DX RTUs and chillers, were analyzed using manufacturer's data and performance algorithms used in building energy modeling tools such as eQUEST and EnergyPlus.

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

Figure 5 shows the experimental layout for the training facility and represents all the demonstration buildings except the wastewater demonstration, which discharged to the outdoors because of the experimental nature of gray water use in the Coolerado unit. The figure describes a 100% OA displacement cooling application, where no cooling air is recirculated and cooling and dehumidification loads are carried from the building by exfiltrating EA. All units employ MERV 15 filters, have minimal duct SP losses, and conserve water by modulating makeup water in response to a wet bulb depression sensor that predicts evaporation rates at current ambient conditions. For through-the-wall units, SA is ducted in at low elevations to ensure the occupied zone is maintained at the coolest temperature possible, while air that has already picked up internal loads is still cool enough to buffer the space by carrying away solar loads in unoccupied volumes, such as ceiling plenums. For rooftop installations, where ceiling discharge is required, special diffusers force air downward and encourage cooling air throw to the floor to achieve the same displacement effect. Barometric exhaust dampers close when the Coolerado units are not pressurizing the space to ensure maximum displacement cooling without compromising envelope integrity during non-cooling hours.

Each unit modulated its SA flow with an ECM in response to a thermostat control signal. The wastewater unit was an exception; it operated continuously at full flow to accelerate any negative impacts of operating on gray water and discharged its process air to the outdoors to avoid concerns about potential biological growth.

5.4 OPERATIONAL TESTING

Testing was conducted in startup and monitoring phases. During startup, Coolerado and NREL engineers installed sensors and confirmed that HVAC and data systems operated properly. Startup commenced as the equipment installation proceeded in July 2009 and concluded in September 2009. Systems performance was monitored during the 2010 and 2011 cooling seasons (July, August, and September). NREL removed the monitoring equipment after the demonstration ended in September 2011. The onsite O&M contractor took responsibility for operating the units from the beginning of the demonstration, and the units will be used for space conditioning into the foreseeable future.

5.5 SAMPLING PROTOCOL

A data acquisition system (DAS) was installed on 20 of the 24 Coolerado units installed at Fort Carson. The DAS was designed to capture information on the energy and water performance of the Coolerado unit, as well as space temperature and EAT. Multiple DASs were installed at Fort Carson, and the data from all the sensors were stored and partially processed on Campbell Scientific Data Loggers. The data loggers were equipped with cellular modems that allowed for remote monitoring and analysis of metered data. All sensors were sampled every 10 s and any mathematical manipulations of those primary measurements were made on the same 10-s interval. Data are stored as averages or totals in four separate data tables identical in field description but varying in storage interval: 1-min, 15-min, 60-min, and 24-h (midnight-to-midnight). Figure 5 shows the DAS points for the typical Coolerado unit. Appendix B contains a list of sensors and associated accuracy specifications.

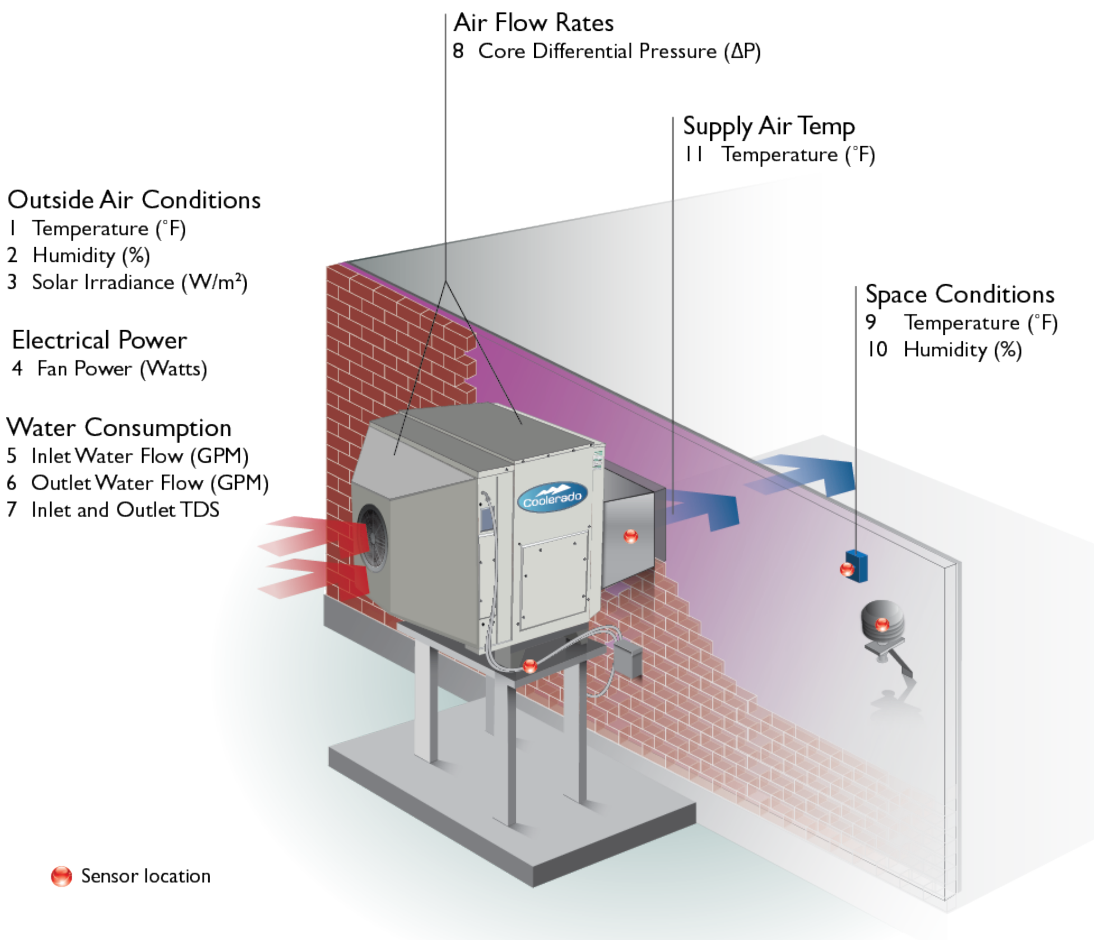


Figure 5. Coolerado DAS

(Source: Joshua Bauer, NREL)

6.0 PERFORMANCE ASSESSMENT

Performance data were collected during the 2010 and 2011 cooling seasons, which included July, August, and September. The results presented in this section highlight the performance objective results of the best- and worst-performing units from those seasons (see Table 7).

Table 7. Quantitative Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Improve comfort provided by evaporative cooling *(Performance)*	• Hours outside psychometric comfort zone • SAT	• Interior space temperature Indoor humidity • SAT	• < 1% outside ASHRAE summer comfort zone • SA < 70°F • OK to apply where design wet bulb ≤< 70°F	*Comfort Zone =* ***Pass*** *SA < 70°F =* ***Pass for 80% of unit monitored*** *Wet Bulb =* ***Pass***
Provide high-efficiency cooling *(Energy Efficiency)*	• kW/ton of building cooling	• SAT • Building EAT • Coolerado power consumption • SA flow rate	• Peak power < 1 kW/ton • Average power < 0.6 kW/ton	*Peak Power =* ***Pass*** *Average Power =* ***Pass***
Sustain high cooling performance *(Service Life)*	• WBE • SA pressure drop	• SAT • Outdoor air temperature • Core pressure drop • Outdoor air humidity	• < 5% degradation of wet-bulb eff. over 3 years • Negligible increase in SA pressure drop	*WBE =* ***Pass*** *Negligible Increase pressure drop =* ***Pass***
Minimize water consumption *(Water Conservation)*	• Gallons/ton-hr of building cooling Site water quality (TDS)	• Water inlet flow • Water outlet flow • Water conductivity	• Demonstrate conservation approach consuming < 2.5 gal/ton·h	Water use = ***Fail***

Table 8. Qualitative Performance Objectives

Performance Objective	Metric	Data Requirements	Success Criteria	Results
Maintainability *(Ease of use)*	Ability of an HVAC technician to operate and maintain the technology	Standard form feedback from the HVAC technician on time required to maintain	A single facility technician able to effectively operate and maintain equipment with minimal training	***Pass***
Maintainability *(Cost)*	Service Frequency	Standard form feedback from the HVAC technician on time required to maintain	> 90% of units fall within nominal IEC maintenance schedule by project end	***Pass***
Maintainability *(Failure)*	Biological Fouling Freezing	Visual inspection	No signs of biological growth, including gray water unit No ruptured water lines	***Pass***

All units were able to maintain room air conditions (temperature and relative humidity) within the ASHRAE thermal comfort zone >99% of the time for both the 2010 and 2011 cooling season. Nine units in 2010 and 13 units in 2011 able to supply air at less than 70 °F for more than 95% of operating hours.

The majority of the units had daily electrical efficiencies less than 0.6 kW/ton for more than 96% of the days in operation over the two year period. The electrical efficiency was significantly better for the classroom facility than the other facilities because the classroom units were properly sized to meet 100% of the cooling load within the space and had the ability to operate at partial fan speeds for the majority of the year. These units operated between 0.2 and 0.3 kW/ton in 2010 and around 0.2 kW/ton during 2011. An average kW/ton of 0.2 is equivalent to an EER of 60, and would result in energy savings of 80% relative to a minimally code compliant packaged rooftop unit with an EER of 12.

Excessive water use was a result of improper cycles of concentration (CoC) settings on the Coolerado control board. For the 2010 cooling season and the majority of the 2011 cooling season, the CoC was set to 1.5-1.6 by the manufactures, which was explained to be standard practice at the time. With this water use setting, the units would send two parts water down the drain for every 1 part of water that was evaporated. This resulted in water consumption between 6 and 10 Gallons/ton-hr. The settings were modified to a CoC of 5 at the end of the 2011 cooling season after determining that this was the recommended setting for the Coolerado. As a result, the units were able achieve a water use amounts of about 3 Gallon/ton-hr, which is only slightly higher than the requirement in the performance metric.

Table 9 summarize the percent of operating hours or days each monitored unit met the performance objectives.

Table 9: 2010 and 2011 Quantitative Performance Results

Building	Unit	Percent of Hours within ASHRAE Comfort Zone		Percent of Hours Average Supply Air Temp < 70 °F		Percent of Days Average Efficiency < 0.6 kW/ton		Percent of Days Average Water Use < 2.5 Gal/ton-hr	
		2010	2011	2010	2011	2010	2011	2010	2011
Training Facility	1	100	100	59.2	96.5	100	100	0.0	0.0
	2	100	100	76.6	99.5	100	98.7	2.3	0.0
	3	100	100	99.4	100	100	100	0.0	0.0
	4	100	100	96.3	97.5	100	100	0.0	0.0
Event Center	1	100	100	100	100	100	100	5.6	8.6
	3	100	100	99.7	99.8	100	100	0.0	21.4
	5	100	100	95.1	99.7	96.7	98.8	0.0	8.2
	7	100	100	98.2	99.8	98.9	96.5	1.1	4.7
Theater	9	100	100	99.3	97.0	96.0	85.5	18.5	0.0
	10	100	100	94.9	100	96.0	93.3	91.5	No data
	11	100	100	62.7	99.9	90.9	96.7	3.3	0.0
	12	100	100	99.3	98.0	100.0	96.9	1.1	0.0
Digester	1	100	100	57.9	77.4	2.3	93.5	0.0	0.0
Jet-Aeration	West	100	100	68.8	77.0	0.0	97.8	0.0	0.0
	East	100	100	No data	84.3	95.3	97.8	2.4	11.0
Wastewater Unit	1	100	100	41.7	70.2	100	75.8	100	No data

6.1 QUALITATIVE PERFORMANCE OBJECTIVES

Qualitative performance objectives included ease of use, cost, and failure. The demonstration met the ease-of-use metric by requiring only a single facility technician to effectively operate and maintain the equipment with minimal training. The standard maintenance time per unit ranged from 7.25 hours/year/unit to 1.7 hours/unit/year depending on the installation and on the extent of the maintenance required. Given the average maintenance time of 3.8 to 5.5 hours per unit per year, more than 90% of units fell within nominal IEC maintenance schedule and therefore met the cost objective. The units showed no signs of failure in regards to biological growth or ruptured water lines. Units at the Training Facility, however, did experience ruptured water lines but were a result of unforeseen issues with installation rather than Coolerado technology malfunctions.

7.0 COST MODEL

Twenty-four Coolerado C60 units were installed across five facilities at Fort Carson including a training center (classrooms), auditorium, events center, a digester facility, and a jet aeration facility. All the systems were set up as zone coolers with 100% OA. Most were ground or stand mounted; a few were roof mounted. The event center, digester facility, and jet aeration facility did not have air-conditioning before the demonstration. The training center was using small spot coolers that could not meet the cooling load and the theater had an antiquated HVAC system that had insufficient cooling capacity.

Because the facilities had insufficient air-conditioning capacity before the Coolerado units were installed, the economics of the Coolerado installation were compared to the economics of installing an appropriately sized packaged RTU and the associated ductwork and controls. The total installed costs, seasonal energy efficiency, energy use, and projected water consumption of the Coolerado units were used to compare the economics and performance to a code-minimum packaged RTU with an IEER of 12.

The seasonal efficiency of each Coolerado unit was calculated as a function of the total building cooling provided over the 2011 cooling season and total electrical energy use. The cooling capacity was calculated as a function of space temperature (building cooling) and OAT (total cooling). Figure 6 shows the annual average operational cooling efficiency for each unit.

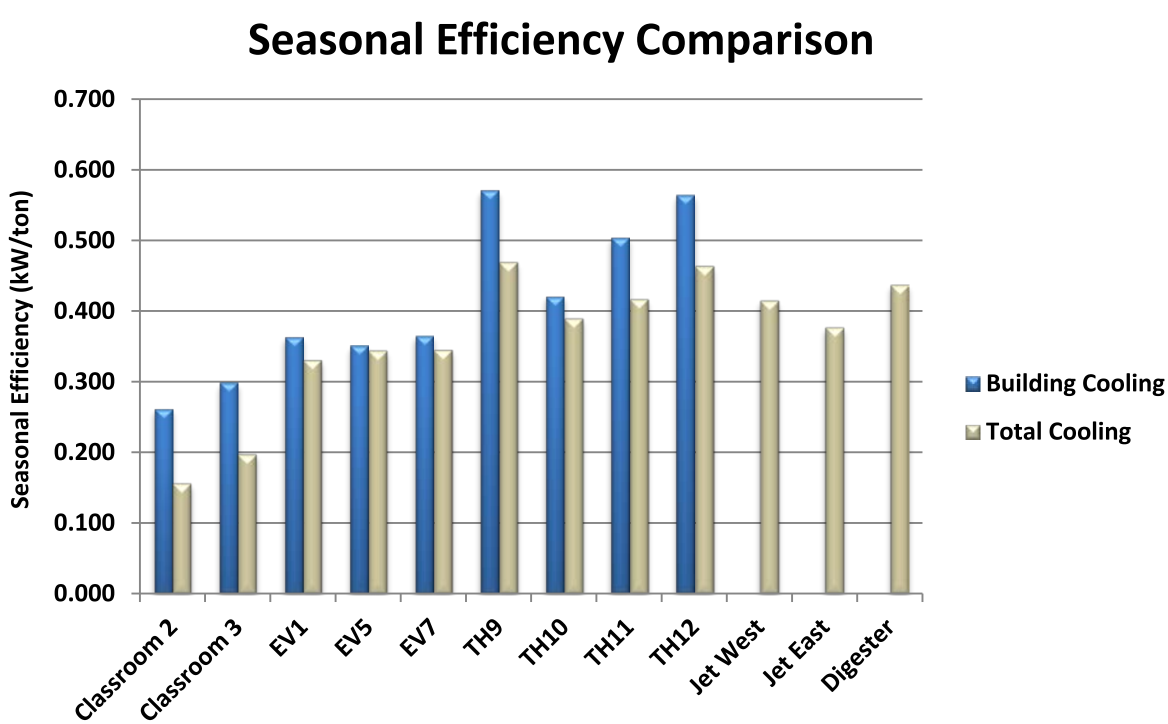


Figure 6. Coolerado seasonal efficiency comparison

The total energy use for each unit was multiplied by the ratio of the seasonal building efficiency of the Coolerado unit and the IEER of the proposed packaged unit (in kW/ton). The seasonal efficiency was calculated as a function of building cooling for all facilities except the jet aeration and digester units, where the total cooling efficiency was increased by 20% to properly model the seasonal building cooling efficiency.

The annual energy use for the 2011 cooling season was taken directly from measured energy use data and the water consumption was calculated based on the total cooling provided over the 2011 cooling season, assuming a water consumption rate of 3 gal/ton·h. Because the water settings were modified during the 2010 and 2011 cooling seasons, the water consumption rate during the first part of the summer was higher than at the end of the 2011 cooling season. The water consumption rate for the later part of the summer when the CoC setting was set to 5 was approximately 3 gal/ton·h and is indicative of future operation. The electricity rate at Fort Carson is $0.07/kWh and the water rate is $3.80/1000 gal.

The O&M costs of the Coolerado unit were based on maintenance logs from the Fort Carson demonstration. The maintenance time per unit was 7.25–2.65 h/unit/yr, depending on the installation and required maintenance. For this analysis, the annual O&M time is assumed to be 2.65 h. Using a standard maintenance labor rate from RSMeans ($54.375/h), the labor cost was assumed to be $144/unit and the material cost was assumed to be $15/unit for a total O&M cost of $160/unit/yr and the total cost premium per Coolerado unit was assumed to be $34/yr.[9]

Given the measured performance of the Coolerado units, the annual energy savings are estimated at 63.3% compared to a code-minimum RTU. The energy savings would be greater if compared to an older packaged RTU with an EER of 8–9.

Table 10 shows the installed costs for the five facilities and the wastewater unit.

Table 10. Coolerado Installed Costs

Location	Number of Units	Total Cost ($)	Cost per Unit ($)
Training center	4	$67,416	$16,854
Event center	8	$131,770	$16,471
Theater	8	$126,099	$15,762
Jet aeration	2	$25,625	$12,813
Wastewater facility	1	$13,141	$13,141
Wastewater unit ($)	1	$8,170	$8,170

The installed costs for the packaged RTUs was assumed to be $4,000–$5,200 per cooling ton and includes installed costs for the RTU and associated ductwork. The range was based on the amount of internal ductwork that would be needed. The RTU capacity was calculated assuming each Coolerado unit was rated at 3 tons of cooling, and one to two RTUs were assumed to be installed at each facility.

Table 11 shows the annual cost savings, incremental installed costs, and simple payback (SPP).

[9] RS Means Facilities Maintenance and Repair Cost Data Book, http://rsmeans.reedconstructiondata.com/

Table 11. Fort Carson Coolerado Economics

Facility Name	Annual Cost Savings ($)	Incremental Installed Cost ($)	Simple Payback (yrs)	NPV ($)
Training facility	–$16	$5,016	–312.6	-$5,416
Theater	–$38	$1,299	–33.8	-$2,249
Event center	$65	$6,970	107.9	-$5,344
Jet aeration	$111	$1,625	14.60	$1,151

The jet aeration facility had the best payback period, primarily because the units ran 24/7 throughout the cooling season because of the high internal loads. The increased runtime increased annual kilowatt-hour energy savings. The event center also had positive annual cost savings. The other facilities would have shown positive cost savings if the savings had been compared to an older RTU with an EER of 8–9.

Although the units significantly reduced energy use, the increased O&M and water consumption costs increased annual operating costs for facilities with reduced cooling loads and runtimes. Figure 7 shows the annual operating costs for the four units at the training facility compared to the annual energy costs of the RTU. The O&M costs represent a higher percentage of the total annual costs than the energy costs.

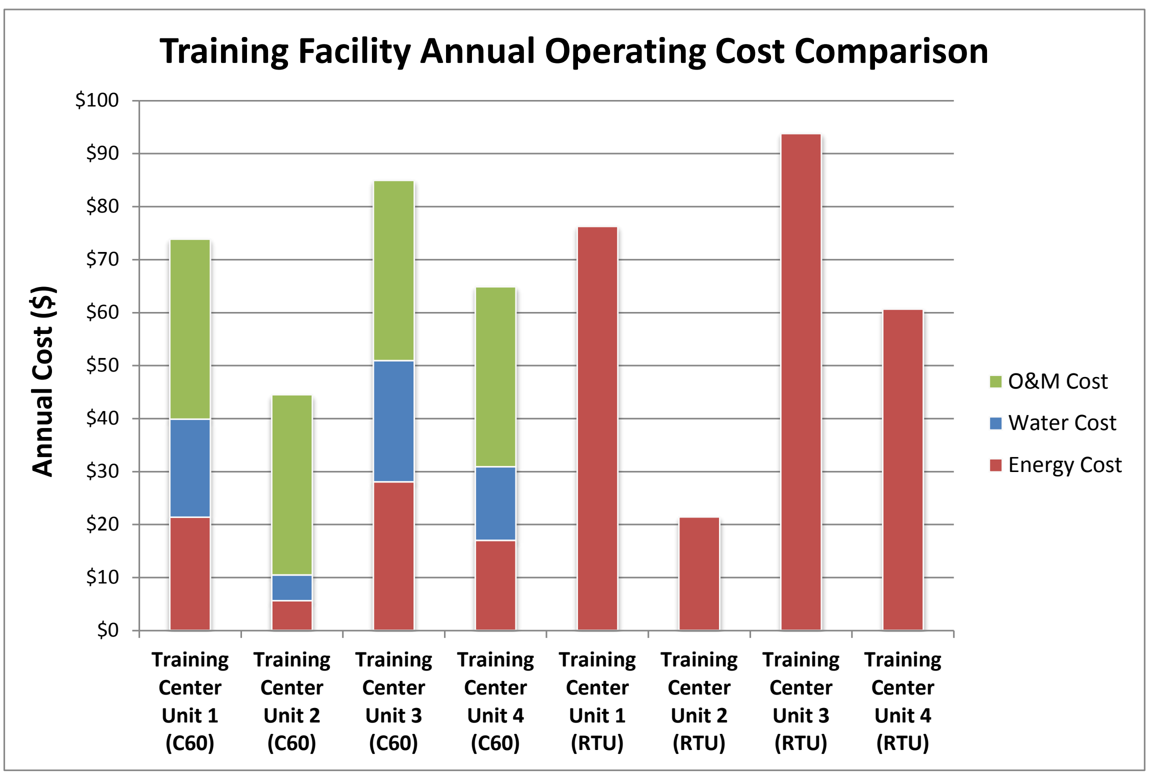


Figure 7. Training Facility Annual Operating Cost Comparison

The economics are very sensitive to O&M costs; any increase or decrease in O&M costs has a significant impact on the economics of the installation (see Table 12). Given that the O&M costs are subjective and the O&M costs for packaged RTUs can exceed the costs assumed here, the economics of the installation are provided without incremental increase in O&M.

Table 12. Fort Carson Coolerado Economics

Facility Name	Annual Cost Savings ($)	Incremental Installed Cost ($)	Simple Payback (yrs)	Net Present Value ($)
Training facility	$120	$5,016	41.8	-$2,015
Theater	$98	$1,299	13.3	$1,152
Event center	$201	$6,970	34.7	-$1,943
Jet aeration	$213	$1,625	7.62	$3,703

The estimated SPP was 7.62–41.8 yr, depending on the facility where the unit was installed.

7.1 COST ANALYSIS AND COMPARISON

The building types that were evaluated included a small classroom (400 ft^2), a data center (19,994 ft^2), and a quick-serve restaurant (2,500 ft^2). Coolerado performance was compared to common cooling technologies with respect to energy and water savings and a number of cost parameters. Energy savings, simple payback period, and net present value results are presented.

The baseline HVAC systems included a packaged single zone (PSZ) unit with DX coils (EER = 9) for the small classroom, a constant volume AHU with an air-cooled screw chiller (EER = 8.76) for the data center, and two constant volume RTUs for the quick-serve restaurant (one serving the kitchen, one serving the dining area). For the small classroom, a C60 Coolerado was modeled as a standalone zone cooler if the unit was able to meet 98% of the cooling load; otherwise, the M30 was modeled as an outside air pre-conditioner for the packaged unit. Thirty M30 Coolerados were modeled as zone coolers in the data center model. One C60 Coolerado was modeled as a pre-cooler retrofit on the RTU serving the kitchen in the quick-serve restaurant.

The utility rates applied to each model are listed in Table 13; water rates based on data from Fort Carson. Note that O&M and capital costs used in the models were adjusted for each location based on the following *RS Means* city cost adjustment factors: Phoenix, 93.7%; Las Vegas, 104.2%; Los Angeles, 105.3%, Albuquerque 87.4%; Colorado Springs, 90.0%; Helena, 88.2%.

Table 13: Utility Rates for Selected Locations

Location	Electricity Rate ($/kWh)	Natural Gas Rate ($/MMBtu)	Water Rate* ($/1000 gal)
Phoenix, AZ	0.116	7.81	3.75
Las Vegas, NV	0.139	8.13	3.75
Los Angeles, CA	0.101	7.29	3.75
Albuquerque, NM	0.075	6.52	3.75
Colorado Springs, CO	0.075	6.53	3.75
Helena, MT	0.076	7.48	3.75

7.1.1 Results

The results for the energy simulations are provided in Table 14; energy savings, simple payback, and net present value of the Coolerados are compared to the baseline technologies. (The quick-serve restaurant was modeled in two locations only.) Note that, the capital, consumables, and O&M costs used in the baseline models were taken from the *RS Means Facilities Maintenance and Repair 2001 Data Book*. Results show annual Coolerado energy savings ranging from 57% to 92% across all locations and building types. The economics were calculated using the federal life cycle costing procedures outlined in the Federal Energy Management Program Building Life Cycle Costing. The real discount rate for 2012 is 2%, with an inflation rate of 3.6% and a nominal discount rate of 5.6%. The real electricity escalation rate was set to -0.54%, which the nominal rate slightly less than the inflation rate, and the project lifetime is specified as 40 years.

Table 14: Energy Savings and Cost Analysis Results

Location	Metric	Small Classroom	Data Center	Quick-Serve Restaurant
Phoenix, AZ	Percent Energy Use Reduction	65%	77%	70%
	Simple Payback (yrs)	11	14.3	9.9
	Net Present Value	$6,552	$1,241,631	$1,999
Las Vegas, NV	Percent Energy Use Reduction	68%	76%	
	Simple Payback (yrs)	12.7	13.1	
	Net Present Value	$5,599	$1,666,419	
Los Angeles, CA	Percent Energy Use Reduction	63%	81%	
	Simple Payback (yrs)	52.1	16.5	
	Net Present Value	-$3,016	$969,384	
Albuquerque, NM	Percent Energy Use Reduction	66%	86%	
	Simple Payback (yrs)	173.5	17.7	
	Net Present Value	-$12,345	$638,040	
Colorado Springs, CO	Percent Energy Use Reduction	64%	88%	57%
	Simple Payback (yrs)	275.2	13	61.8
	Net Present Value	-$8,827	$1,091,370	$-6,835
Helena, MT	Percent Energy Use Reduction	65%	92%	
	Simple Payback (yrs)	345.4	14.4	
	Net Present Value	-$9,002	$1,060,271	

Coolerado applications have the best economics in data center applications due to their year-round cooling requirements. Simple payback periods and net present values vary across location due to variable capital costs, onsite water and electricity costs, O&M costs, and, in the case of the small classroom, application methodology. The quick service restaurant had favorable economics in Phoenix and unfavorable economics in Colorado Springs, and the simple payback was better in both climate zones than the single zone classroom. The single zone classroom unit showed favorable economics in Phoenix and Las Vegas.

The economic analysis indicates that the Coolerado technology has the best economics as a retrofit technology when it is competing against smaller air cooled air conditioning systems with energy efficiency ratios (EER) ranging from 8 to 12. DoD should target facility types with high internal loads and/or high ventilation rates that require year around cooling. A detailed description of applicable DoD bases, building types, and design guidelines is provided in the main of the report.

8.0 IMPLEMENTATION ISSUES

8.1 LESSONS LEARNED

Demonstration projects are an effective way to uncover hidden issues that can arise during operation. The following is a list of lessons learned during the demonstration at Fort Carson, which provide design considerations for future installations:

- *Water runoff.* Wastewater from the units installed at the theater was collected through polyvinyl chloride piping and flowed across a cement sidewalk to the adjoining grass. The water eventually created a safety hazard. Wastewater that will not be used for irrigation needs to be routed to a sewer drain or diverted to avoid puddles and prevent safety hazards. Another solution that should be explored is underground water storage tanks. Two 800-gal storage tanks were installed to collect wastewater for four Coolerado units at the theater before the 2011 cooling season. The tanks were tied into the local irrigation system and sump pumps supplied the water to the irrigation system (see Figure 8 and Figure 9).

Figure 8. Coolerado drain water piping

(Source: Jesse Dean, NREL)

Figure 9. Coolerado units and manhole over water storage tank

(Source: Jesse Dean, NREL)

- *CoCs.* The CoC setting (ratio of parts water evaporated to parts wastewater) has a significant impact on water consumption. For the 2010 and most of the 2011 cooling seasons, the CoC was set at 1.5–1.6 by Coolerado. This was standard practice at the time. Water consumption was 6–10 gal/ton·h. However, the recommended set point for the Coolerado is 5 CoC, with four parts evaporated for every one part drained. A CoC of 5 should be considered the upper limit for CoC in order to ensure cooling performance per design intent. At the end of the 2011 cooling season the settings were modified with the CoC setting of 5. As a result, the units were able achieve a water use rate of about 2.8 gal/ton·h, which is slightly higher than the requirement in the performance metric.
- *Sizing.* The Coolerado properly must be sized properly to achieve the highest possible efficiency. To meet indoor comfort conditions with undersized units, the temperature set points must be at a low setting, which could in turn lead to higher energy consumption and lower efficiencies than if the units were slightly bigger. Properly sized units will spend more time operating at partial fan speeds and at higher WBEs.
- *Sealing and winterization.* All units should be sealed with caulk when installed and winterized during the off season to minimize infiltration in climate zones that experience freezing. Observations showed air gaps around the ductwork on the through-the-wall units. Also, diligent winterization of units not used in the off-season will prevent drafts, reduce heating energy consumption, and maintain indoor comfort.

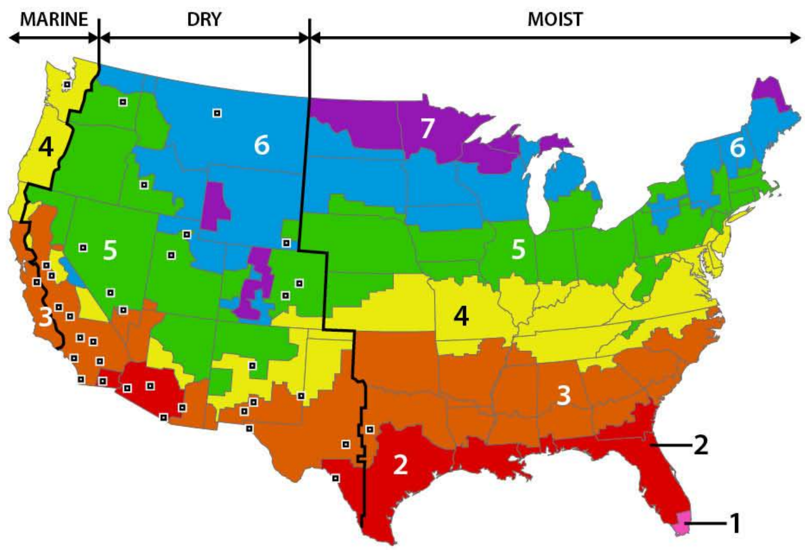
8.2 DECISION MAKING FACTORS

The following factors should be considered when evaluating the applicability of Coolerado Coolers in a particular area.

8.2.1 Climate

The target climate zones for the Coolerado technology are ASHRAE climate zones 2B, 3B, 4B, 5B, and 6B. The system should be installed as an OA pre-conditioner in climate zones 2B and 3B and can be applied as a zone cooler for climate zones 4B, 5B, and 6B.

Figure 10 shows a list of applicable military bases.



DYESS AFB	Abilene, TX	Air Force
GOODFELLOW AFB	San Angelo, TX	Air Force
LAUGHLIN AFB	Del Rio, TX	Air Force
HOLLOMAN AFB	HOLLOMAN AFB, NM	Air Force
WHITE SANDS MISSILE RANGE	WHITE SANDS, NM	Army
FORT BLISS	FORT BLISS, TX	Army
CANNON AFB	CANNON AFB, NM	Air Force
KIRTLAND AFB	KIRTLAND, NM	Air Force
EDWARDS AFB	California city, CA	Air Force
CHINA LAKE NAVAL AIR WEAPONS STATION	Ridgecrest, CA	Navy
DAVIS-MONTHAN AFB	Tucson, AZ	Air Force
FORT HUACHUCA	Huachuca City, AZ	Army
YUMA PROVING GROUND	Yuma, AZ	Army
YUMA MCAS	Yuma, AZ	Marine Corps
EL CENTRO NAVAL AIR FACILITY	EL CENTRO, CA	Navy
FORT IRWIN	Barstow, CA	Army
LEMOORE NAS	LEMOORE, CA	Navy
BARSTOW MC LOGISTICS BASE	BARSTOW, CA	Marine Corps
TWENTYNINE PALMS MC AIR-GROUND COMBAT CENTER	TWENTYNINE PALMS, CA	Marine Corps
NELLIS AFB	NELLIS AFB, NV	Air Force
Creech Air Force Base	Indian Springs, NV	Air Force
LOS ANGELES AFB	LOS ANGELES, CA	Air Force
FORT MacARTHUR	Los Angeles, CA	Army
LUKE AFB	Luke AFB, AZ	Air Force
CORONADO NAVAL AMPHIBIOUS BASE	CORONADO, CA	Navy

NORTH ISLAND NAS	San Diego, CA	Navy
FLEET ANTISUBMARINE WARFARE TRAINING CENTER	San Diego, CA	Navy
SAN DIEGO NAVAL MEDICAL CENTER	SAN DIEGO, CA	Navy
SAN DIEGO NS	SAN DIEGO, CA	Navy
SAN DIEGO NAVAL SUBMARINE BASE	SAN DIEGO, CA	Navy
AIR STATION MIRAMAR	San Diego, CA	Marine Corps
CAMP PENDLETON	Oceanside, CA	Marine Corps
SAN DIEGO MC RECRUIT DEPOT	SAN DIEGO, CA	Marine Corps
BEALE AFB	Yuba City, CA	Air Force
McCLELLAN AFB	North Highlands, CA	Air Force
TRAVIS AFB	Fairfield, CA	Air Force
BUCKLEY ANGB	Aurora, CO	Air Force
CHEYENNE MOUNTAIN AIR STATION	Colorado Springs, CO	Air Force
PETERSON AFB	Colorado Springs, CO	Air Force
SCHRIEVER AFB	Colorado Springs, CO	Air Force
U.S. AIR FORCE ACADEMY	Colorado Springs, CO	Air Force
FORT CARSON	Colorado Springs, CO	Army
MOUNTAIN HOME AFB	MOUNTAIN HOME, ID	Air Force
MALMSTROM AFB	Great Falls, MT	Air Force
HILL AFB	HILL, UT	Air Force
DUGWAY PROVING GROUNDS	DUGWAY PROVING GROUNDS, UT	Army
FAIRCHILD AFB	FAIRCHILD, WA	Air Force
WHIDBEY ISLAND NAS	WHIDBEY ISLAND, WA	Navy
F.E. WARREN AFB	F.E. WARREN, WY	Air Force
FALLON NAS	FALLON, NV	Navy

Figure 10. Military bases by ASHRAE climate zone

(Source: Joelynn Schroeder, NREL)

8.2.2 HVAC Equipment Replacement

When the HVAC equipment is at the end of its useful life and needs to be replaced, the economics of the Coolerado improve over the retrofit costs presented in the market analysis. For example, if the CRAC units in a data center need to be replaced it would be more cost effective to use that funding to supplement the installation of Coolerado units and leave the CRAC units as the backup supplementary cooling system.

8.2.3 Facilities with No Cooling and New Construction

The economics of the units will also improve when there is no air-conditioning system and when applied to new construction. In this case the installed costs were associated with the incremental costs above those of traditional air-conditioning equipment and the associated ductwork.

8.2.4 Facility Types

The technology has the best economics when applied to facilities with high internal cooling loads that require year-round cooling and when competing against air-cooled direct refrigeration-based air-conditioning systems. The top facility types are discussed here:

- *Data centers.* Data centers have the highest internal loads of any facility type. These facilities typically have no economizer cooling and can accept higher SATs.
- *Quick service.* Quick-service restaurants have very high internal loads and ventilation rates, and are typically conditioned with packaged RTUs. This facility type is also ideal for Coolerado units.
- *Supermarket, dining/restaurant, small medical, laboratory, computer room classroom*. All these building types have strict environmental regulations, high internal loads, or high ventilation rates and are good candidates for the Coolerado unit as an OA pre-conditioner in climate zones 2B and 3B.
- *Office, warehouse, barracks, other.* All the building types with lower internal loads and ventilation rates are potential candidates for the unit, but the reduced hours of operation will increase the SPP period.

APPENDIX A: POINTS OF CONTACT

All points of contact involved in the demonstration are provided in Table A-1.

Table A-1. Points of Contact

POINT OF CONTACT Name	ORGANIZATION Name Address	Phone Fax E-mail	Role in Project
Jesse Dean	National Renewable Energy Laboratory	303-384-7539 Jesse.Dean@nrel.gov	Co-Principal Investigator
Eric Kozubal	National Renewable Energy Laboratory	303-384-6155 Eric.Kozubal@nrel.gov	Co-Principal Investigator
Lesley Herrmann	National Renewable Energy Laboratory	(303) 275-4318 Lesley.Herrmann@nrel.gov	Investigator
Scott Clark	Fort Carson DPW	719-526-1739 scott.b.clark@us.army.mil	Site Sponsor, Fort Carson Project Manager
Tim Heaton	Coolerado	720-974-9612 timheaton@coolerado.com	Industry Partner, Coolerado Vice President
Mark Eastment	Eastment Consulting	303-956-3927 meastment@gmail.com	DAS
Ed Hancock	Mountain Energy Partnership	(303) 517-8238 CEHancock3@aol.com	DAS
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