YORK®

INSTALL CONFIDENCE.

# EcoAdvance™

## HLR1000E

## Application Guide


Johnson Controls

With the YORK® EcoAdvance™ HVAC load reduction (HLR®) module, you can maintain indoor air quality while reducing energy costs associated with Heating, Ventilation and Air Conditioning (HVAC) systems. The EcoAdvance HLR module is a "smart scrubber" that replaces costly ventilation methods with a practical, proven, energy-saving approach using the latest advances in materials and chemical engineering as well as digital technology. By treating the indoor air, YORK's innovative EcoAdvance solution minimizes the amount of outdoor air required to maintain indoor air quality and thereby reduces the load on the HVAC system and its energy consumption.


A typical building installation contains a network of multiple HLR modules that remove molecular contaminants from indoor air, control outside air usage, and continuously monitor and analyse the indoor air quality. The HLR1000E module is designed specifically for indoor installation and is easily installed within a mechanical room or an indoor air plenum, without any change or impact to your HVAC system.

# Functionality

The HLR module actively and automatically manages HVAC cooling and heating load and indoor air quality (IAQ). Its dramatic results are enabled by the following four integrated capabilities:

## Indoor Air Treatment

- Eliminate carbon dioxide, formaldehyde and volatile organic compounds (TVOCs)
- Embedded sensors continually monitor indoor air quality, sorbent performance, and system operating conditions to ensure optimal IAQ management

## Outside Air Management

- Electromechanical control of the HVAC system's outside air damper minimizes the amount of outside air ventilation based on energy and air quality considerations
- Automatic failsafe setting in case of fire emergency, power outage or malfunction

## Automated Regeneration

- Typically once a day, cartridges are regenerated, causing the sorbents to release the captured contaminants
- Regeneration is scheduled, managed and timed for optimal performance and minimal energy use

## Monitoring and Reporting

- Built-in electronics and software, including networking for on-line internet connectivity, engineered to control, record and report all aspects of the HLR system operation
- Sophisticated proprietary algorithms designed to maximize energy savings

*HLR is a registered trademark of enVerid Systems, Inc.*

# Introduction

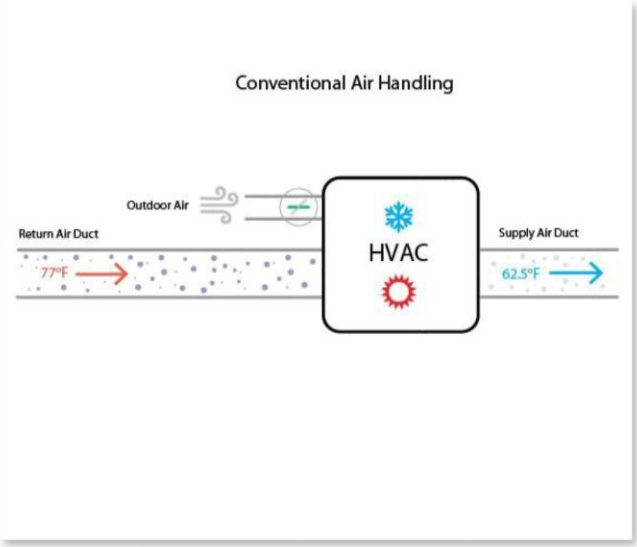
The YORK® EcoAdvance™ HVAC Load Reduction (HLR®) module is a 'smart scrubber' that replaces costly ventilation control methods with a practical, proven, energy-saving approach using the latest advances in materials and chemical engineering as well as digital technology. By treating the indoor air, YORK's innovative EcoAdvance solution minimizes the amount of outdoor air required to maintain indoor air quality (IAQ) and thereby reduces the load on the HVAC system and its energy consumption.

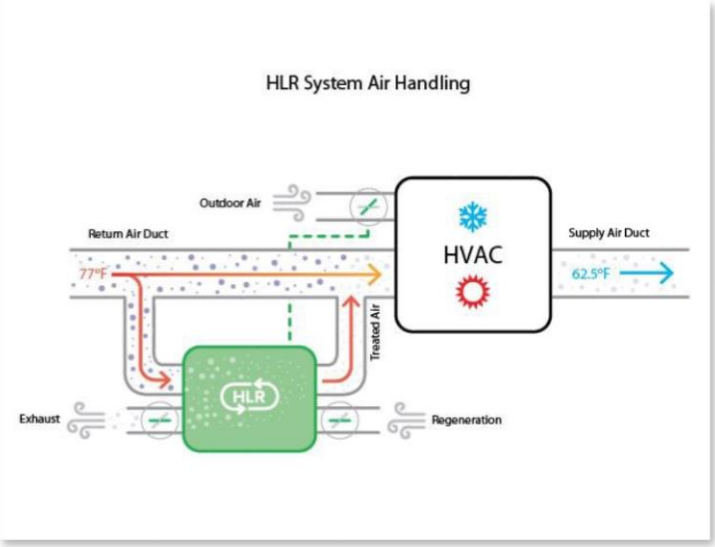
The HLR1000E offers the benefits of double-digit energy savings while maintaining indoor air quality (IAQ) and is an 'all season' system, automatically managing HVAC cooling and heating loads. The HLR1000E is a closed-loop design with each module having an integrated heating, mechanical, electrical, and communication system.

# The Problem the YORK® EcoAdvance™ Addresses

Widely adopted approaches to maintaining indoor air quality are outdated and inefficient. Rather than the costly process of continually taking in outdoor air to maintain indoor air quality, the HLRmodule directly treats the indoor air by scrubbing out contaminants with its patented sorbent technology. This minimizes the load on the HVAC system, therefore significantly reducing its energy consumption.

The YORK EcoAdvance HLR1000E guarantees ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality IAQP compliance levels and is recognized as an acceptable method to achieve this standard.



# EcoAdvance Overview: The System, the Module and the Sorbents

## The EcoAdvance System

The system is a group of networked HLR1000E modules installed in the mechanical rooms or indoor air plenums in a building.

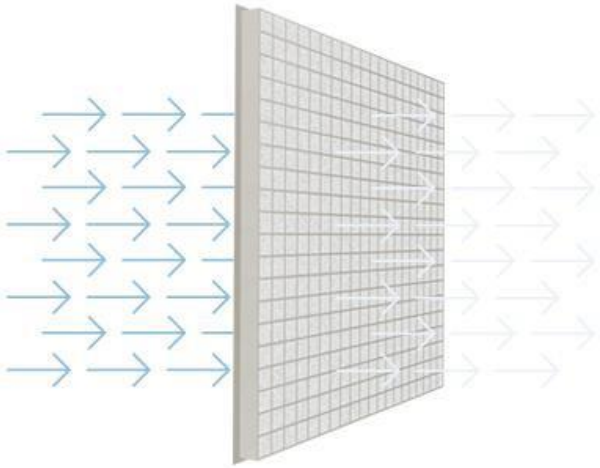
The HLR1000E incorporates state-of-the-art wireless technology for peer-to- peer and cloud connectivity enabling enhanced real-time monitoring, reporting and system results validation


## The HLR1000E Module

A fully self-contained mechanical design with easy side- by-side retrofit to existing HVAC infrastructure.


- All season module; heating and cooling
- Designed to maximize energy efficiency & savings
- Operates using standard single-phase power
- Light-weight, easy to install

### The Sorbents



Two processes sequentially operate to scrub the indoor air and purge the captured contaminants to maintain indoor air quality. Advanced technology, including materials and chemical science breakthroughs, enables patented sorbents to capture $CO_2$, formaldehyde and VOCs during the sorption process. Air travels through the sorbents housed in the cartridge set for the air to be cleaned. Sensors monitor the sorbents for saturation, and then the regeneration process is automatically launched to purge the sorbents of the captured contaminants, exhausting them outside the building.

## Functionality and Benefits

### Functionality

The HLR1000E module actively and automatically manages HVAC heating and cooling load and indoor air quality. Its dramatic results are enabled by the following four integrated capabilities:

#### Indoor Air Treatment

- Proprietary cartridges contain patented sorbents that eliminate carbon dioxide, formaldehyde and volatile organic compounds (VOCs).
- Embedded sensors continually monitor indoor air quality, sorbent performance and system operating conditions to ensure optimal IAQ management.

#### Automated Regeneration

- Several times a day, cartridges are 'regenerated', causing the sorbents to release the captured contaminants to the outside of the building.
- Regeneration is scheduled, managed and timed for automatic performance and minimal energy use.

### Outside Air Management

- Electromechanical control of the HVAC system's outside air damper minimizes the amount of outside air ventilation based on energy and air quality considerations.
- Automatic fail-safe setting in case of fire emergency, power outage or malfunction.

### Monitoring and Reporting

- Built-in electronics and software, including networking for online internet connectivity, engineered to control, record and report all aspects of the HLR system operation.
- Sophisticated proprietary algorithms designed to maximize energy savings.

## Benefits

The HLR1000E module delivers significant energy savings while maintaining indoor air quality. The benefits of the EcoAdvance solution include:

### Load Reduction and Energy Savings

- Over 30% reduction in peak power load
- 20% average energy cost savings (heating and/or cooling)

### Indoor Air Quality

- The only commercial solution that effectively addresses $CO_2$, formaldehyde and VOCs
- Dramatically reduced intake of outdoor pollutants

### Real-time Monitoring, Reporting and Validation

- 24/7 online access to performance metrics including air quality and real-time, validated energy savings
- Remote control of the system at your fingertips by computer or smart phone

### Scalability and Flexibility

- Easy side-by-side retrofit with existing HVAC infrastructure
- A network of multiple HLR1000E modules offers a scalable solution for any building
- Simple, turn-key installation; vertical or horizontal installation; fits through standard doorway; lightweight
- Requires minimal labor for installation

### Reliability

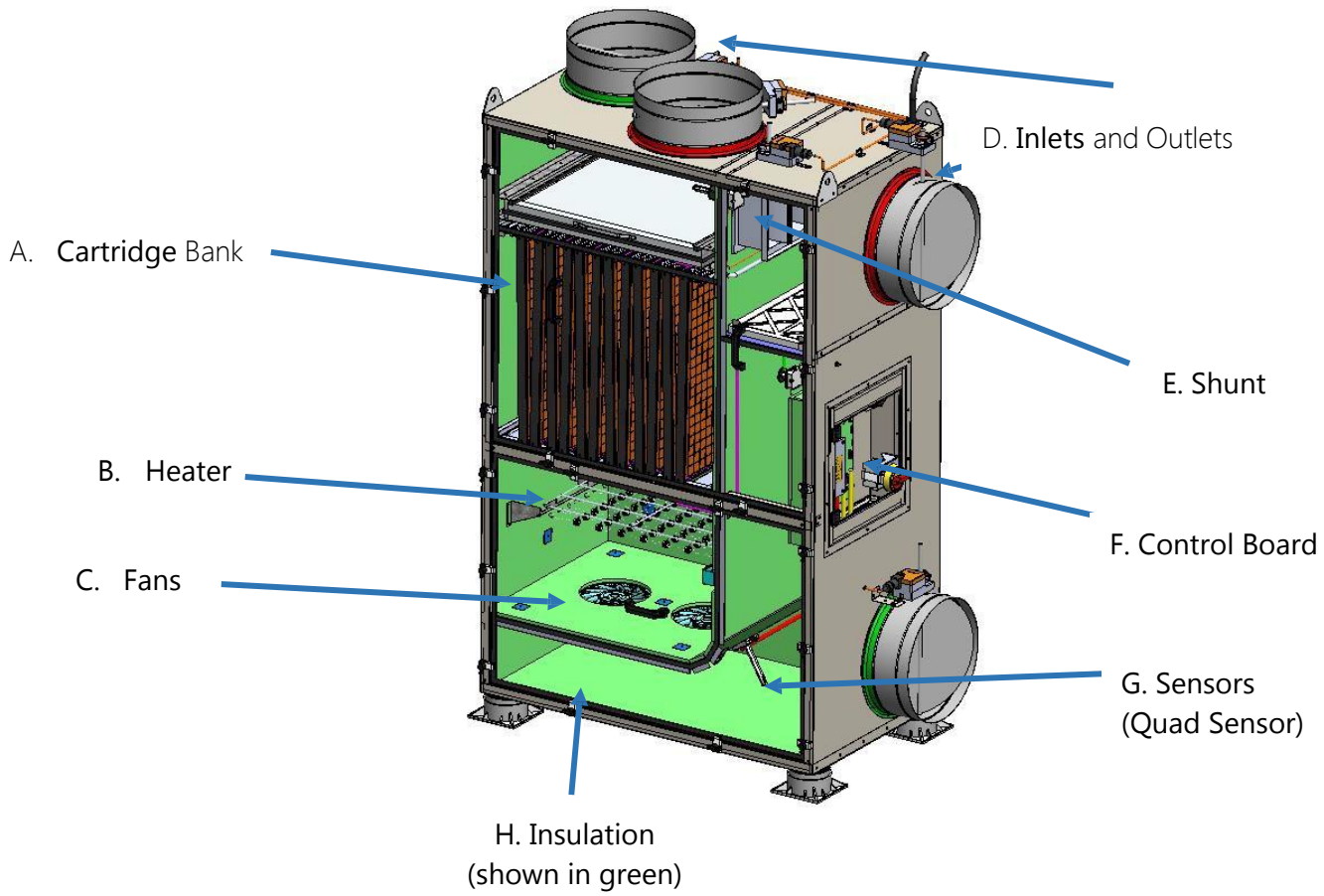
- Minimal routine maintenance; cartridge set replacement only once a year
- Robust design delivers 20+ year operating life

### Compliance and Sustainability

- Meets ASHRAE Standard 62.1 for ventilation and indoor air quality
- Qualifies for U.S. Green Business Council LEED credits

## Component Location and Description

The HLR1000E works in all climates. Each HLR1000E module is a self-contained cabinet pre-assembled with the following components




A. **Cartridge Bank** – The cartridge bank houses a set of twelve cartridges which contain the sorbents that collect select contaminants ($CO_2$, formaldehyde and VOCs) during the sorption (cleansing) cycle and then release the captured contaminants during the regeneration (outdoor purge) cycle. Cartridges are constructed in polypropylene further reducing total weight of the unit.

B. **Heater** – The integrated heater raises the internal temperature of the HLR1000E to initiate the process of releasing the captured contaminants. During this time all external dampers are closed, and air is re-circulated inside the HLR1000E to accelerate the release process.

C. **Fans** – Integrated DC brushless fans control the airflow through the HLR1000E during the sorption and regeneration cycles. The controller has speed control and active feedback from the fans verifying correct operation.

D. **Inlets and Outlets –** The HLR1000E module has 2 circular inlets and two circular outlets controlled by dampers. The inlets that route the air during sorption are highlighted in green. The outlets that route the air during the purge portion of the regeneration cycle are highlighted in red.

E. The internal **Shunt** that is used during the heating portion of the regeneration cycle is controlled by a damper that is only open when all other dampers are closed.

F. **Control Board –** The electronic enclosure contains the HLR1000E power supply and the controller board. The power supply converts the incoming AC power to the necessary voltages to operate all aspects of the unit. The controller contains the systems software, all controls/relays/sensor interfaces, as well as all wireless and wired communication modules.

G. **Sensors –** The HLR1000E unit contains three integrated internal multi-sensor modules used to measure temperature, humidity, $CO_2$ concentration, formaldehyde and VOC levels during the sorption and regeneration cycles. The HLR1000E has two additional temperature and humidity sensors for monitoring the incoming outside air and the supply air from the air handling unit (AHU) to the conditioned space.

H. **Insulation –** The inside walls of the HLR1000E unit are covered in heat-reflective insulation material for improved efficiency of the unit and soundproofing.

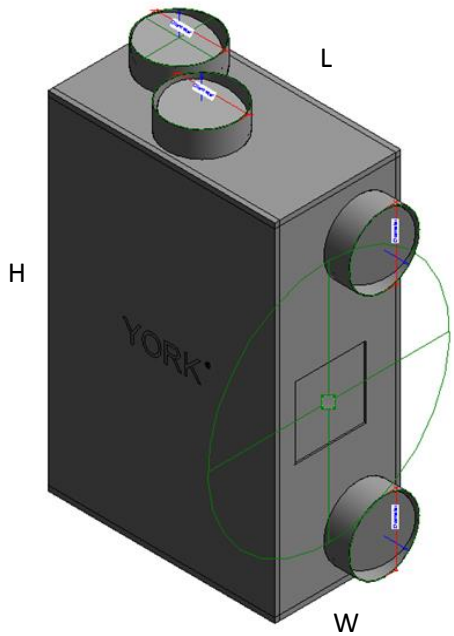
## ASHRAE Standard 62.1 Compliance

The YORK EcoAdvance HLR1000E guarantees ASHRAE Standard 62.1: Ventilation for Acceptable Indoor Air Quality IAQP compliance levels. The HLR scrubbing system is formally in compliance with ASHRAE 62.1 Standard requirement and fits within the IAQP. The ASHRAE official document issued on January 25, 2015 publicly states and affirms that the use of air cleaning as a method to remove contaminants of concern is an acceptable method to decrease outdoor airflow.
Interpretation 62.1-2013-4-January 25, 2015

## Air Flow Capacity

The HLR1000E is designed to handle 800 CFM (cubic feet per minute) of air in a slipstream configuration drawn from the return air path of the HVAC system. The number of modules required for any given building is determined by multiple considerations including contaminant sources, floor space, occupancy, exhaust systems and building pressurization. A typical guideline for office buildings is to have one HLR1000E for approximately every 20,000 square feet of floor space, however only a qualified EcoAdvance installation professional can determine the correct number and configuration of units required.

## Weight and Dimensions




| Weight | lbs (kg) |
|---|---|
| Unit Cabinet | 208 (94.3) |
| Unit with Cartridge Set | 428 (194.1) |

| Dimensions | Unit | Unit with Dampers & Handles |
|---|---|---|
| Length | 43.5" (110.5 cm) | 48.5" (128.2 cm) |
| Width | 25" (63 cm) | 26" (66 cm) |
| Height | 68" (172 cm) | 73" (185.4 cm) |

# Electrical Panel

## a. Power Requirements

The HLR is designed to work with single phase AC power and can accommodate a range of line voltages and frequencies.

| | Unit | Heaters |
|---|---|---|
| Supply | 208-240 Vac / 50-60Hz / 40A | (2 circuits) = 2.750 Kw each = Total 5.5 Kw |
| | 277 Vac / 50-60Hz / 35A | (2 circuits) = 3.250 Kw each = Total 6.5 Kw |

## b. Communications

Each HLR1000E module includes wireless communication capabilities for ongoing monitoring and reporting of indoor air quality, sorbent performance and system operating conditions. This wireless link is a state-of-the art solution with a long-range reach and ultralow power consumption. The HLR1000E is able to communicate with all BACnet™ based building management systems.

| | | |
|---|---|---|
| Communications | Cellular Link | 2.5G/3G |
| | Wireless Link | 915 MHz |
| | BACnet over MSTP | ISO-RS485 |

## c. Fans & Heaters

Powerful, light-weight digitally controlled fans combined with an integrated heater deliver an effective and efficient variable air flow solution.

| | | Voltage/Power |
|---|---|---|
| Air Flow Components | Fan(s) | 24VDC/72W (each) |
| | Heater with PID control | 277VAC/6.5kW |

## d. Built-in Connections – Required

The HLR1000E interfaces to the AHU (air handling unit) using the required built-in connections listed below. The minimum number of connections in order to operate the HLR1000E with an AHU are as follows:

1. Outside Air Damper Actuator – The HLR1000E must take control of the Outside Air Damper actuator. This is the key factor that enables the energy savings and load management when using the HLR1000E.

2. Outside Air Damper Reading – The HLR1000E requires reading the position signal from the OA damper to ensure that the HLR1000E is setting the damper to the correct position.

3. Fire Signal – The fire signal is commonly generated from the fire panel or building automation system in the event of a fire in the building and is used to put the outside air damper and the HLR1000E and other air handling devices in a mode that will inhibit smoke/fire from spreading throughout the building through the air ducts.

4. Air Handler Mode – The HLR1000E operates in conjunction with the AHU.

| | | |
|---|---|---|
| Connections | OA Damper Control | Output from HLR1000E: 2-10 VDC |
| | OA Damper Position Monitoring | Output from HLR1000E: 2-10 VDC |
| | Fire Signal Dry Contact Input | Input to HLR1000E |
| | AHU Mode Input | Input to HLR1000E |

### e. Building Automation System Capabilities – Additional Available Connections

| | | |
|---|---|---|
| Connections | AHU Fan Speed Input | Input to HLR1000E |
| | BAS* Open OA Damper Input | Input to HLR1000E |
| | BAS Close OA Damper Input | Input to HLR1000E |
| | Energy Meter D Input | Input to HLR1000E |
| | Available 24 V Relay Output | Output from HLR1000E 24V/1A |
| | Available Dry Contact Output | Output from HLR1000E 1A (max) |
| | Available Dry Contact Input | Input to HLR1000E |

*BAS - Building Automation System

### e. Sensors

| | Sensor Function | Location | Measurement* |
|---|---|---|---|
| Multi Sensor | Measures incoming air | HLR Interior | T,RH, IAQ |
| TRH Sensor - AHU | These sensors measure energy use | SA Duct | T,RH |
| | | OA Duct | T,RH |
| Pressure Sensor | Measures pressure | HLR Interior | P |
| Sorbent Temp | Measures temperature during regeneration | HLR Interior | T |

*Legend: T (temperature); RH (relative humidity); IAQ (Air Quality); P (pressure)

*(Note: BAS Point list on Page 61)*

## Description of HLR1000E Modes

- Sorption Mode – The HLR1000E forces air to pass through the sorbents, capturing CO2, formaldehyde and VOCs, and returns the cleansed air back into the airstream.
- Regeneration Mode – The HLR1000E is disconnected from the normal airstream, purging the sorbents with heated air and exhausting contaminants outside the building.
- Standby Mode – When not in an active mode, the HLR1000E does not carry air flow, but does continue to monitor its air quality sensors.

## Monitoring and Reporting

Each HLR1000E module has built-in electronics and software to record and report all aspects of the HLR system operation. A custom SCADA (supervisory control and data acquisition) interface allows users to view real-time and historical data to monitor IAQ and energy savings results. Authorized users have a login with defined permission levels providing access to a website where results can be monitored. The data is uploaded via a wireless link.

## Annual Maintenance - Cartridge Set Replacement

The HLR1000E module is designed to require minimal on-site routine maintenance. Annual cartridge set replacement is the only required standard maintenance. This can be performed by any certified technician. With ongoing maintenance, the HLR1000E modules are designed for a long operating life of 20+ years.

### Cartridge storage

HLR cartridge sets should be stored indoors away from direct sunlight in -10 °C to +35 °C (14°F to 95°F). Cartridges should be kept in their plastic wrap to protect them from moisture or damage prior to installation.

### Recycling of cartridges

when cartridges are replaced, the used cartridges should be placed in the packaging from the replacement cartridges, sealed, and shipped back using the return mailing label provided in the cartridge packaging.

## Installation Specifications

The HLR1000E is designed for simple, turn-key installation.

- Simple Installation - the HLR1000E is designed for simple installation with physical dimensions enabling each unit to fit through a standard doorway; its light weight provides for easy transportation and positioning. Three requirements:

    1. Electrical power
    2. A wireless data connection is built-in; for a wired connection, cable must be hooked up during installation.
    3. Air duct connections. The round control dampers ensure quick and cost-effective installation to ducts without needing transitions

- The HLR1000E can be installed by one person in approximately 30 minutes.

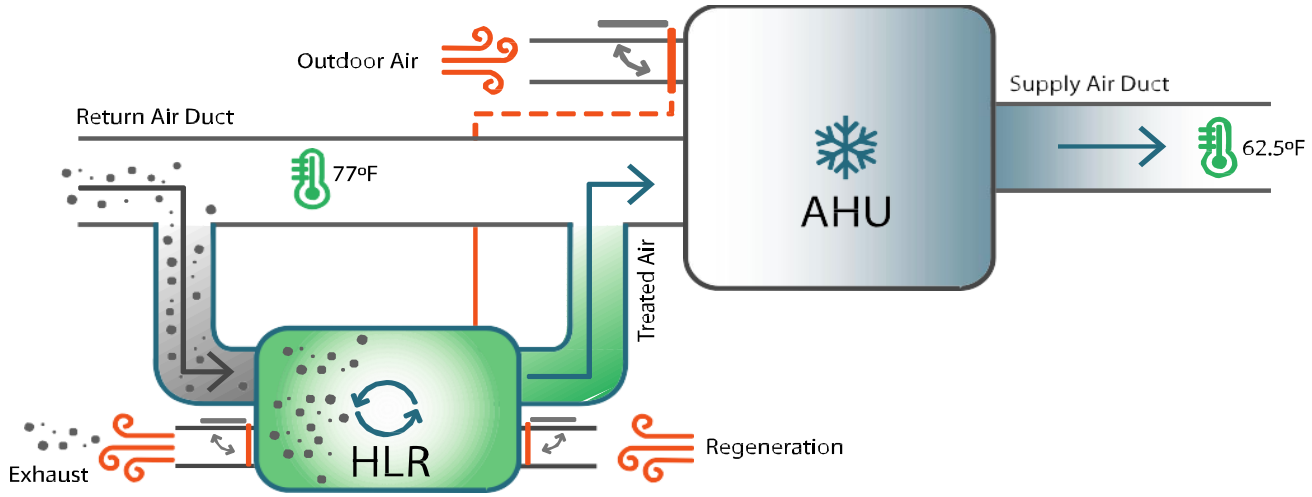
  Indoor installation - durable finish, sturdy construction and reflective insulation make the HLR1000E compatible with indoor installations. The modules can be located anywhere in the general vicinity of the Air Handling Unit (AHU), in the building's mechanical rooms.

- Vertical or horizontal installation for easy side-by-side retrofit to existing HVAC infrastructure
- Two options for installation:

  Case I: Ducted Return
  Case II: Plenum Return

## Case I: Ducted Return

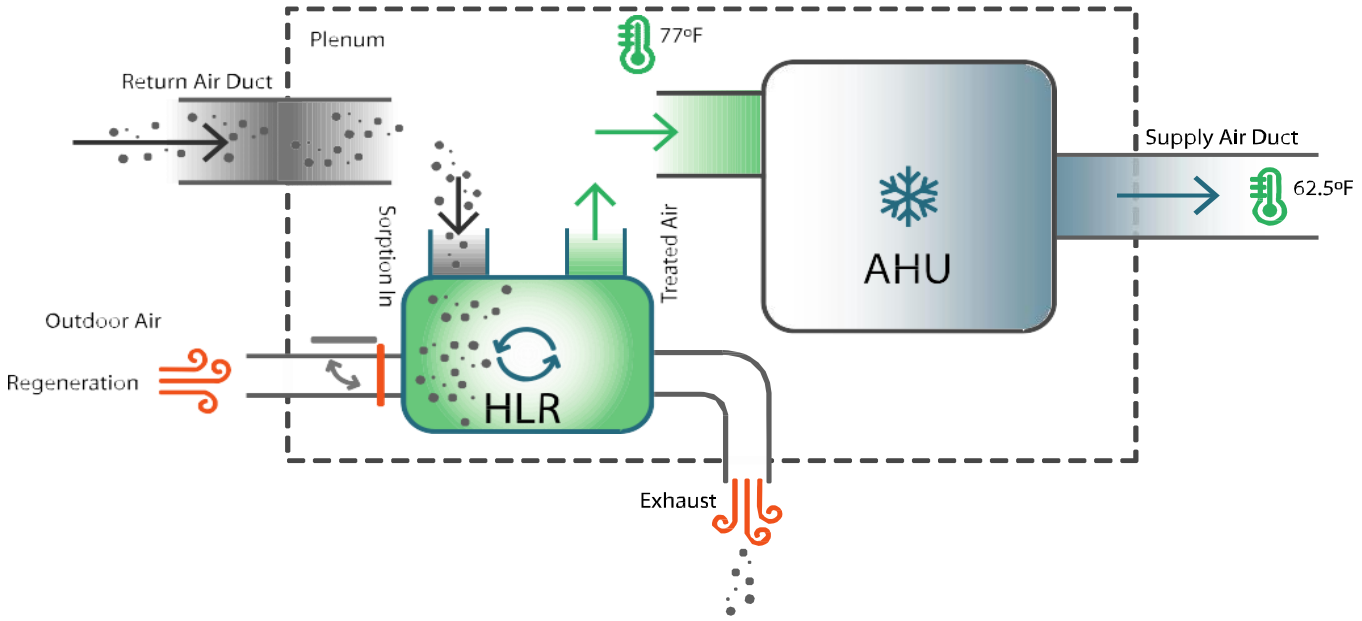
The HLR1000E module is designed for a slipstream topology, and the air flow through the module is, by design, a small fraction of the total circulation.




The slipstream topology, as shown in the schematic above, is a unique feature of the EcoAdvance solution. Among other things, it allows the system to go offline for regeneration or for maintenance without any disruption to the building ventilation systems. The inlet and the outlet of the HLR1000E module are independently ducted to the indoor air ducts. The flow rate through the HLR1000E is a small fraction of the total circulation and varies by indoor contaminant load

## Case II: Plenum Return

In plenum-based return air systems, the HLR1000E module can be positioned inside the plenum with no ductwork for the indoor air. The module pulls in air from the plenum and ejects treated air back into the plenum. However, in this type of installation, the purge air inlets and outlets must be ducted to an appropriate outside air source and exhaust, respectively.



Below are some high level installation steps for the HLR1000E. Consult the installation manual and any relevant National and Local codes as required.

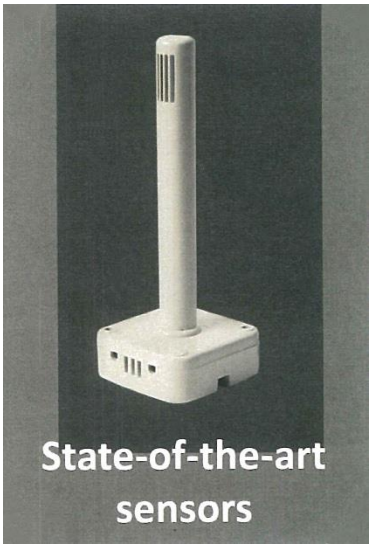
1. Bring the HLR1000E and cartridges to the installation area. The HLR1000E and cartridge set are shipped in separate containers and should be transported in these separate containers until the cartridges are ready to be installed.
2. Unpack the HLR1000E and place in the orientation required for the particular installation.
   Note: the HLR1000E operates in either a horizontal or vertical configuration.
3. Remove the upper door exposing the cartridge compartment.
4. Install the cartridges per the installation instructions.
5. Install the upper door closing the cartridge compartment.
6. Connect the four (4) required ducts. All ducts are standard round 14-inch style.
7. Connect the two (2) remote sensors to the HLR1000E unit per the installation instructions.
8. Connect AC power to the HLR1000E unit per the power requirement instructions.
9. Turn on the HLR1000E unit using the front panel power switch.
10. Complete the commissioning and testing procedure per the installation instructions.

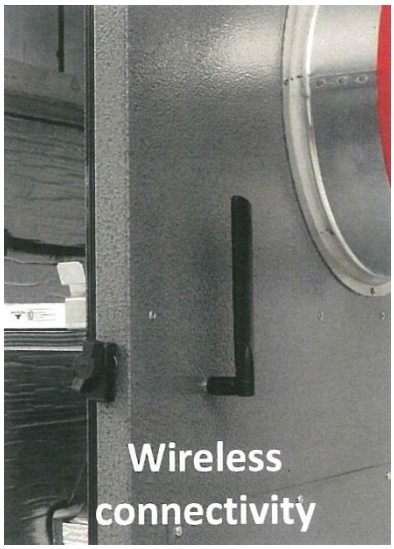
## Support

For additional support required during installation or operation, please contact the Product Technical Support.

ALL PRODUCTS, PRODUCT SPECIFICATIONS AND DATA ARE SUBJECT TO CHANGE WITHOUT NOTICE TO IMPROVE RELIABILITY, FUNCTION, DESIGN OR OTHERWISE

# Leveraging Internet of Things (IOT)



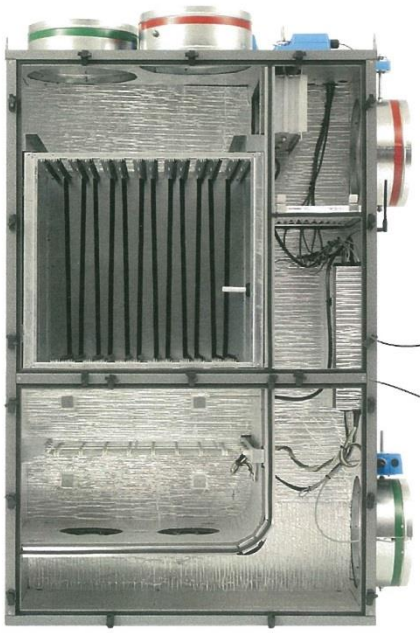

# IOT: Comprehensive Sensing

### Other Connections

- Outside air (OA) damper control
- OA damper position monitoring
- Air handling unit (AHU) status
- Fire signal dry contact

### Output Sensor

- Temperature
- Humidity
- $CO_2$



### Outside duct sensor

- Temperature
- Humidity

### Cartridge Bank

- Temperature
- Pressure

### AHU Supply duct sensor

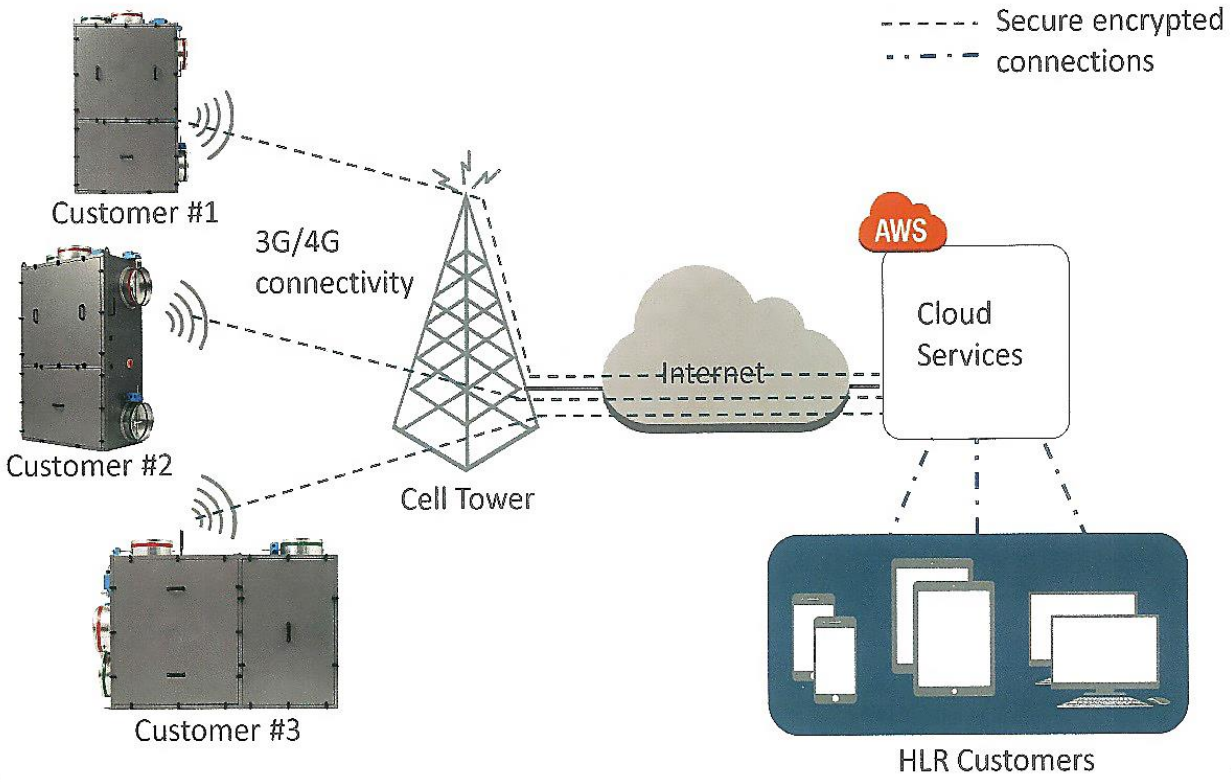
- Temperature
- Humidity

### Input Sensor

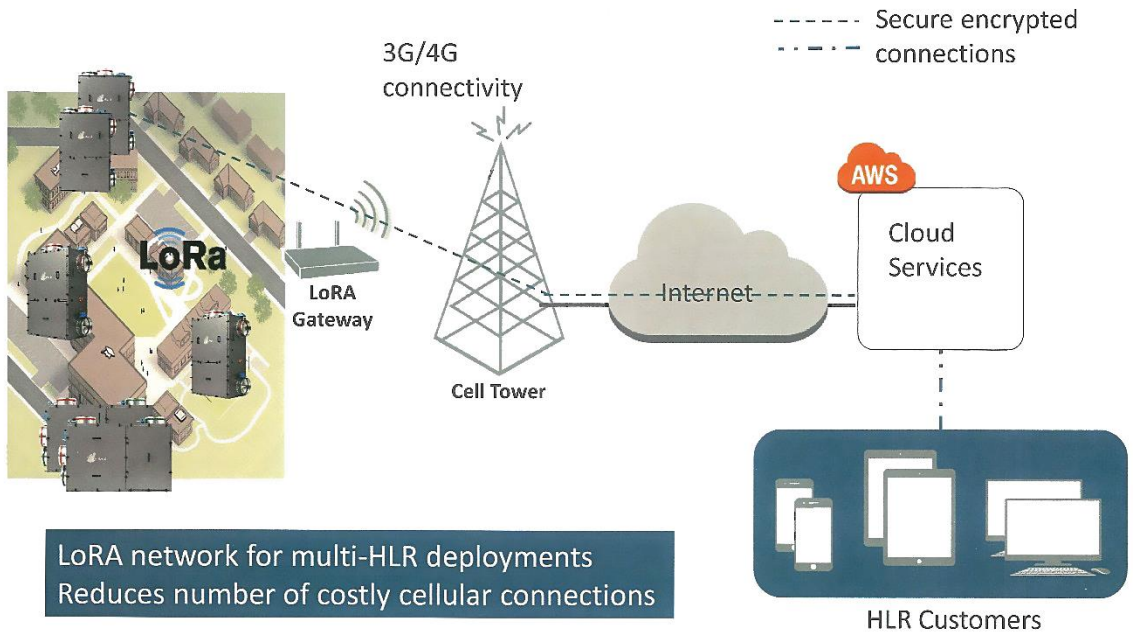
- Temperature
- Humidity
- $CO_2$
- Total VOC (tVOC)

## Advanced algorithms use sensor data to optimize energy saving & IAQ

## IOT: Connectivity Architecture




## IOT: "HLR Cluster" Architecture (ROADMAP)



# Johnson Controls

Preliminary Joint Technical Report:
**Installation and Initial Operation of an HLR Retrofit Unit**
Citibank, San Antonio

Report Date: October 23, 2013

## I. Executive Summary

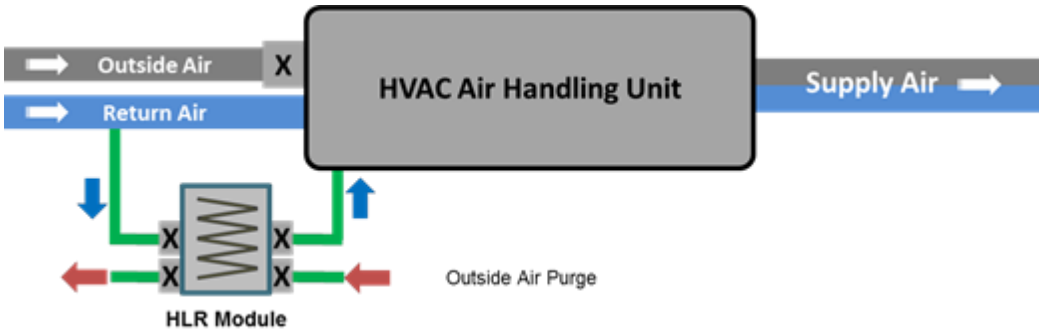
We report on the installation and early results of the first US deployment of HLR technology for energy savings in commercial HVAC systems. An add-on retrofit module was attached to a rooftop air handling unit in one of Citibank's office buildings in San Antonio, Texas. Installation was successfully performed in August 2013 by employees of Johnson Controls and HLR Systems. The system has been operational since August 28, 2013. We have run in in comparative mode, namely intermittently for several days at a time, over the subsequent weeks while carefully monitoring chilled water consumption, outdoor conditions and indoor air quality. This allows accurate comparison of energy consumption and air quality, with and without the system. The results confirmed an average **savings of 35 - 40%** in chilled water energy consumption while keeping indoor carbon dioxide and volatile organic compound levels comfortably below target levels of **excellent indoor air quality**. The energy savings are climate sensitive and represent the September climate of central Texas with characteristically hot dry weather midday and moderate, humid nights. The energy savings need to be adjusted for the HLR units' energy use but based on current estimates this will only cause a minor correction in overall energy saved. Data will continue to be gathered over the fall season and beyond to allow estimate of annualized energy savings. Our preliminary conclusion is validation that the technology can **safely offer significant, double digit energy savings** in a warm climates.

## II. Background

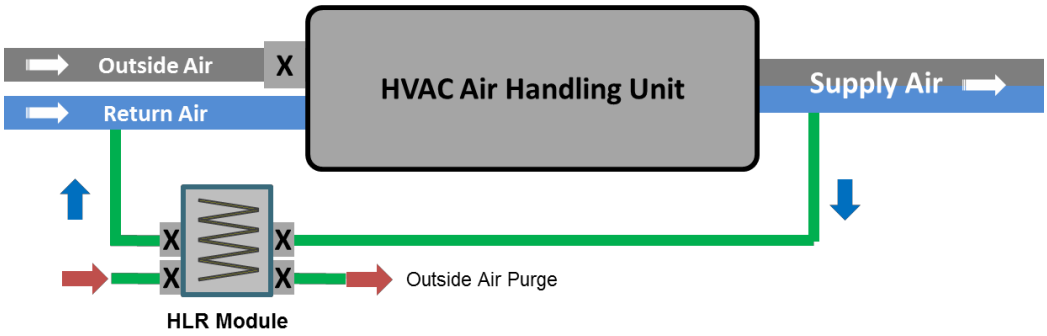
Johnson Controls Inc. have been working into commercialize new air treatment technology that is designed to reduce energy consumption in commercial HVAC systems. The technology, which was developed and patented by HLR, removes carbon dioxide ($CO_2$) and volatile organic compounds (VOCs) from indoor air. This largely reduces the need for outside air ventilation. Ventilation air represents a substantial fraction of a building's overall heat load, so reducing outside air intake is expected to yield commensurate energy savings, especially when outside temperature and humidity are significantly higher than indoors.

The solution is implemented in the form of an add-on unit called the HLR1000E module, which is designed to be retrofitted alongside the existing central air handling unit. A slip stream of about 5 – 10% of the total circulation is directed to flow through the HLR module. As the air flows through the module, $CO_2$, VOCs and other airborne contaminants are captured and removed by a combination of novel adsorbent materials. Essential for long term cost effective operation is the system's ability to perform automatic, in-situ regeneration, several times a day, using warm outdoor air to purge the sorbents. The sorbents are held in replaceable cartridges that enable scalability of the HLR to any size of facility, and greatly simplify the once-a-year maintenance required.

Two configurations can be implemented. In the conventional or "forward" configuration, the slip stream takes return air and sends the treated air back to the return air, upstream from the AHU coils, as shows in the first diagram.




An alternative configuration, also known as "reverse flow", the slip stream is collected downstream from the coils, on the supply side of the AHU – and treated air is sent to the return air side as before. This configuration, shown in the following figure, was implemented at the Citibank site.




In June 2013, Johnson Controls Systems proposed to demonstrate the HLR at Citibank's offices in San Antonio. A single HLR module would be linked to one of the rooftop air handling units (AHU) and operated for a period of time while collecting detailed data on the performance of the solution, in terms of energy impact and indoor air quality.

In close coordination with the Citibank's on-site facility management and with the approval of Citibank headquarters, the site selected was Building 1 on 100 Citibank Drive. Building 1 has several large rooftop AHUs that receive chilled water from a separate chiller plant. We agreed to target AHU-9.

AHU-9 is a McQuay unit rated at approximately 16,700 CFM, operating 24×7, and serving a section of the second floor with estimated occupancy of up to 150. It is supplied with chilled water and has an outside air intake with a motorized damper. The damper had been kept at a fixed position. Using a portable flow meter and we compared the outside air intake being measured by the AHU's static flow meter. We estimate the flow to be about 3000 CFM in the configuration in which the system has been operated prior to our installation. The damper setting appears consistent with ASHRAE standards based on indoor air quality measurements we took while the system was in its regular configuration.

## III. The HLR Unit

The HLR unit delivered to the site was a prototype originally designed for up to a 40,000 CFM circulation. It was manufactured and shipped to a nearby warehouse ahead of the installation. The unit had 40 cartridge slots and 3000 CFM booster fans.

A separate heating module was designed for Standalone operation.
The main unit weighed approximately 2000 lbs.
In addition to the mechanical functionality of the system, it incorporates a relatively large number of sensors that monitor $CO_2$ and VOC levels as well as flow, pressure, temperature and humidity, at multiple points along the air flow paths.
Data is samples continuously and recorded electronically.
The system comes with its own electrical panel that included a programmable controller. Specialized algorithms have been developed and implemented in the controller to manage the systems operation for optimal energy savings and failsafe indoor air quality control. The control panel also includes a wireless transmitter that uploads all the sensor readings and system operation parameters to the cloud, allows real-time remote monitoring of energy consumption, indoor air quality and system operation, as well as outdoor temperature and humidity conditions.
The system's size and complexity are not representative of the commercial version that is already designed (but was not available in time for this installation). The commercial HLR-1000 would be the appropriate solution for AHU-9; it would come in at a substantially smaller footprint and weight, about 75% smaller and lighter. The heating element in the new design is configured as a detachable module. In order to better simulate operation with a smaller module, as would be the case in the future, air flow in the HLR was reduced by partially closing the inlet damper on the HLR, as discussed below.

## IV. Installation

Structural engineers recommended that the unit be mounted on horizontal steel beams, similarly to all the AHUs on the roof. (We note that the reinforcement beams are not expected to be a normal practice in installing HLR modules in the future, but were done on this installation for compatibility with the other systems on the roof and to a certain extent affected by the relatively larger size of this demo unit, which is substantially larger and heavier than the current design HLR-1000). The preparations were completed in early August and the unit itself was mounted on the roof on Aug. 13, 2013
Subsequently the connecting ducts were installed to the system, as was the electrical power, at which point it became ready for acceptance tests, which began on August 23, 2013.

Subsequently the connecting ducts were installed to the system, as was the electrical power, at which point it became ready for acceptance tests, which began on August 23, 2013.


Importantly, energy meters were installed on AHU-9 and linked to an electronic data logger. The energy meters monitor the flow and temperature of the chilled water supply going into and out of the AHU coil. This represents the most accurate way to isolate the cooling load and the commensurate energy consumption of the particular AHU in question.

The energy metering began on Aug 15, 2013. This was done ahead of the installation to begin to accrue the baseline performance of the AHU in its current "conventional" operating mode, namely without the benefit of HLR and with the standard intake of outside air. The data logger kept track of energy consumption as well as outdoor temperature and humidity.

Acceptance test were performed starting Aug. 23 and continued through Aug 28, when the unit had passed all its initial tests and checklist. The system was declared operational as of Thursday, Aug. 29. At that point the outside air intake dampers were reduced to their minimum position and the automated control panel managed the HLR, notably switching it between its three modes of operation:

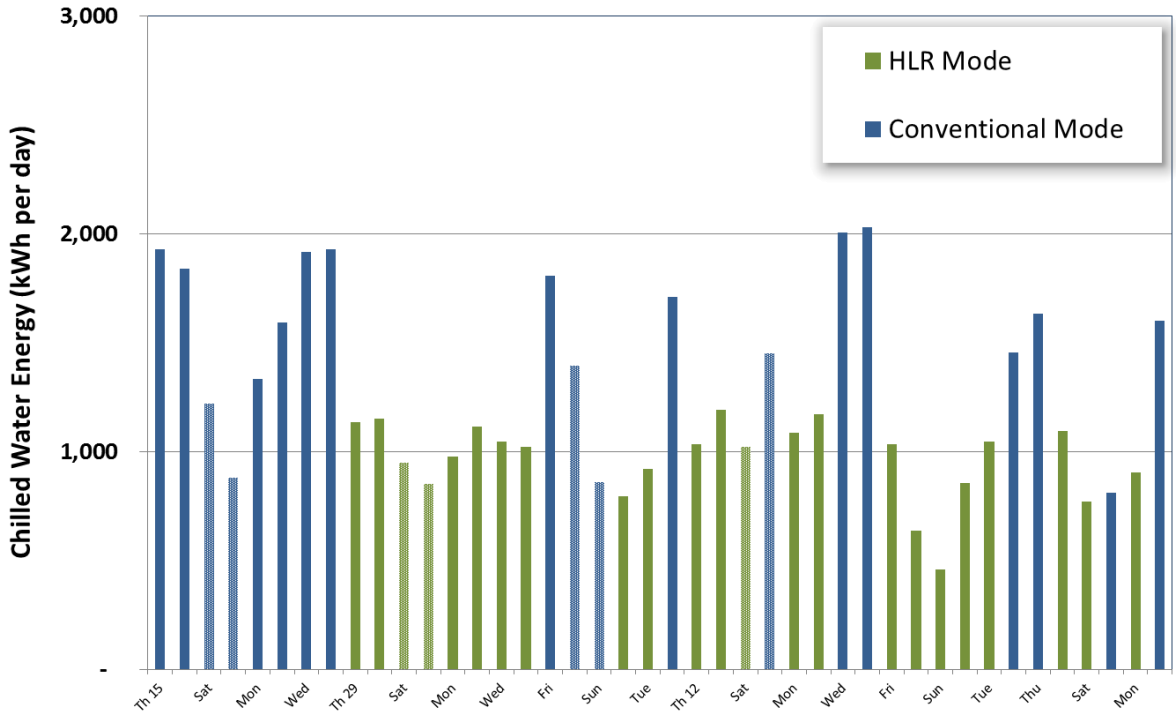
i. Air cleaning mode
ii. Regeneration mode
iii. Standby mode

Because the system was nominally designed for larger air flow capability than required for this installation, the air flow rate was reduced by adjusting the maximum opening of the HLR inlet damper. A smaller sized unit would be expected to deliver the same air flow with lower energy and higher efficiency, but the expected difference would not be significant. $CO_2$ levels were constantly monitored at the inlet and outlet of the HLR unit as well as in key locations in the building.

# V. Initial Results

## a. Energy Consumption

In order to ascertain as accurately as possible the energy savings impact, the AHU and the HLR were deliberately operated in alternating sequences of several days in "conventional" mode and several days in HLR mode. At the time of this report we have accrued almost 5 weeks of data in total, beginning with baseline data starting Aug 15, and excluding the acceptance testing period between 8/23 – 8/28.
The following chart reflects total cooling power per each 24-hour period, as determined by integrating the readings on the chilled-water meters. Note that this represents the chilled water energy consumption and not the electric power consumption of the central chiller plant. The bars in red represent days where the system was run in conventional mode, and the bars in green represent days in HLR mode. Solid color is for weekdays and hash marks are for weekends.




Several observations are readily made:

- Energy consumption varies from day to day
- Weekends generally appear to have lower energy usage
- HLR operation mode is associated with substantially lower energy usage

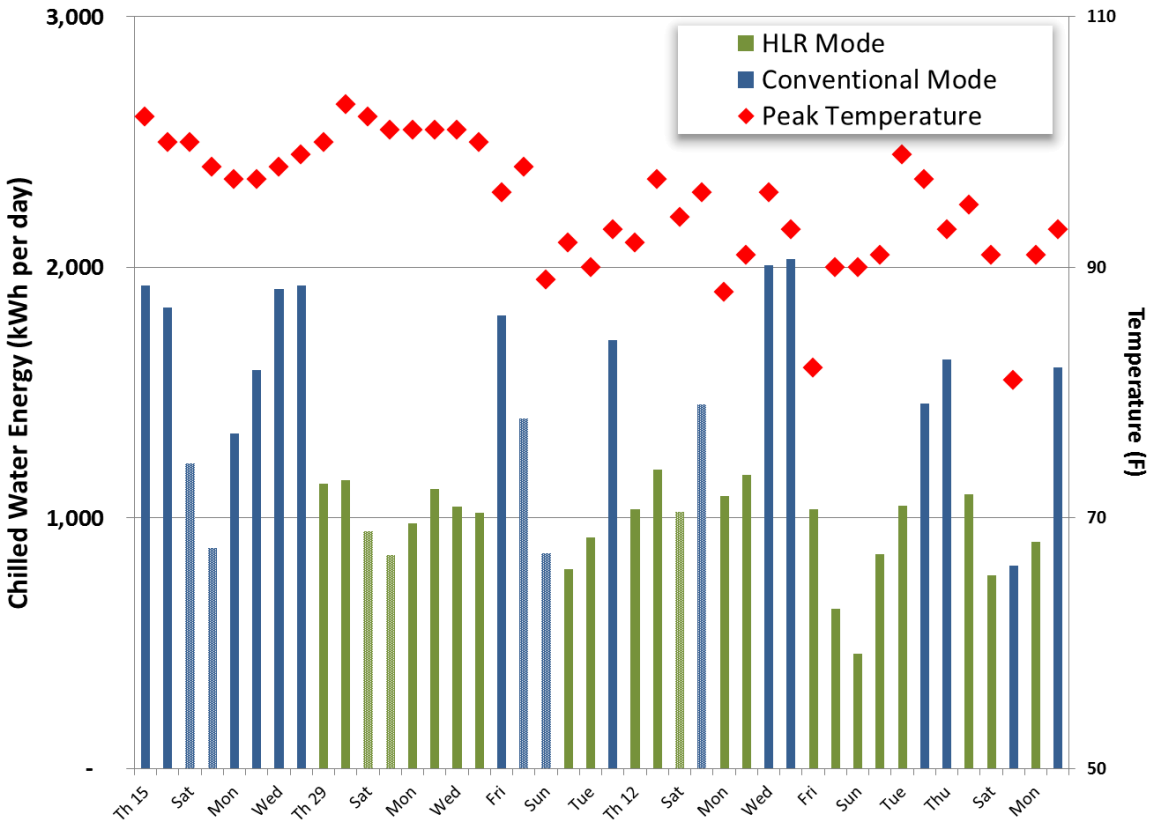
In aggregate the data accumulated at the time this report was compiled had 34 total days of operation, including 15 days on conventional mode (10 weekdays, 5 weekend) and 19 days in HLR mode (15 weekdays, 4 weekend). The building runs 24 × 7 but weekend occupancy and activity levels are lower.

In order to quantify the energy savings we looked at the average daily load over the period and compare the conventional mode days to the HLR days:

| **Category** | **Average Daily Cooling Load*** | | **Energy Savings** |
|---|---|---|---|
| | Conventional | HLR | |
| Total 8/15 – 9/25 | 1,594 | 972 | **39%** |
| Weekdays only | 1,809 | 1,043 | **42%** |

*Measured by chilled water consumption

Naturally there are day to day variations in outdoor temperature and humidity and as the season was already transitional from summer to fall, the beginning of a general reduction in outdoor heat load. Outside temperature and humidity were monitored continuously and logged alongside the energy consumption, allowing comparison and even first-order corrections against outside enthalpy.



The chart only shows the peak daily temperature, not its changes over the course of the day. Furthermore it does not account for humidity, whose impact can be greater than temperature itself. Generally, relative humidity coinciding with at the peak temperature was in the vicinity of 30%, but day to day variations in humidity were more significant than the variations in peak temperature. For example, Friday Sept 20 was a rainy day, with peak temperature only reaching 82˚F – the lowest during of the entire dataset – but with a relative humidity of 79% at the same time, which places the outdoor enthalpy at 39.5 lb/btu, one of the highest during the entire measured period, similar to 100˚F with 34% RH. Overall, adjusting the average daily savings against the temperature changes has a minor impact on the overall energy savings in terms of percentage.

For example, the following chart compares the first full week of conventional mode data with the first full week of HLR operation results, including a first order correction for peak outdoor daytime enthalpy.

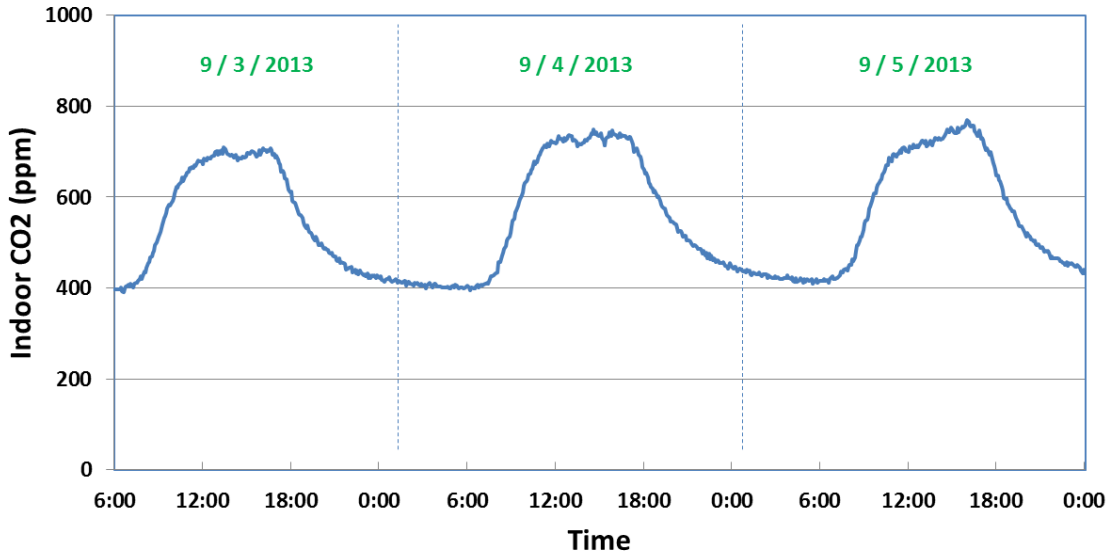
| | **Peak Daytime Conditions** | | | | **Enthalpy Adjustment** | | |
|---|---|---|---|---|---|---|---|
| | Conventional | | HLR | | | Energy Savings | |
| | Temp. | **Enthalpy** | Temp. | **Enthalpy** | **Factor** | **Raw** | Adjusted |
| Whole Week | 98.9 | **98.9** | 101.3 | **38.5** | 1.29 | 33% | **42%** |
| Weekdays only | 98.8 | **98.8** | 101.2 | **38.1** | 1.12 | 37% | **41%** |

We hasten to note that this is only an approximate adjustment for enthalpy for a number of reasons, including the fact that the actual outdoor enthalpy value changes from hour to hour, so averaging the peak daytime enthalpy is not the same as the average enthalpy over the week; and HVAC energy consumption is not exactly linear with enthalpy. But at a minimum it is directionally correct and a reasonable first-order approximation, namely that in comparing the first of conventional and HLR operation, outdoor conditions were actually more difficult during the latter week and therefore raw energy comparison would underestimate the impact of the HLR module.

### b. Indoor Air Quality

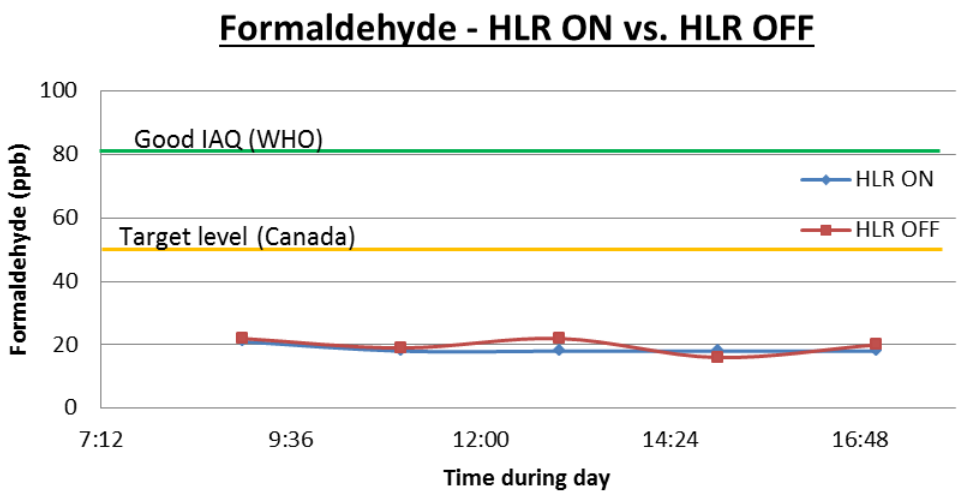
The second critical test for the system was maintaining indoor air quality with reduced ventilation, including $CO_2$ levels and VOC levels. We had constant monitoring of these contaminants measured in the return air. While in general indoor air quality can vary from room to room in a building and is an important factor to consider in designing HVAC systems, these variations are not going to be affected by replacement of outside air with HLR scrubbing. The test of the HLR is its ability to maintain low overall contaminant levels in the building. First and foremost is $CO_2$. The following chart shows indoor $CO_2$ concentration in the zone of AHU-9, as measured in the return airflow using a high precision Vaisala $CO_2$ meter inserted in the return air duct. The change in $CO_2$ levels is clearly affected by building occupancy: Nighttime $CO_2$ levels are close to the baseline atmospheric $CO_2$ concentration of 400 ppm while daytime levels rise, typically to the maximum level in the vicinity of 800 ppm. The HLR unit is designed to maintain $CO_2$ safely below 1000 ppm which it has done every day of its operation. The target $CO_2$ level is in fact a programmable feature of the HLR, where control algorithms and feedback logic to determine the flow rate as well as the timing and extent of the sorbent regeneration cycle, all of which combine to affect indoor $CO_2$ levels.

To lower $CO_2$ targets with an incremental energy cost, the latter typically small relative to the HVAC cooling energy savings, but the 800 ppm level is considered to be very good by virtually all indoor air standards.




Secondly, total VOC levels were monitored using a Greystone Air-300 IAQ sensor. This is a metal oxide relative sensor that captures changes in VOC levels. It is calibrated on a range of 0 – 100% and anything below 15% is considered "excellent" IAQ. Over multiple days of operation, the reading on the Air-300 was always below 10% and usually in the vicinity of 7%. The complexity of VOC species is not represented by these measurements but with the total level is clearly low and very similar to the levels measured under high outdoor ventilation.

In addition to this online VOC monitoring, highly sensitive and specific VOC tests were conducted by taking air samples and having them analyzed in 3rd party analytical lab, Prism Analytical Technologies Inc.1. (PATI). Collected sampled were sent for analysis at PATI laboratory using the the NIOSH 2549 method. This analysis detects many species of VOCs and can identify and quantify the most prevalent species in each sample, as well as the total VOC load.




[1] Prism Analytical Technologies Inc. is an AIHA accredited industrial hygiene laboratory.

Air samples were collected in PATI's proprietary adsorption tubes placed inside the return air duct. Multiple samples were collected during normal work hours, five samples per day, on two separate days: one with the HVAC working with conventional outside air ventilation and the other with the HLR unit with outside air.

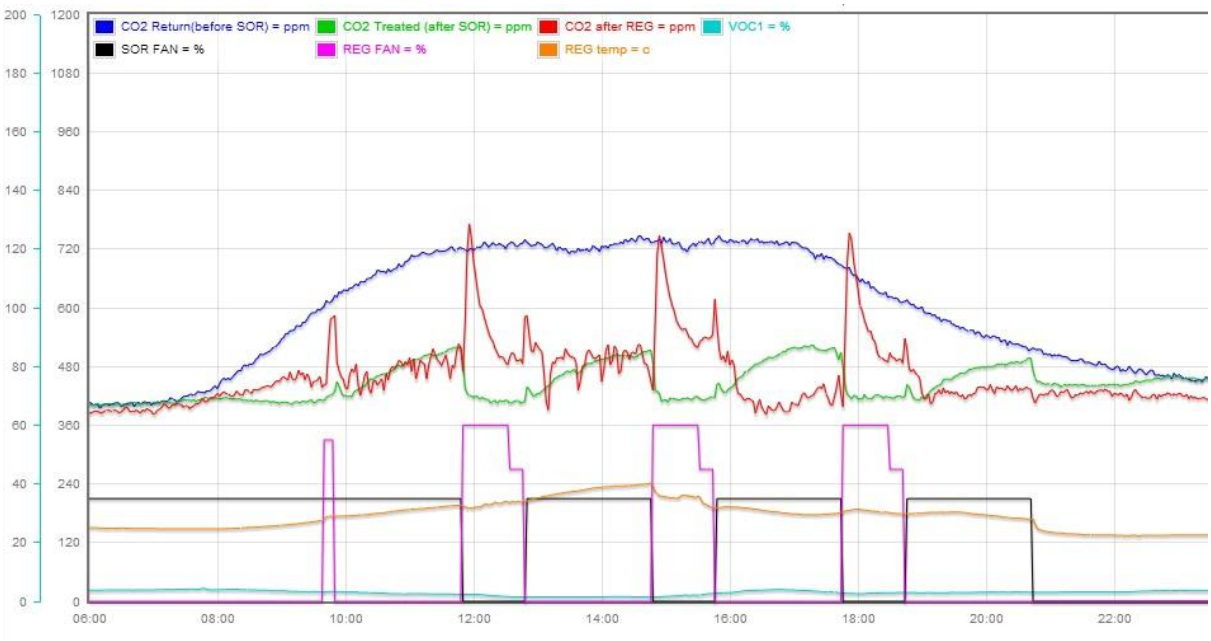
A typical result is seen in the chart above, specifically showing formaldehyde levels during a regular work day. Blue – HLR unit on with reduced outside air, Red – HLR unit off (standard HVAC operation) with conventional outside air ventilation. The green line indicates reference level of 81 ppb, considered "Good IAQ" according to the World Health Organization (WHO), and the yellow line shows the target level of 50 ppb required by to Canadian regulations.

The tests confirmed that VOC levels in general, and specifically for the VOC of highest concern (formaldehyde), were maintained and essentially the same levels on both modes of operation, which are good IAQ levels.
The conclusion of this demonstration, from both the online monitoring as well as the more accurate detailed air sampling laboratory analysis is that, under the conditions tested in this building, the HLR unit maintains good air quality in the building.

### C. System Performance and Control

In addition to the measurement of energy impact and air quality, we keep a detailed log of system performance, in terms of air flow, pressure, temperature, and the automatic activation of the regeneration cycles. This is in large part a verification of the proper function of the control algorithms and the control hardware, but it also allows us to test the validity of the control logic as it relates to energy savings and air quality.

Typical data for one entire day are shown in the following chart. The lines show indoor $CO_2$ levels, as well as the level of $CO_2$ in the air flow exiting from the HLR. In normal mode indoor air enters the HLR and emerged with reduced $CO_2$. In regeneration mode, low-$CO_2$, heated outside air enters the HLR and emerged with elevated $CO_2$. The system kicks into regeneration mode as needed, typically when a combination of conditions coincide including elevated indoor $CO_2$ and reduced adsorption efficiency of the HLR due to sorbent saturation.




Importantly, the installation used real time data collection and remote control and monitoring via a wireless uplink. The software and the communication protocols worked seamlessly, allowing our technical team to view the systems state and operating parameters in real time from a remote location. The software, and especially the data collection and aggregation capabilities of the system, are an important and valuable feature of the technology and was demonstrated successfully.

## VI. Discussion

The most important conclusions from the initial period of system operation is that the HLR operates reliably and effectively, and that the energy impact is confirmed to be very substantial. The energy saving is always a relative measurement compared to the cooling load under conventional outside-air ventilation, and course the savings are dependent on outdoor climate, primarily the excess enthalpy of outdoor air relative to indoor conditions. The climate in San Antonio in late August and early September is relatively stable, with peak afternoon temperatures between 97F – 102F and low relative humidity at peak temperature, typically in the vicinity of 30%. Under these conditions we see over 40% reduction in cooling load as the outside air is reduced from conventional rate to the reduced rate (and estimated 80% reduction in outside air intake). Meanwhile $CO_2$ levels are easily kept below 1000 ppm and in fact on most days $CO_2$ was kept at the vicinity of 800 ppm even during peak occupancy. The zone of AHU-9 had a very high daytime occupancy, estimated at about 120 persons for an airflow of approximately 16000 CFM, which is on the high end of expected $CO_2$ load, suggesting that the HLR is fully capable of dealing with the typical contaminant load it is designed for and, by extension, in many buildings would not have to operate at full capacity most of the time.

The building tested is operated 24 × 7; this represents a robust test for the HLR, which is tested here for continuous round-the-clock operation. While absolute energy savings are higher in a system that operates 24 × 7, the percentage of energy savings may in fact be higher for systems that operate only during the daytime (like 12 × 7 or 12 × 5).

The main drawback we see of the demonstration is the size and weight of the system, with ramifications for rooftop structural preparation and space requirements, as well as manufacturing costs. Even before it was installed we had already concluded that the system size and be reduced very significantly. The benefits of size reduction are numerous, and go beyond the manufacturing cost and the structural requirements, and impact questions like heat capacity for regeneration energy consumption and space availability for indoor installations. Fortunately new designs have already been implemented that reduce the unit size and weight by 70 – 80%. Not only is the reduced size not expected to degrade performance, in fact to the contrary, faster thermal cycling and more flexible positioning of the smaller, lighter unit will improve overall performance and reduce operating costs as well as manufacturing and installation costs. The new design has already been prototyped and will be the basis for all future installations.

## VII. Summary

The installation and the results from the first month of operation have so far provided a very positive confirmation of the technology's impact, safety and readiness. The energy impact is in the significant double digit percentage, easily around 40% during the central Texas summer season and potentially higher in humid coastal climates. Air quality was very good, and no unwanted effects like noise or odors were observed at any stage. A new design, substantially reduced in size and weight, is under way that will deliver better performance at much lower cost and effort, and is expected to become commercially available within a few months.

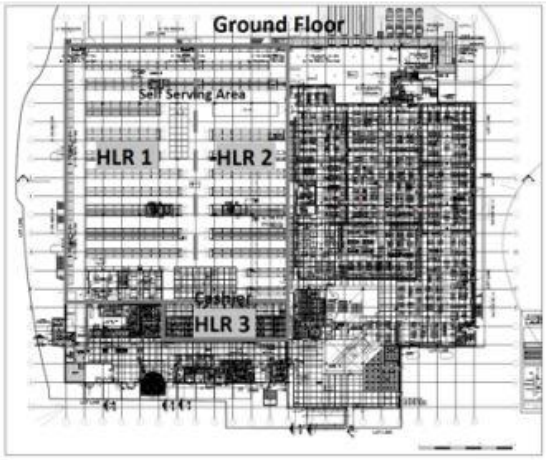
# IKEA's initial installation saved 20% energy and reduced outside air consumption by 53%.

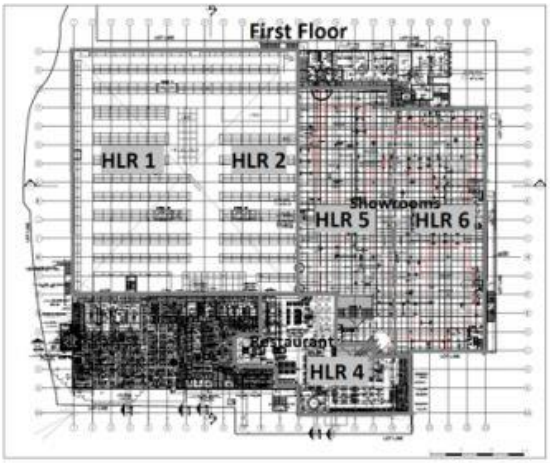

## Summary

October 2015, Company installed six HLR® (HVAC Load Reduction) 1000B modules on the roof of IKEA store located in Netanya, Israel. The installation was done in collaboration with the HVAC Company Tadiran and in coordination with Ikea's facility management team.

The scope of this HLR® installation included self-service and cashier areas on the ground floor and all areas (restaurants, showrooms, and self-serving areas) on the first floor, as shown on the diagrams to the right

Company installed six HLR 1000B modules on the roof of IKEA store located in Netanya, Israel together with Tadiran and in coordination with Ikea's facility management. The scope of this HLR installation included self-serving and cashier area on the ground floor and all areas (restaurants, showrooms, and self-serving areas) on the first floor



## Energy Savings

During October 2015, initial energy monitoring and reporting were conducted. Energy savings was calculated from measured water flow, water supply and return temperature of chillers read from the Building Management System. During HLR ® ON mode, outside air volume was reduced by 53%. In October, data shows an average energy consumption decrease of 2,204 kWh (20%) per day when HLR ® ON compared to HLR ® OFF. We expect to obtain higher energy savings over the hot summer season. York and Tadiran will continue with the demonstration and will issue a full report to document the energy savings in the summer season.

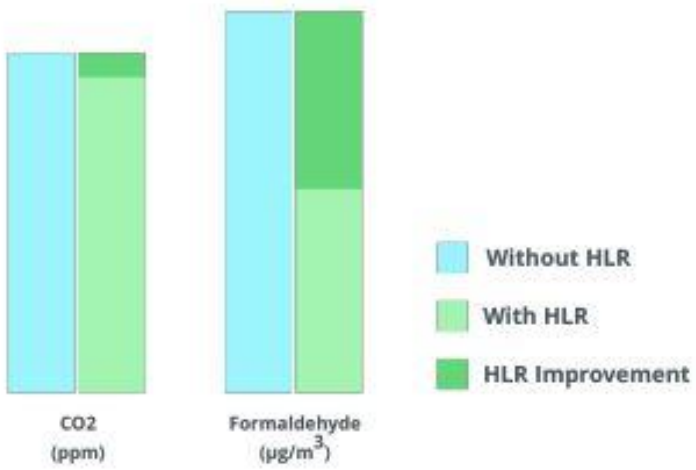
## Indoor Air Quality

For the monitoring of indoor air quality (IAQ), the concentration of the contaminants of concern (i.e., aldehydes, spectated volatile organic compounds, and carbon dioxide) were measured prior to the HLR ® operation and then again after the HLR ® was operational for at least one week. Indoor air quality monitoring and testing was performed according to EPA Standards and the air samples taken on site were calibrated by an independent certified lab (Prism Analytical Technologies).

We measured six testing locations that correspond to the different areas served by each HLR ®. To obtain a good representation of the air quality in the space, we performed mobile sampling: we put IAQ instruments in a cart and relocated to different sampling locations within each testing location. An example of testing is shown in the pictures below. The pollutant concentrations database is

Used to show compliance with the ASHRAE Standard 62.1 indoor air quality procedure (IAQP; ASHRAE Standard 62.1, 2013)

Although the Outside Air volume was reduced by 53%, the HLR successfully maintained the contaminants of concern below their established threshold values. See graph below for the summary of IAQ comparison of two contaminants of concern: formaldehyde and carbon dioxide



# Elbit Systems
## Haifa, Israel

### Background

The Elbit Systems facility is a three-story office building located in the MATAM industrial park in Haifa, Israel. The building, with an area of 10,000 m2 (107,639 ft2), includes offices and open spaces. The HVAC system has nine air-handling units (AHUs), all of which are located on the roof. The airflow in these AHUs ranges from 9,000-20,000 CFM while operating from 7 am to 7 pm Sunday through Thursday, and 7 am to 1 pm on Friday. The AHUs use chilled water supplied from the central plant at the MATAM Park.

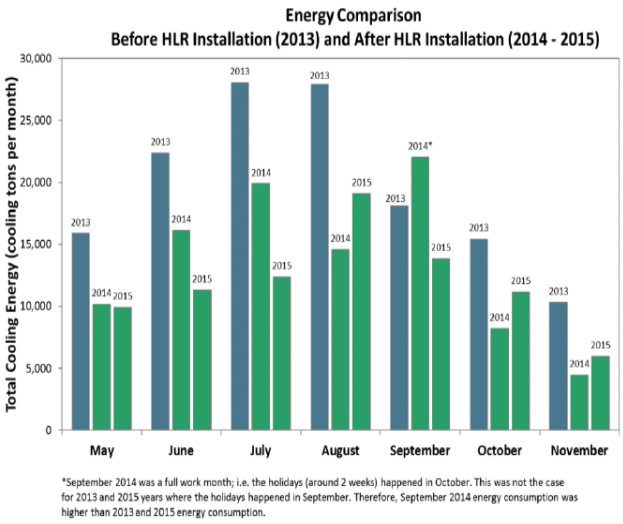
In July 2012, Company installed one HLR® (HVAC Load Reduction) module on the roof of the building. After demonstrating the system's success, in May 2014, York installed six additional HLR units on the roof of the building in coordination with Elbit's facility management team. The installed HLR units serve around 42% of the building's footprint.
Energy savings and indoor air quality in the building have been continuously monitored since 2013.

### HLR Operation

The HLR module is a smart scrubber with unique air-cleaning and sensing capabilities. It includes patented $CO_2$, formaldehyde, and volatile organic compound (VOC) sorbents housed in proprietary cartridges; a heating element for regeneration; two small fans for regeneration and sorption; and a set of sensors measuring temperature, relative humidity, carbon dioxide, and volatile organic compounds of return, supply, treated, and regenerated air. The HLR system interprets the output of these sensors using control algorithms to actively and automatically manage the outside air, HVAC load, and indoor air quality.
Figure 1 compares conventional air handling to HLR system air handling. As shown in the figure below, during normal operation, a fraction of the return airstream (open plenum air in this case) is directed through the sorbent cartridges to remove contaminants of concern. The sorbent cartridges automatically regenerate, releasing the captured contaminants and performing a self-cleaning process. During the regeneration cycle, the HLR system is blocked from the building's air systems, and warm air is blown over the cartridges and exhausted into the ambient air via the building's existing restroom exhaust ducts.

## Energy Savings Results

HLR performed energy comparisons between HVAC Conventional Mode (before HLR installation) in 2013 and after installation, beginning in May 2014 and continuing throughout 2015. In the summer months (May through November), HLR operation resulted in 31% savings in 2014 and 39% savings in 2015 when compared to HVAC Conventional Mode (before HLR units were installed) in 2013. For these months, HLR operation decreased energy consumption by 42,574 cooling tons in 2014 and 54,338 cooling tons in 2015. The graph below compares energy consumption before and after HLR installation.




## Indoor Air Quality

In HLR Savings Mode, the contaminants of concern ($CO_2$ and VOCs) were successfully maintained below their established threshold values.

## Conclusion

Since installation of the HLR modules, energy savings has exceeded 31% for two consecutive years while indoor air quality has been

# Research Paper: CO2 Concentrations

## Is $CO_2$ an Indoor Pollutant? Direct Effects of Low-to-Moderate $CO_2$ Concentrations on Human Decision-Making Performance

***Usha Satish,[1] Mark J. Mendell,[2] Krishnamurthy Shekhar,[1] Toshifumi Hotchi,[2] Douglas Sullivan,[2] Sieafried Streufert.[1] and William J. Fisk [2]***

[1]Department of Psychiatry and Behavioral Science, Upstate Medical University, State University of New York, Syracuse, New York, USA; [2]Indoor Environment Department, Lawrence Berkeley National Laboratory, Berkeley, California, USA

**Background: Associations Of Higher Indoor Carbon Dioxide ($CO_2$) Concentrations With Impaired Work Performance, Increased Health Symptoms, And Poorer Perceived Air Quality Have Been Attrib- Uted To Correlation Of Indoor $CO_2$ With Concentrations Of Other Indoor Air Pollutants That Are Also Influenced By Rates Of Outdoor-Air Ventilation.**

**Objectives: We Assessed Direct Effects Of Increased $CO_2$, Within The Range Of Indoor Concentrations, On Decision Making.**

**Methods: Twenty-Two Participants Were Exposed To $CO_2$ At 600, 1,000, And 2,500 Ppm In An Office-Like Chamber, In Six Groups. Each Group Was Exposed To These Conditions In Three 2.5-Hr Sessions, All On 1 Day, With Exposure Order Balanced Across Groups. At 600 Ppm, $CO_2$ Came From Outdoor Air And Participants' Respiration. Higher Concentrations Were Achieved By Injecting Ultrapure $CO_2$. Ventilation Rate and Temperature Were Constant. Under Each Condition, Participants Completed A Computer-Based Test Of Decision-Making Performance As Well As Questionnaires On Health Symptoms And Perceived Air Quality. Participants And The Person Administering The Decision-Making Test Were Blinded To $CO_2$ Level. Data Were Analysed With Analysis Of Variance Models.**

**Results: Relative To 600 Ppm, At 1,000 Ppm $CO_2$, Moderate And Statistically Significant Decrements Occurred In Six Of Nine Scales Of Decision-Making Performance. At 2,500 Ppm, Large and Statistically Significant Reductions Occurred In Seven Scales of Decision-Making Performance (Raw Score Ratios, 0.06–0.56), But Performance on the Focused Activity Scale Increased.**

**Conclusions: Direct Adverse Effects of $CO_2$ on Human Performance May Be Economically Important and May Limit Energy-Saving Reductions in Outdoor Air Ventilation per Person In Buildings. Confirmation Of These Findings Is Needed.**

**Key Words: Carbon Dioxide, Cognition, Decision Making, Human Performance, Indoor Environ- Mental Quality, Ventilation. Environ Health Perspect 120:1671–1677 (2012).**

**Http://Dx.Doi. Org/10.1289/Ehp.1104789 [Online 20 September 2012]**

Because humans produce and exhale carbon dioxide ($CO_2$), concentrations of $CO_2$ in occupied indoor spaces are higher than concentrations outdoors. As the ventilation rate (i.e., rate of outdoor air supply to the indoors) per person decreases, the magnitude of the indoor–outdoor difference in $CO_2$ concentration increases. Consequently, peak indoor $CO_2$ concentrations, or the peak elevations of the indoor concentrations above those in outdoor air, have often been used as rough indicators for outdoor-air ventilation rate per occupant (Persily and Dols 1990). The need to reduce energy consumption provides an incentive for low rates of ventilation, leading to higher indoor $CO_2$ concentrations.

Although typical outdoor $CO_2$ concentrations are approximately 380 ppm, outdoor levels in urban areas as high as 500 ppm have been reported (Persily 1997). Concentrations of $CO_2$ inside buildings range from outdoor levels up to several thousand parts per million (Persily and Gorfain 2008). Prior research has documented direct health effects of $CO_2$ on humans, but only at concentrations much higher than those found in normal indoor settings. $CO_2$ concentrations > 20,000 ppm cause deepened breathing; 40,000 ppm increases respiration markedly; 100,000 ppm causes visual disturbances and tremors and has been associated with loss of consciousness; and 250,000 ppm $CO_2$ (a 25% concentration) can cause death (Lipsett et al. 1994). Maximum recommended occupational exposure limits for an 8-hr workday are 5,000 ppm as a time- weighted average, for the Occupational Safety and Health Administration (OSHA 2012) and

the American Conference of Government Industrial Hygienists (ACGIH 2011). Epidemiologic and intervention research has shown that higher levels of $CO_2$ within the range found in normal indoor settings are associated with perceptions of poor air quality, increased prevalence of acute health symptoms (e.g., headache, mucosal irritation), slower work performance, and increased absence (Erdmann and Apte 2004; Federspiel et al. 2004; Milton et al. 2000; Seppanen et al. 1999; Shendell et al. 2004; Wargocki et al. 2000). It is widely believed that these associations exist only because the higher indoor $CO_2$ concentrations at lower outdoor air ventilation rates are correlated with higher levels of other indoor-generated pollutants that directly cause the adverse effects (Mudarri 1997; Persily 1997). Thus $CO_2$ in the range of concentrations found in buildings (i.e., up to 5,000 ppm) has been assumed to have no direct impacts on occupants' perceptions, health, or work performance.

Researchers in Hungary have questioned this assumption (Kajtar et al. 2003, 2006). The authors reported that controlled human exposures to $CO_2$ between 2,000 ppm and 5,000 ppm, with ventilation rates unchanged, had subtle adverse impacts on proofreading of text in some trials, but the brief reports in conference proceedings provided limited details.

This stimulated our group to test effects of variation in $CO_2$ alone, in a controlled environment, on potentially more sensitive high-level cognitive functioning. We investigated a hypothesis that higher concentrations of $CO_2$, within the range found in buildings and without changes in ventilation rate, have detrimental effects on occupants' decision-making performance.

## Methods

This study addresses responses among human participants under three different conditions in a controlled environmental chamber outfitted like an office, with $CO_2$ concentrations of approximately 600, 1,000, and 2,500 ppm. Six groups of four participants were scheduled for exposure to each of the three conditions for 2.5 hr per condition. The experimental sessions for each group took place on a single day, at 0900–1130, 1230–1500, and 1600–1830 hours, with 1-hr breaks outside the exposure chamber between sessions. During the first break, participants ate a self-provided lunch. The order in which participants were exposed to the different $CO_2$ concentrations was balanced across groups, including all possible orders of low,

Address correspondence to M.J. Mendell, Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., 90R3058, Berkeley, CA 94720 USA. Telephone: (510) 486-5762. Fax: (510) 486-6658. E-mail: mjmendell@lbl.gov

Funding for this research was provided by Collaborative Activities for Research and Technology Innovation (CARTI), which supports research in the areas of air quality and water resource management. CARTI, part of the Syracuse Center of Excellence located in Syracuse, New York, is supported by the U.S. Environmental Protection Agency under award EM-83340401-0. Information about CARTI is available at http://www.syracusecoe.org/coe/sub1. html.skuvar=68.

The authors declare they have no actual or potential competing financial interests. Received 28 November 2011; accepted 20 September 2012.

medium, and high-concentration sessions. Participants and the person administering the tests of decision-making performance were not informed about specific $CO_2$ conditions in each session. During each exposure condition, participants completed a computer-based test of decision-making performance in which they were presented with scenarios and asked to make decisions based on a standardized protocol (Krishnamurthy et al. 2009; Satish et al. 2009; Streufert and Satish 1997). Before and after each test of decision-making performance, participants also completed computer- based questionnaires on perceived indoor air quality and health symptoms.

We received approval for the study proto- col and the informed consent procedures from the Human Subjects Committee at Lawrence Berkeley National Laboratory (LBNL). We recruited primarily from among a local population of university students, all at least 18 years old. We scheduled 24 participants, with extras in case of no-shows, for participation. All participants provided written informed consent before participation. Scheduled participants were provided a small amount of financial compensation for their time.

*Exposure protocol.* Experimental sessions were conducted in a chamber facility at LBNL. The chamber has a 4.6 m x 4.6 m floor plan, 2.4 m high ceiling, standard gypsum board walls, and vinyl flooring, and is equipped with four small desks, each with an Internet-connected computer. The chamber is located inside a heated and cooled building, with all external surfaces of the cham- ber surrounded by room-temperature air. The chamber has one window (~ 1 m x 1 m) that views the interior of the surrounding indoor space; hence, changes in daylight or the view to outdoors were not factors in the research. The chamber has a relatively airtight envelope, including a door with a refrigerator-style seal. The chamber was positively pressurized relative to the surrounding space. A small heating, ventilating, and air-conditioning system served the chamber with thermally conditioned air filtered with an efficient particle filter. The out- door air supply rate was maintained constant at approximately 3.5 times the 7.1 L/sec per person minimum requirement in California (California Energy Commission 2008); the flow rate was monitored continuously with a venturi flow meter (model VWF 555 - 4"; Gerand Engineering Co, Minneapolis, MN).

$CO_2$ was recorded in real time at 1-min intervals. During the baseline sessions, with participants and outdoor air as the only indoor source of $CO_2$, measured $CO_2$ concentrations were approximately 600 ppm. In sessions with $CO_2$ added, $CO_2$ from a cylinder of ultra- pure $CO_2$ (at least 99.9999% pure) was added to the chamber supply air, upstream of the supply-air fan to assure mixing of the $CO_2$ in the air, at the rate needed to increase the $CO_2$ concentration to either 1,000 or 2,500 ppm. A mass flow controller monitored and regulated injection rates in real time. All other conditions (e.g., ventilation rate, temperature) remained unchanged.

The outdoor air exchange rate of the chamber was about 7/hr; and in sessions with $CO_2$ injected into the chamber, injection started before the participants entered the chamber. In sessions with no $CO_2$ injection, $CO_2$ concentrations were close to equilibrium levels 25 min after the start of occupancy, and in sessions with $CO_2$ injection (because $CO_2$ injection started before participants entered the chamber), 10–15 min after the start of occupancy.

Before participants entered the chamber, the desired chamber temperature and ventilation rate were established at target values of 23oC (73oF) and 100 L/sec (210 ft3/min). Indoor chamber temperature during the experimental sessions was maintained at approximately 23oC (73.4oF) by proportionally controlled electric resistance heating in the supply airstream. Relative humidity (RH) was approximately 50% ± 15%. We continuously monitored temperature and RH in real time. Temperature was averaged for each session for comparisons.

Calibrations of all instruments were checked at the start of the study. Calibration of the $CO_2$ monitors was checked at least every week during experiments using primary standard calibration gases. Given the instruments used and calibration procedures, we anticipated measurement accuracies of ± 5% at the lowest $CO_2$ concentrations and as high as ± 3% at the highest concentrations. Real- time logged environmental data ($CO_2$, temperature, RH, outdoor air supply rate) were downloaded from environmental monitors to Excel and imported into SAS statistical analysis software (version 9.1; SAS Institute Inc., Cary, NC).

The design of the $CO_2$ injection system included features to prevent unsafe $CO_2$ concentrations from developing in the event of a failure in the $CO_2$ injection system or human error. The $CO_2$ cylinder was outdoors so that any leaks would be to outdoors. A pressure relief valve located downstream of the pressure regulator was also located outdoors and set to prevent pressures from exceeding our target pressure at the inlet of the mass flow controller by > 50%. Valves would automatically stop $CO_2$ injection if the outdoor air ventilation to the chamber or the ventilation fan failed.

A flow limiter prevented $CO_2$ concentrations from exceeding 5,000 ppm if the mass flow controller failed in the fully open position, and a second $CO_2$ analyzer with control sys- tem would automatically stop $CO_2$ injection if the concentration exceeded 5,000 ppm. Also, a research associate monitored $CO_2$ concentrations in the chamber using a real- time instrument. Given the purity level of the carbon dioxide in the gas cylinder (99.9999%) and the rate of outdoor air supply to the cham- ber, the maximum possible chamber air con- centration of impurities originating from the cylinder of $CO_2$ was only 2 ppb. The impurity of highest concentration was likely to be water vapor, and at a concentration ≤ 2 ppb, short- term health risks from exposures to impurities would have been far less than risks associated with exposures to many normal indoor or out- door pollutants. Finally, before participants entered the chamber we added $CO_2$ from the cylinder to the chamber air, and collected an air sample on a sorbent tube for analysis by thermal desorption gas chromatography mass spectrometry. There was no evidence that the $CO_2$ injection process increased indoor con- centrations of volatile organic compounds (VOCs). VOCs at low concentrations, typical of indoor and outdoor air concentrations, were detected.

On the morning of each of 6 experimental days, groups of participants came to LBNL for a full day of three experimental sessions. To ensure a full set of four participants for each scheduled day (after one unanticipated no-show on each of the first 2 days), we scheduled five participants each day and selected four at random to participate. On each experimental day, as soon as all participants had arrived, the selected participants were seated in the environmental chamber facility. Before they entered the chamber, a research associate distributed to participants a handout describing the session plans and answered any questions.

During the first 45 min of each session, participants were free to perform school work, read, or engage in any quiet, nondisruptive activity. Participants were then asked by the LBNL research associate to complete the computer-based questionnaire on perceived air quality and symptoms, available via web connection on the laptop computers on their desks. Participants then had a 10-min break, to stretch or exit the chamber to use the bath- room, but no participant elected to exit the chamber during a session.

A 20-min protocol was then used to train participants in the decision-making task. A technician trained in administering this test was present to answer questions before the test, and could enter the chamber to answer questions during the test. We estimated that $CO_2$ emissions of the technician, who was in the chamber for about 10 min during each session, would increase chamber $CO_2$ concentrations by no more than 17 ppm. (The technician was not required to give informed consent for this because the study conditions are commonly experienced in indoor environments and are not associated with adverse health effects.) Over the next 1.5 hr, participants took the computerized test of decision- making performance, which involved reading text displayed on a laptop computer and selecting among possible responses to indicate their decisions.

When the performance test was completed, participants repeated the computer- based questionnaire on perceived air quality and symptoms and then left the chamber until the next session. At any time during each session, participants were free to exit the facility to use a nearby bathroom, but were asked to return within 10 min. Participants were also free to terminate their participation and leave the facility at any time during the day, but no participants exercised these options.

***Testing of decision-making performance.*** We used a testing method designed to assess complex cognitive functioning in ways more relevant to the tasks of workers in buildings than the tests of simulated office work generally used (e.g., proofreading text, adding numbers) (Wargocki et al. 2000). A computer-based program called the Strategic Management Simulation (SMS) test collects data on performance in decision making under different conditions. The SMS test has been used to study the impact on people's decision-making abilities of different drugs, VOCs from house painting, stress overload, head trauma, and the like (Breuer and Satish 2003; Cleckner 2006; Satish et al. 2004, 2008; Swezey et al. 1998). (SMS testing is available for research by contract with State University of New York Upstate Medical University, and for commercial applications via Streufert Consulting, LLC. See http://www.upstate.edu/psych/research/sms.php.)

The SMS measures complex human behaviors required for effectiveness in many work- place settings. The system assesses both basic cognitive and behavioral responses to task demands, as well as cognitive and behavioral components commonly considered executive functions. The system and its performance have been described in prior publications (e.g., Breuer and Satish 2003; Satish et al. 2004; Swezey et al. 1998). Participants are exposed to diverse computer-generated situations presenting real-world equivalent simulation scenarios that are proven to match real-world day-to-day challenges. Several parallel scenarios are avail- able, allowing retesting individuals without bias due to experience and learning effects. Participants are given instructions via text messages on a user-friendly computer interface, and respond to the messages using a drop-down menu of possible decisions. All participants receive the same quantity of information at fixed time points in simulated time, but participants have flexibility to take actions and

make decisions at any time during the simulation, as in the real world. The absence of requirements to engage in specific actions or to make decisions at specific points in time, the absence of stated demands to respond to specific information, the freedom to develop initiative, and the freedom for strategy development and decision implementation allow each participant to use his or her own preferred or typical action, planning, and strategic style. The SMS sys- tem generates measurement profiles that reflect the underlying decision-making capacities of the individual.

The computer calculates SMS performance measures as raw scores, based on the actions taken by the participants, their stated future plans, their responses to incoming information, and their use of prior actions and outcomes. The validated measures of task performance vary from relatively simple competencies such as speed of response, activity, and task orientation, through intermediate level capabilities such as initiative, emergency responsiveness, and use of information, to highly complex thought and action processes such as breadth of approach to problems, planning capacity, and strategy. The nine primary factors and factor combinations that have predicted real-world success are basic activity level (number of actions taken), applied activity (opportunistic actions), focused activity (strategic actions in a narrow endeavor), task orientation (focus on concurrent task demands), initiative (development of new/creative activities), information search (openness to and search for information), information usage (ability to use information effectively), breadth of approach (flexibility in approach to the task), and basic strategy (number of strategic actions).

The raw scores assigned for each measure are linearly related to performance, with a higher score indicating superior performance. Interpretation is based on the relationship to established standards of performance excel- lence among thousands of previous SMS participants (Breuer and Streufert 1995; Satish et al. 2004, 2008; Streufert and Streufert 1978; Streufert et al. 1988; Streufert and Swezey 1986). Percentile ranks are calculated through a comparison of raw scores to the overall distribution of raw scores from a reference population of > 20,000 U.S. adults, 16–83 years of age, who had previously completed the SMS. The reference population was constructed nonrandomly to be generally representative of the job distribution among the adult U.S. population, including, for example, college students, teachers, pilots, medical residents, corporate executives, homemakers, and the unemployed. The percentile calculations for individual participants are not further adjusted for age, sex, or Education level.

*Data management and analysis.* The main predictor variable of interest was $CO_2$, included in analyses as a categorical variable with three values: 600, 1,000, and 2,500 ppm. Real-time $CO_2$ concentrations and temperature were averaged for each session for comparison.

Nine measures from the SMS, representing validated independent assessments of performance in complex task settings, were compared across $CO_2$ conditions. Raw scores on the different SMS measures were computer- calculated based on procedures (software formulas) that are discussed by Streufert and Swezey (1986). The formulas are based on numerically and graphically scored decision actions, on the interrelationships among decisions over time, the interrelationships among decisions with incoming information, as well as decision planning and other components of participant activity. Each of the activity event components that are used in the formulas are collected by the SMS computer software program (Streufert and Swezey 1986). A separate SMS software system is subsequently used to calculate the value for each measure. Where appropriate where maximum performance levels have limits (cannot be exceeded) the obtained scores are expressed by the program as percentages of maximally obtainable values. A higher score on a measure indicates better performance in that area of performance. For each measure, ratios of scores across conditions were calculated to show the magnitude of changes.

Initial data analysis used multivariate analysis of variance (MANOVA) to assess overall significance across all conditions, to assure that subsequent (post hoc) analysis across the nine different simulation measures would be legitimate. With high levels of significance established, post hoc analysis for each simulation measure using analysis of variance (ANOVA) techniques becomes possible. Separate ANOVA procedures across $CO_2$ conditions were used for each of the nine SMS measures (within participants, with participants as their own controls). Percentile ranks were calculated from the raw scores and normative data, without adjustments for demographic or other variables. Percentile levels are divided into categories with descriptive labels based on prior test findings from different populations, normal and impaired.

## Results

Because 2 of the 24 originally scheduled participants cancelled at a time when they could not be replaced, 22 participants pro- vided complete SMS data. Of these, 10 were male; 18 were 18–29 years of age, and 4 were 30–39

years of age. One participant had completed high school only, 8 had completed some college, and 13 had a college degree. None were current smokers, 1 reported cur- rent asthma, and 5 reported eczema, hay fever, or allergy to dust or mold.

Median $CO_2$ values for the low, medium, and high $CO_2$ conditions were 600, 1,006, and 2,496 ppm (which we refer to as 600, 1,000, and 2,500 ppm), and ranges were 132, 92, and 125 ppm, respectively (Table 1). Temperatures in the study chamber were controlled effectively, varying overall within about 0.2oC (from 22.9 to 23.1oC in each condition), and with median values across the three $CO_2$ conditions varying < 0.1oC.

The raw scores for each of the SMS performance measures were plotted for each partici- pant according to $CO_2$ level (Figure 1). The plots indicate clear relationships between raw scores and $CO_2$ level for all performance mea- sures other than focused activity and information search, with dramatic reductions in raw scores at 2,500 ppm $CO_2$ for some measures of decision-making performance.

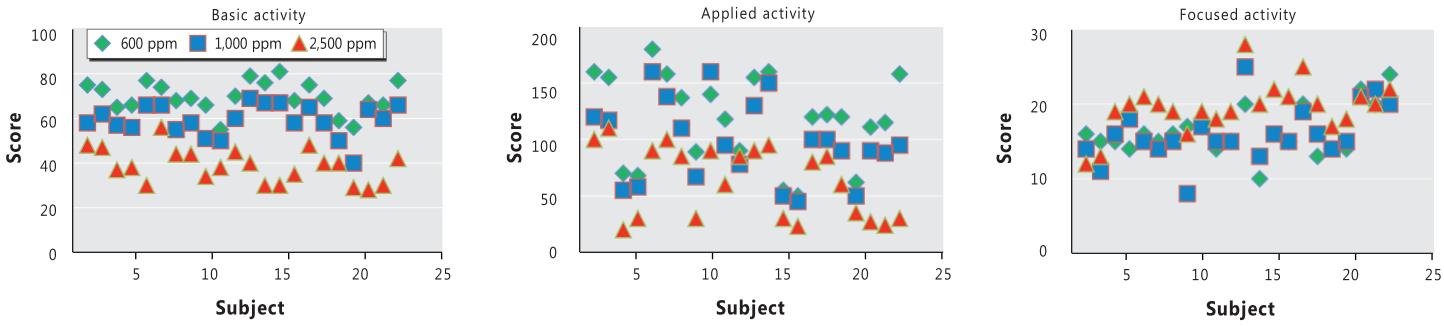
**Table 1.** $CO_2$ concentrations during study conditions.

| $CO_2$ condition | $CO_2$ concentration (ppm) | | | |
|---|---|---|---|---|
| | Minimum | Median | Maximum | Range |
| Low | 542 | 600 | 675 | 132 |
| Medium | 969 | 1,006 | 1,061 | 92 |
| High | 2,418 | 2,496 | 2,543 | 125 |
| Overall | 542 | 1,006 | 2,543 | - |

For seven of nine scales of decision-making performance (basic activity, applied activity, task orientation, initiative, information usage, breadth of approach, and basic strategy), mean raw scores showed a consistently monotonic decrease with increasing $CO_2$ concentrations, with all overall p-values < 0.001 (Table 2). In post hoc pairwise comparisons by $CO_2$ con- centration, performance on these seven scales differed between concentrations with $p < 0.01$ for all comparisons, except for performance on the task orientation, initiative, and basic strategy scales between 600 and 1,000 ppm $CO_2$ ($p < 0.05$, $p < 0.10$, and $p < 0.05$, respectively) (Table 3). For these seven scales, compared with mean raw scores at 600 ppm $CO_2$, mean raw scores at 1,000 ppm $CO_2$ were 11–23% lower, and at 2,500 ppm $CO_2$ were 44–94% lower. Relative to raw scores at 1,000 ppm $CO_2$, raw scores at 2,500 ppm were 35–93% lower.

For information search, mean raw scores were similar at all three $CO_2$ conditions. Neither the overall analysis across the three conditions (Table 2) nor the post hoc pair- wise analyses (Table 3) indicated significant differences. For focused activity, raw scores at 600 ppm $CO_2$ and 1,000 ppm $CO_2$ were nearly identical (16.27 and 16.09), but the mean raw score at 2,500 ppm was higher (19.55), resulting in an overall p-value ≤ 0.001 (Table 2). Post hoc tests indicated no difference between mean raw scores at 600 and 1,000 ppm $CO_2$, but significant differences ($p \leq 0.01$) between the mean raw score at 2,500 ppm $CO_2$ and scores at both 600 and 1,000 ppm (Table 3).

Figure 2 shows the percentile scores on the nine scales at the three $CO_2$ conditions (based on the raw scores shown in Table 2), with the percentile boundaries for five normative levels of performance: superior, very good, average, marginal, and dysfunctional. At 1,000 ppm $CO_2$ relative to 600 ppm, per- centile ranks were moderately diminished at most. However, at 2,500 ppm $CO_2$, percentile ranks for five performance scales decreased to levels associated with marginal or dysfunctional performance.



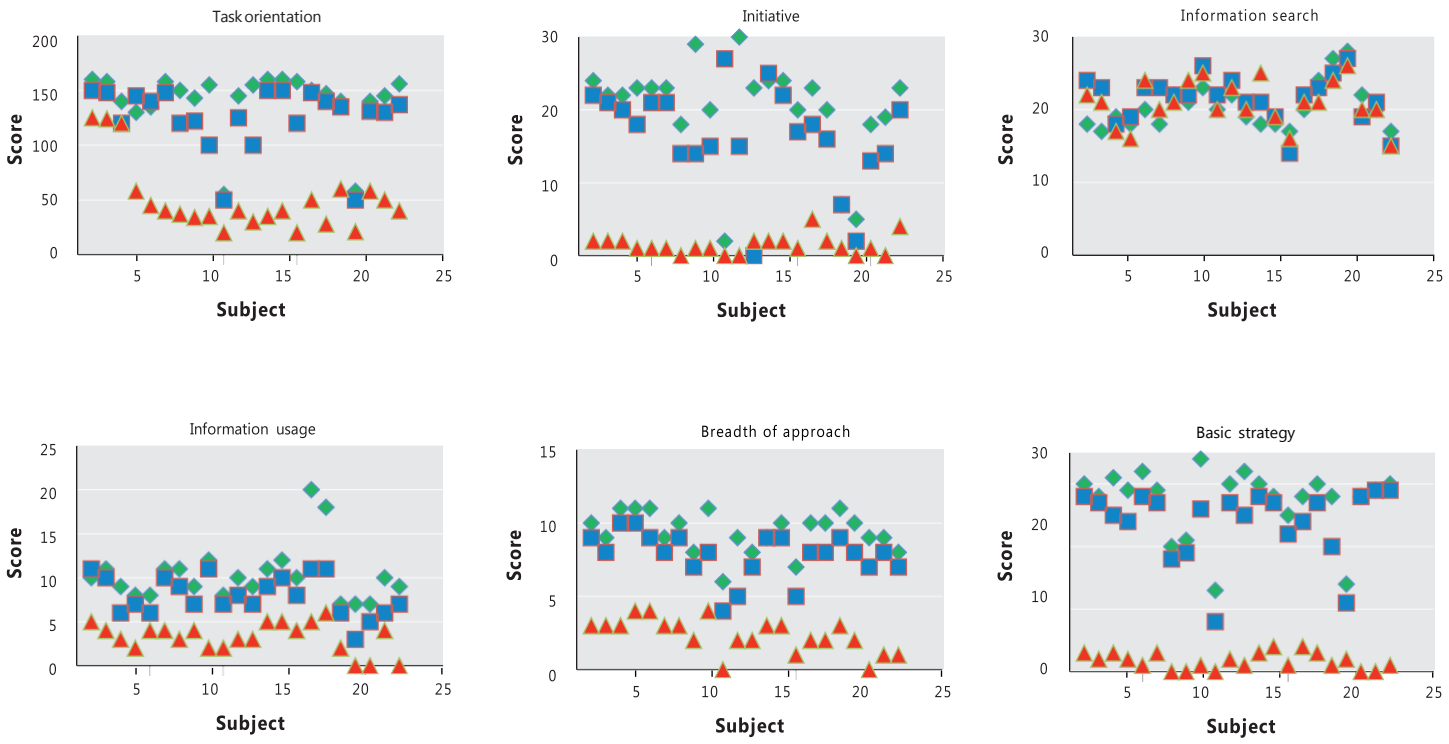



**Figure 1**. Plots of individual scores, by condition, for each of the SMS measures of decision-making performance (n= 22 subjects).

## Discussion

***Synthesis and interpretation of findings.*** Performance for six of nine decision-making measures decreased moderately but significantly at 1,000 ppm relative to the baseline of 600 ppm, and seven decreased substantially at 2,500 ppm. For an eighth scale, "information search," no significant differences were seen across conditions. In contrast to other scales, an inverse pattern was seen for "focused activity," with the highest level of focus obtained at 2,500 ppm and the lowest at 600 ppm.

Thus, most decision-making variables showed a decline with higher concentrations of $CO_2$, but measures of focused activity improved. Focused activity is important for overall productivity, but high levels of focus under nonemergency conditions may indicate "overconcentration." Prior research with the SMS has shown repeatedly that individuals who experience difficulty in functioning [e.g., persons with mild-to-moderate head injuries (Satish et al. 2008), persons under the influence of alcohol (Streufert et al. 1993), and persons suffering from allergic rhinitis (Satish et al. 2004)] tend to become highly focused on smaller details at the expense of the big picture.

High levels of predictive validity for the SMS ($r > 0.60$ with real-world success as judged by peers and as demonstrated by income, job level, promotions, and level in organizations), as well as high levels of test– retest reliability across the four simulation scenarios ($r = 0.72–0.94$) have repeatedly been demonstrated (Breuer and Streufert 1995; Streufert et al. 1988). Additional validity is demonstrated by the deterioration of various performance indicators with 0.05% blood alcohol intoxication and seriously diminished functioning with intoxication at the 0.10 level (Satish and Streufert 2002). Baseline scores at 600 ppm $CO_2$ for the participants in this study, mostly current science and engineering students from a top U.S. university, were all average or above.

Although the modest reductions in multiple aspects of decision making seen at 1,000 ppm may not be critical to individuals, at a societal level or for employers an exposure that reduces performance even slightly could be economically significant. The substantial reductions in decision-making performance with 2.5-hr exposures to 2,500 ppm $CO_2$ indicate, per the available norms for the SMS test, impairment that is of importance even for individuals. These findings provide initial evidence for considering $CO_2$ as an indoor pollutant, not just a proxy for other pollutants that directly affect people.

***$CO_2$ concentrations in practice.*** The real-world significance of our findings, if confirmed, would depend on the extent to which $CO_2$ concentrations are ≥ 1,000 and ≥ 2,500 ppm in current or future buildings. There is strong evidence that in schools, $CO_2$ concentrations are frequently near or above the levels associated in this

study with sig nificant reductions in decision-making performance. In surveys of elementary school classrooms in California and Texas, average $CO_2$ concentrations were > 1,000 ppm, a substantial proportion exceeded 2,000 ppm, and in 21% of Texas classrooms peak $CO_2$ con- centration exceeded 3,000 ppm (Corsi et al. 2002; Whitmore et al. 2003). Given these concentrations, we must consider the possibility that some students in high-$CO_2$ classrooms are disadvantaged in learning or test taking. We do not know whether exposures that cause decrements in decision making in the SMS test will inhibit learning by students; how- ever, we cannot rule out impacts on learning. We were not able to identify $CO_2$ measurements for spaces in which students take tests related to admission to universities or graduate schools, or from tests related to professional accreditations, but these testing environments often have a high occupant density, and thus might have elevated $CO_2$ levels.

**Table 2.** Mean raw scores for nine outcome variables at three conditions of $CO_2$ concentration among 22 participants, and comparison using MANOVA.

| Outcome variables | Conditions (ppm of $CO_2$) (mean ± SD) 600 ppm | 1,000 ppm | 2,500 ppm | Overall *F-statistic* (df = 2,42) | p-Value |
|---|---|---|---|---|---|
| Basic activity | 69.59 ± 7.04 | 59.23 ± 7.12 | 38.77 ± 7.57 | 172.77 | < 0.001 |
| Applied activity | 117.86 ± 39.28 | 97.55 ± 35.51 | 62.68 ± 31.86 | 72.13 | < 0.001 |
| Focused activity | 16.27 ± 3.20 | 16.09 ± 3.70 | 19.55 ± 3.40 | 17.26 | < 0.001 |
| Task orientation | 140.82 ± 28.66 | 125.41 ± 28.62 | 50.45 ± 31.66 | 115.08 | < 0.001 |
| Initiative | 20.09 ± 6.96 | 16.45 ± 6.70 | 1.41 ± 1.26 | 81.45 | < 0.001 |
| Information search | 20.36 ± 3.06 | 21.5 ± 3.20 | 20.91 ± 3.08 | 2.51 | > 0.10 |
| Information usage | 10.32 ± 3.21 | 7.95 ± 2.24 | 3.18 ± 1.71 | 129.20 | < 0.001 |
| Breadth of approach | 9.36 ± 1.36 | 7.82 ± 1.56 | 2.32 ± 1.17 | 679.88 | < 0.001 |
| Basic strategy | 27.23 ± 5.48 | 23.95 ± 5.65 | 1.68 ± 1.32 | 414.51 | < 0.001 |

df, degrees of freedom.

**Table 3.** Comparison of mean raw scores for nine decision-making measures between three different $CO_2$ concentrations among 22 participants.

| Variables | Ratios of condition scores[a] Score at 1,000 ppm/ score at 600 ppm | Score at 2,500 ppm/ score at 1,000 ppm | Score at 2,500 ppm/ score at 600 ppm |
|---|---|---|---|
| Basic activity | 0.85# | 0.65# | 0.56# |
| Applied activity | 0.83# | 0.64# | 0.53# |
| Focused activity | 0.99 | 1.22# | 1.20# |
| Task orientation | 0.89** | 0.40# | 0.36# |
| Initiative | 0.82* | 0.09# | 0.07# |
| Information search | 1.06 | 0.97 | 1.03 |
| Information usage | 0.77# | 0.40# | 0.31# |
| Breadth of approach | 0.84# | 0.30# | 0.25# |
| Basic strategy | 0.88** | 0.07# | 0.06# |

df, degrees of freedom.

[a]p-Values based on F-test, df = 1,21, calculated for difference between score in numerator and score in denominator.

*p < 0.10. **p < 0.05. #p < 0.01.

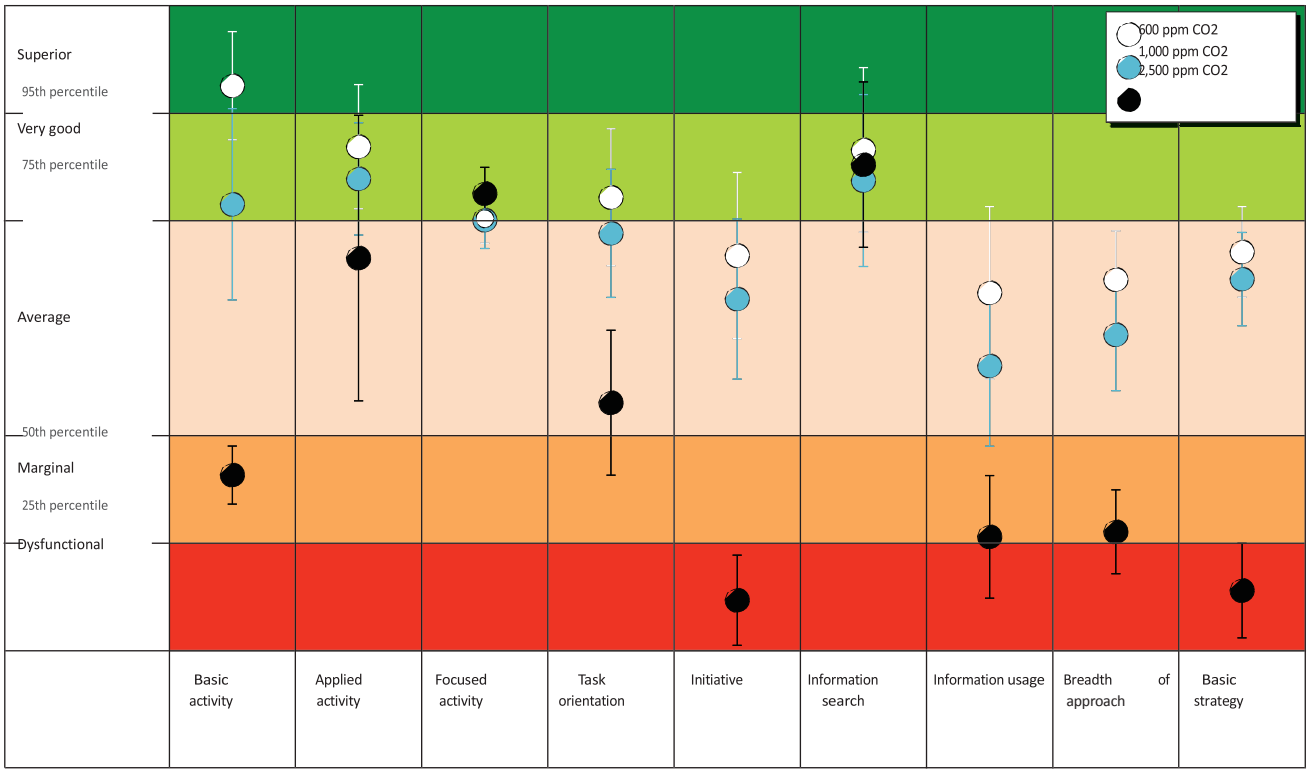



**Figure 2.** Impact of $CO_2$ on human decision-making performance. Error bars indicate 1 SD.

## Satish et al.

In general office spaces within the United States, $CO_2$ concentrations tend to be much lower than in schools. In a representative survey of 100 U.S. offices (Persily and Gorfain 2008), only 5% of the measured peak indoor $CO_2$ concentrations exceeded 1,000 ppm, assuming an outdoor concentration of 400 ppm. One very small study suggests that meeting rooms in offices, where important decisions are some- times made, can have elevated $CO_2$ concentrations for example, up to 1,900 ppm during 30- to 90-min meetings (Fisk et al. 2010).

In some vehicles (aircraft, ships, sub- marines, cars, buses, and trucks), because of their airtight construction or high occupant density, high $CO_2$ concentrations may be expected. In eight studies within commercial aircraft, mean $CO_2$ concentrations in the passenger cabins were generally > 1,000 ppm and ranged as high as 1,756 ppm, and maximum concentrations were as high as 4,200 ppm (Committee on Air Quality in Passenger Cabins of Commercial Aircraft 2002). We did not identify data on $CO_2$ concentrations in automobiles and trucks. One small study (Knibbs et al. 2008) reported low ventilation rates in vehicles with ventilation systems in the closed or recirculated air positions. From those results, and using an assumption of one occupant and a 0.0052 L/sec $CO_2$ emission rate per occupant (Persily and Gorfain 2008), we estimated steady-state $CO_2$ concentrations in an automobile and pickup truck of 3,700 ppm and 1,250 ppm, respectively, above outdoor concentrations. These numbers would increase in proportion to the number of occupants. It is not known whether the findings of the present study apply to the decision making of vehicle drivers, although such effects are conceivable.

There is evidence that people wearing masks for respiratory protection may inhale air with highly elevated $CO_2$ concentrations. In a recent study, dead-space $CO_2$ concentrations within a respirator (i.e., N95 mask) were approximately 30,000 ppm (Roberge et al. 2010), suggesting potentially high $CO_2$ con- centration in inhaled air. The inhaled concentration would be lower than that within the mask, diluted by approximately 500 mL per breath inhaled through the mask. Although the study did not report the actual inhaled-air $CO_2$ concentrations, partial pressures of $CO_2$ in blood did not differ with wearing the mask. Caretti (1999) reported that respirator wear with low-level activity did not adversely alter cognitive performance or mood.

***Findings by others.*** The Hungarian studies briefly reported by Kajtar et al. (2003, 2006) were the only prior studies on cognitive effects of moderate $CO_2$ elevations that we identified. In these studies, the ventilation

rate in an experimental chamber was kept constant at a level producing a chamber $CO_2$ concentration of 600 ppm from the occupant-generated $CO_2$; in some experiments, however, the chamber $CO_2$ concentration was increased above 600 ppm, to as high as 5,000 ppm, by injecting 99.995% pure $CO_2$ from a gas cylinder into the chamber. In two series of studies, participants blinded to $CO_2$ concen- trations performed proofreading significantly more poorly in some but not all sessions with $CO_2$ concentrations of 4,000 ppm relative to 600 ppm. Similar, marginally significant differences were seen at 3,000 versus 600 ppm. (Differences were seen only in proportion of errors found, not in speed of reading.) The studies by Kajtar et al. (2003, 2006) were small (e.g., 10 participants) and found only a few significant associations out of many trials; these results may have been attributable to chance, but they did suggest that $CO_2$ con- centrations found in buildings may directly influence human performance. Our research, which was motivated by the Hungarian studies, involved lower concentrations of $CO_2$, a larger study population, and different methods to assess human performance.

Prior studies on $CO_2$ exposures, mostly at higher levels, have focused on physiologic effects. $CO_2$ is the key regulator of respiration and arousal of behavioral states in humans (Kaye et al. 2004). The initial effects of inhaling $CO_2$ at higher concentrations are increased partial pressure of $CO_2$ in arterial blood ($PaCO_2$) and decreased blood pH. However, $PaCO_2$ is tightly regulated in healthy humans through reflex control of breathing, despite normal variation within and between individuals (Bloch-Salisbury et al. 2000). Inhaled $CO_2$ at concentrations of tens of thousands of parts per million has been associated with changes in respiration, cerebral blood flow, cardiac output, and anxiety (Brian 1998; Kaye et al. 2004; Lipsett et al. 1994; Roberge et al. 2010; Woods et al. 1988). Little research has documented physiological impacts of moderately elevated $CO_2$ concentrations, except one small study that reported changes in respiration, circulation, and cerebral electrical activity at 1,000 ppm $CO_2$ (Goromosov 1968).

We do not have hypotheses to explain why inhaling moderately elevated $CO_2$, with the expected resulting increases in respiration, heart rate, and cardiac output to stabilize $PaCO_2$, would affect decision-making performance. Bloch-Salisbury et al. (2000) have summarized prior knowledge on effects of elevated $PaCO_2$. $PaCO_2$ has a direct linear relationship with cerebral blood flow in a broad range above and below normal levels, through dilation and constriction of arterioles. Moderately elevated (or reduced) $PaCO_2$ has dramatic effects on central nervous system and cortical function. Bloch- Salisbury et al. (2000) reported that experimental changes in $PaCO_2$ in humans within the normal range (in 2-hr sessions involving special procedures to hold respiration constant and thus eliminate the normal reflex control of $PaCO_2$ through altered breathing), showed no effects on cognitive function or alertness but caused significant changes in electroencephalogram power spectra.

***Limitations.*** This study successfully con- trolled the known environmental confounding factors of temperature and ventilation rate. Although exposures to $CO_2$ in prior sessions may theoretically have affected performance in subsequent sessions, such carryover effects should not invalidate study results because of the balanced order of exposures. Suggestion effects were unlikely, because participants and the researcher explaining the SMS to them were blinded to specific conditions of each session. Although we conclude that the causality of the observed effects is clear, the ability to generalize from this group of college/university students to others is uncertain. Effects of $CO_2$ between 600 and 1,000 ppm and between 1,000 and 2,500 ppm, and effects for longer and shorter periods of time are also uncertain. The strength of the effects seen at 2,500 ppm $CO_2$ is so large for some metrics as to almost defy credibility, although it is possible that such effects occur without recognition in daily life. Replication of these study findings, including use of other measures of complex cogni- tive functioning and measures of physiologic response such as respiration and heart rate, is needed before definitive conclusions are drawn.

***Implications for minimum ventilation standards.*** The findings of this study, if replicated, would have implications for the standards that specify minimum ventilation rates in buildings, and would also indicate the need to adhere more consistently to the existing standards. Many of the elevated $CO_2$ concentrations observed in practice are a consequence of a failure to supply the amount of outdoor air specified in current standards; however, even the minimum ventilation rates in the leading professional standard [American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) 2010] correspond to $CO_2$ concentrations > 1,000 ppm in densely occupied spaces. There is current interest in reducing ventilation rates and the rates required by standards, to save energy and reduce energy- related costs. Yet large reductions in ventilation rates could lead to increased $CO_2$ concentrations that may adversely affect decision-making performance, even if air-cleaning systems or low-emission materials were used to control other indoor pollutants. It seems unlikely that recommended minimum ventilation rates in future standards would be low enough to cause

$CO_2$ levels > 2,500 ppm, a level at which decrements in decision-making performance in our findings were large, but standards with rates that result in 1,500 ppm of indoor $CO_2$ are conceivable.

## Conclusions

**Increases in indoor $CO_2$ concentrations resulting from the injection of ultrapure $CO_2$, with all other factors held constant, were associated with statistically significant and meaningful reductions in decision-making performance. At 1,000 ppm $CO_2$, compared with 600 ppm, performance was significantly diminished on six of nine metrics of decision-making per- formance. At 2,500 ppm $CO_2$, compared with 600 ppm, performance was significantly reduced in seven of nine metrics of performance, with percentile ranks for some performance metrics decreasing to levels associated with marginal or dysfunctional performance. The direct impacts of $CO_2$ on performance indicated by our findings may be economically important, may disadvantage some individuals, and may limit the extent to which outdoor air supply per person can be reduced in buildings to save energy. Confirmation of these findings is needed.**

## References


ACGIH (American Conference of Governmental Industrial Hygienists). 2011. TLVs and BEIs. Cincinnati, OH:American Conference of Governmental Industrial Hygienists.

ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers). 2010. ANSI/ASHRAE Standard 62.1-2010: Ventilation for Acceptable Indoor Air Quality. Atlanta, GA:ASHRAE.

Bloch-Salisbury E, Lansing R, Shea SA. 2000. Acute changes in carbon dioxide levels alter the electroencephalogram without affecting cognitive function. Psychophysiology 37(4):418–426.

Breuer K, Satish U. 2003. Emergency management simulations: an approach to the assessment of decision-making processes in complex dynamic crisis environments. In: From Modeling To Managing Security: A System Dynamics Approach (González JJ, ed). Kristiansand, Norway:Norwegian Academic Press, 145–156.

Breuer K, Streufert S. 1995. The strategic management simulation (SMS): a case comparison analysis of the German SMS version. In: Corporate Training for Effective Performance (Mulder M, Brinkerhoff RO, eds). Boston:Kluwer, 1–17.

Brian JE Jr. 1998. Carbon dioxide and the cerebral circulation.
Anesthesiology 88(5):1365–1386.

California Energy Commission. 2008. 2008 Building Energy Efficiency Standards for Residential and Nonresidential Buildings. CEC-400-2008-001-CMF. Sacramento, CA:California Energy Commission.

Caretti DM. 1999. Cognitive performance and mood during respirator wear and exercise. Am Ind Hyg Assoc J 60(2):213–218.

Cleckner LB. 2006. Pilot study of using strategic management simulation to assess human productivity. In: Proceedings of Indoor Environmental Quality: Problems, Research, and Solutions Conference 2006, 17–19 July 2006, Durham, NC. Red Hook, NY:Air and Waste Management Association; Curran Associates, Inc., 973–981.

Committee on Air Quality in Passenger Cabins of Commercial Aircraft. 2002. The Airliner Cabin Environment and the Health of Passengers and Crew. Washington, DC:National Research Council.

Corsi RL, Torres VM, Sanders M, Kinney KL. 2002. Carbon dioxide levels and dynamics in elementary schools: results of the TESIAS Study. In: Indoor Air 2002, 9th International Conference on Indoor Air Quality and Climate (Levin H, ed). Monterey, CA:Indoor Air, 74–79.

Erdmann CA, Apte MG. 2004. Mucous membrane and lower respiratory building related symptoms in relation to indoor carbon dioxide concentrations in the 100-building BASE dataset. Indoor Air 14(s8):127–134.

Federspiel CC, Fisk WJ, Price PN, Liu G, Faulkner D, Dibartolomeo DL, et al. 2004. Worker performance and ventilation in a call center: analyses of work performance data for registered nurses. Indoor Air 14(s8):41–50.

Fisk WJ, Sullivan DP, Faulkner D, Eliseeva E. 2010. $CO_2$ Monitoring for Demand Controlled Ventilation in Commercial Buildings. LBNL-3279E. Berkeley, CA:Lawrence Berkeley National Laboratory.

Goromosov MS. 1968. The Physiological Basis of Health Standards for Dwellings. Geneva:World Health Organization. Kajtar L, Herczeg L, Lang E. 2003. Examination of influence of $CO_2$ concentration by scientific methods in the laboratory.
In: Proceedings of Healthy Buildings 2003, 7–11 December
2003. Singapore:Stallion Press, 176–181.

Kajtar L, Herczeg L, Lang E, Hrustinszky T, Banhidi L. 2006. Influence of carbon-dioxide pollutant on human well-being and work intensity. In: Proceedings of Healthy Buildings 2006, 4–8 June 2006, Lisbon, Portugal:Universidade do
Porto, 85–90.

Kaye J, Buchanan F, Kendrick A, Johnson P, Lowry C,

Bailey J, et al. 2004. Acute carbon dioxide exposure in healthy adults: evaluation of a novel means of investigating the stress response. J Neuroendocrinol 16(3):256–264.

Knibbs LD, De Dear RJ, Morawska L, Atkinson SE. 2008. On-road quantification of the key characteristics of automobile HVAC systems in relation to in-cabin submicrometer particle pollution [Abstract]. In: 11th International Conference on Indoor Air Quality and Climate: Indoor Air 2008. Copenhagen, Denmark. Available: http://eprints.qut.edu.au/13822/ [accessed 23 October 2012].

Krishnamurthy S, Satish U, Foster T, Streufert S, Dewan M, Krummel T. 2009. Components of critical decision making and ABSITE assessment: toward a more comprehensive evaluation. J Grad Med Educ 1(2):273–277.

Lipsett MJ, Shusterman DJ, Beard RR. 1994. Inorganic compounds of carbon, nitrogen, and oxygen. In: Patty's Industrial Hygiene and Toxicology (Clayton GD, Clayton FD, eds). New York:John Wiley & Sons, 4523–4554.

Milton DK, Glencross PM, Walters MD. 2000. Risk of sick leave associated with outdoor air supply rate, humidification, and occupant complaints. Indoor Air 10(4):212–221.

Mudarri DH. 1997. Potential correction factors for interpreting $CO_2$ measurements in buildings. ASHRAE Transactions 103(2):244–255.

OSHA (Occupational Safety and Health Administration). 2012. Sampling and Analytical Methods: Carbon Dioxide in Workplace Atmospheres. Available: http://www.osha.gov/dts/sltc/methods/inorganic/id172/id172.html [accessed 7 May 2012].

Persily AK. 1997. Evaluating building IAQ and ventilation with carbon dioxide. ASHRAE Transactions 103(2):193–204.

Persily A, Dols WS. 1990. The relation of $CO_2$ concentration to office building ventilation. In: Air Change Rate and Airtightness in Buildings (Sherman MH, ed). West Conshohocken, PA:ASTM, 77–92.

Persily AK, Gorfain J. 2008. Analysis of Ventilation Data from the U.S. Environmental Protection Agency Building Assessment Survey and Evaluation (BASE) Study. NISTIR- 7145-Revised. Gaithersburg, MD:National Institute for Standards and Technology.

Roberge RJ, Coca A, Williams WJ, Powell JB, Palmiero AJ. 2010. Physiological impact of the N95 filtering facepiece respirator on healthcare workers. Respir Care 55(5):569–577.

Satish U, Manring J, Gregory R, Krishnamurthy S, Streufert S, Dewan M. 2009. Novel assessment of psychiatry residents: SMS simulations. Accreditation Council for Graduate Medical Education (ACGME) Bulletin, 18–23 January. Available: http://www.lj.se/newsdoc_files/upl_6120257683244412738.pdf [accessed 23 October 2012].

Satish U, Streufert S. 2002. Value of a cognitive simulation in medicine: towards optimizing decision making performance of healthcare personnel. Qual Saf Health Care 11(2):163–167.

Satish U, Streufert S, Dewan M, Voort SV. 2004. Improvements in simulated real-world relevant performance for patients with seasonal allergic rhinitis: impact of desloratadine. Allergy 59(4):415–420.

Satish U, Streufert S, Eslinger PJ. 2008. Simulation-based executive cognitive assessment and rehabilitation after traumatic frontal lobe injury: a case report. Disabil Rehabil 30(6):468–478.

Seppanen O, Fisk WJ, Mendell MJ. 1999. Association of ventilation rates and $CO_2$ concentrations with health and other responses in commercial and institutional buildings. Indoor Air 9(4):226–252.

Shendell DG, Prill R, Fisk WJ, Apte MG, Blake D, Faulkner D. 2004. Associations between classroom $CO_2$ concentrations and student attendance in Washington and Idaho. Indoor Air 14(5):333–341.

Streufert S, Pogash RM, Gingrich D, Kantner A, Lonardi L, Severs W, et al. 1993. Alcohol and complex functioning. J Appl Soc Psychol 23(11):847–866.

Streufert S, Pogash R, Piasecki M. 1988. Simulation based assessment of managerial competence: reliability and validity. Personnel Psychology 41(3):537–557.

Streufert S, Satish U. 1997. Graphic representations of processing structure: the time event matrix. J Appl Soc Psychol 27(23):2122–2148.

Streufert S, Streufert SC. 1978. Behavior in the Complex Environment. New York:John Wiley and Sons.

Streufert S, Swezey RW. 1986. Complexity, Managers, and Organizations. Orlando, FL:Academic Press.

Swezey RW, Streufert S, Satish U, Siem FM. 1998. Preliminary development of a computer-based team performance assessment simulation. Int J Cogn Ergonomics 2:163–179.

Wargocki P, Wyon DP, Sundell J, Clausen G, Fanger PO. 2000. The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity. Indoor Air 10(4):222–236.

Whitmore CA, Clayton A, Akland A. 2003. California Portable Classrooms Study, Phase II: Main Study, Final Report, Vol II. Research Triangle Park, NC:RTI International.

Woods SW, Charney DS, Goodman WK, Heninger GR. 1988. Carbon dioxide–induced anxiety: behavioral, physiologic, and biochemical effects of carbon dioxide in patients with panic disorders and healthy subjects. Arch Gen Psychiatry 45(1):43–52.

# ASHRAE 62.1 Compliance Report

# IAQP Calculation for HLR® Installation

# Office Building

Contact Info:

Dr. Marwa Zaatari, System Performance & IAQ,

HLR Systems Isaac Krull, Johnson Controls

March 16, 2016

## 1. Objective

The objective of this report is to document the compliance of HLR System's HVAC Load Reduction (HLR) installation with ASHRAE Standard 62.1-2013 Indoor Air Quality Procedure (IAQP; Section 6.3, pages 17-18). This document summarizes the indoor air quality (IAQ) compliance calculation results using the HLR system.

## 2. Summary

| Model Recommended | Quantity | 62.1 VRP OA Total | 62.1 IAQP OA Total |
|---|---|---|---|
| HLR1000E | 8 | 56,800 CFM | 22,000 CFM |

## 3. Introduction

This project includes two buildings: located in Michigan. The buildings mainly includes offices and meeting rooms. Each building consists of eleven floors and an approximate usable space of 136,400 $ft^2$. Each building is served by two air handling units. Each air handling unit supplies 71,000 CFM of treated air to the building (142,000 CFM total supply for each building). Outside airflow consists of 20% of the total supply (28,400 OA for each building).

We have proposed to install eight HLR modules (4 HLRs for each building) and decrease total outside air by 34,800 CFM.

A description of the HLR module and calculations according to ASHRAE 62.1-2013 are detailed below.

## 4. HLR Operation

The HLR unit is a smart scrubber with unique air cleaning and sensing capabilities. It includes patented $CO_2$,formaldehyde, and volatile organic compound (VOC) sorbents housed in proprietary cartridges; a heating element for regeneration; two small fans for regeneration and sorption; and a set of sensors measuring temperature, relative humidity, carbon dioxide, and volatile organic compounds of return, supply, treated, and regenerated air. The HLR system interprets the output of these sensors using control algorithms to actively and automatically manage the outside air, HVAC load, and indoor air quality.

## Figure 1

compares conventional air handling to HLR system air handling. As shown in the figure on the right, during normal operation, a fraction of the return airstream (open plenum air in this case) is directed through the sorbent cartridges to remove contaminants of concern. The sorbent cartridges automatically regenerate, releasing the captured contaminants and performing a self-cleaning process. During the regeneration cycle, the HLR system is blocked from the building's air systems, and warm air is blown over the cartridges and exhausted into the ambient air via the building's existing restroom exhaust ducts.

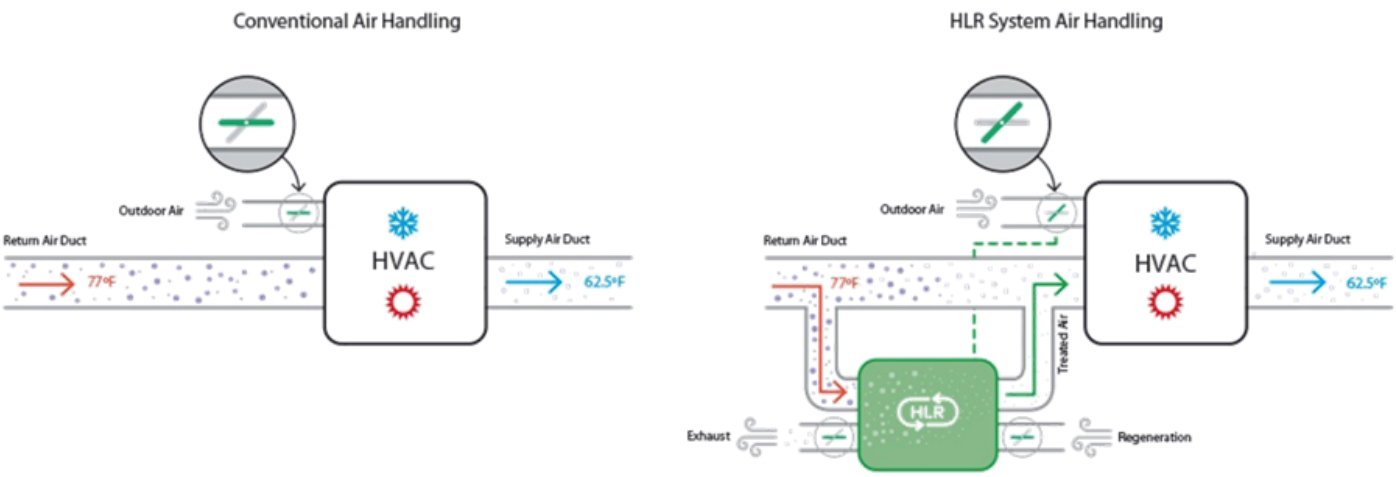



**Figure 1. Conventional Air Handling and HLR System Air Handling**

## 5. Methods

Application of the ASHRAE Standard 62.1-2013, Appendix D, Table D-1, page 40 equation incorporates the HLR module's cleaning capability and calculates the amount of outside air required to maintain the contaminants of concern below their established thresholds.

Below is the mass balance equation used in this calculation:

$$V_{out} = \frac{E_z \times \eta \times V_{HLR} \times C_{in} - N}{E_z \times (C_{out} - C_{in})}$$

- $V_{out}$: outside air required (CFM)
- $E_z$: ventilation effectiveness
- $V_{HLR}$: volume of air cleaned (CFM)
- $C_{in}$: indoor concentration (μg/m$^3$)
- N: emission rate or contaminant strength (μg/hr)

The inputs used in the mass balance equation are based on parameters measured in similar space types and documented in peer-reviewed journals. Verification of the inputs and the list of contaminants of concern (COCs) are derived by checking the detailed measurements that were completed for a new office building (seven floors, 100,000 ft2). For this office building, in eight different locations, carbon dioxide ($CO_2$), total volatile organic compounds (TVOC), speciated (separated by species) VOCs, acetaldehyde, formaldehyde, and particulate matter with an aerodynamic size of less than 2.5 (PM2.5) were measured following EPA Standards. VOCs were analyzed by a third-party certified lab in the US (Prism Analytical Technologies). From measured concentrations, indoor emission rates were calculated assuming a steady-state, well-mixed model, incorporating measured outdoor concentrations, building ventilation rates, and building dimensions. Carbon dioxide emission rates were verified from metabolic data found in ASHRAE Standard 62.1- 2013, Appendix C, Figure C-2, page 38.

## 6. Results

Specific to the buildings, a maximum occupancy of 680 people was assumed in each building. The main contaminants of concern identified for the buildings were formaldehyde, acetaldehyde, acetone, toluene, and carbon dioxide.

**Table 1. Main contaminants of concern emission rates and exposure limits**

| Contaminant of Concern | Contaminant Strength per building (µg/hr) | Contaminant Target Concentration | |
|---|---|---|---|
| | | Limit (8 hours average) | Reference |
| Formaldehyde | 290,601 | 33 µg/m$^3$ | CARB |
| Acetaldehyde | 397,997 | 140 µg/m$^3$ | ATSDR MRL |
| Acetone | 476,332 | 100 µg/m$^3$ | OSHA |
| Toluene | 69,491 | 37,000 µg/m$^3$ | CA OEHHA |
| $CO_2$ | 18,006,741,544 | 1,000ppm | Harvard Study (Allen et al., 2015), Berkeley Lab Study (Satish et al., 2012) |

It performed the mass balance calculations for each of the pollutants shown in the table above. By adding four HLR modules to each building, the outside air can be reduced from 28,400 CFM to **11,000 CFM for each building (total reduction of outside air equal to 34,800 CFM for both buildings)**. This is the maximum amount of outside air needed to keep the contaminants of concern below their established limits.

**Table 2. Example ($CO_2$) of inputs used for calculations for the South Building**

| | | | |
|---|---|---|---|
| Indoor Concentration at Breathing Level | $C_{bz}$ (µg/m$^3$) | 1,938,000 | 1000 ppm |
| Indoor Emission Rate | N (µg/hr) | 18,006,741,544 | |
| Ventilation Effectiveness | $E_z$ | 0.8 | |
| Outdoor Concentration | Co (µg/m$^3$) | 775,000 | 400 ppm |
| Volume HLR | $V_{HLR}$ (CFM) | 3600 | Corresponds to 4 HLRs |
| Air Cleaning Efficiency | $E_f$ | 65% | HLR efficiency |
| Outside Air Rate | Vot (CFM) | 11,000 | |

## 7. Conclusion

Using eight HLR1000E with 22,000 CFM of outside air for this project demonstrates compliance with ASHRAE Standard 62.1-2013. Expected results of incorporating the HLR1000E into the HVAC system include a significant reduction in energy consumption while maintaining acceptable indoor air quality.

## The HLR® 1000E offers 4 main technical Innovations including:

### Indoor Air Treatment Technologies

- Unique new sorbents are at the heart of the unit approach to removing molecular contaminants. Sorbents are housed in nontoxic, recyclable cartridges, with no by products.
- Each type of sorbent is designed to capture specific kinds of particle.

### Outside Air Management

- Through electromechanical control of outside air dampers dynamically controls the amount of outside air entering the building through the HVAC system, guided by air quality sensors and weather conditions. This optimizes energy use. The controls also contain failsafe settings in the event of an emergency, such as a power outage,

### Automated Regeneration

- Revolutionary sensors and machine learning algorithms allow for automated regeneration of sorbents. The HLR® systems to perform in-situ regeneration of the sorbents which is triggered automatically by the system, when needed. Sensors monitor the sorbent status and, at the optimal time for energy savings and air quality, the sorbents are heated causing them to release captured molecular contaminants outside of the building. One cartridge set will last for a full year due to this technology, and the air will be consistently cleaned.

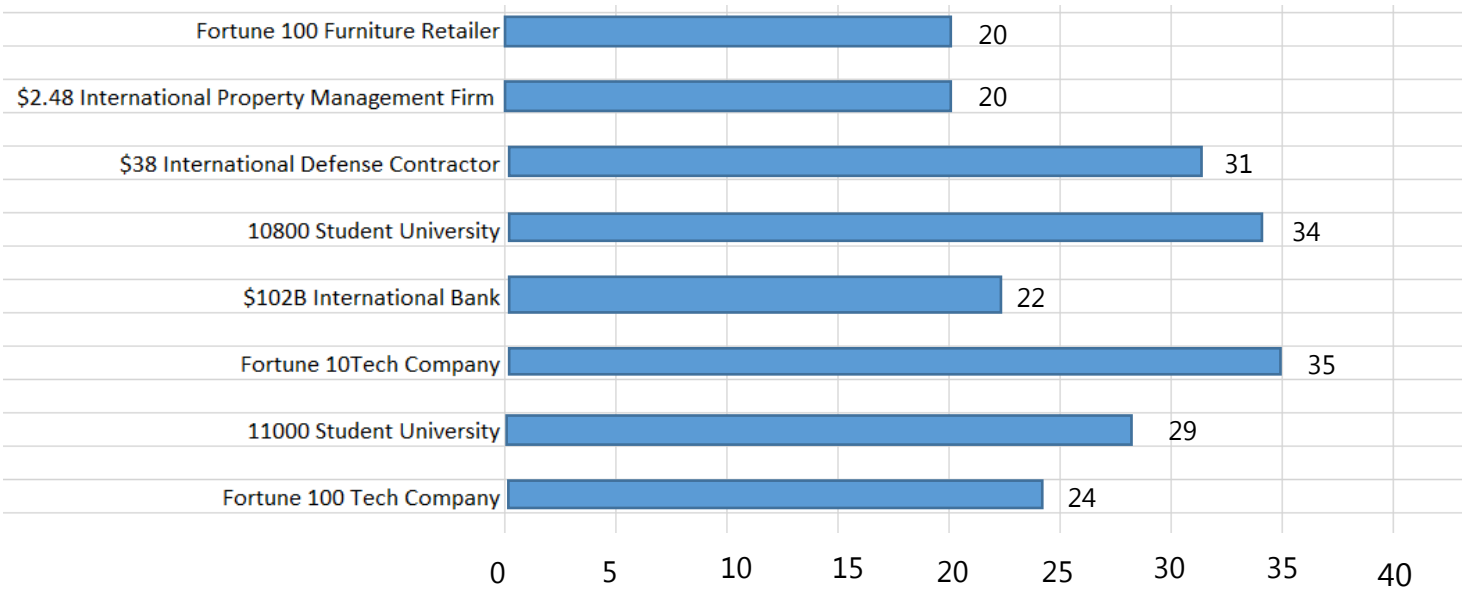
### Monitoring and Reporting

- 24/7 Online Connectivity provides real time visibility control of system. Embedded sensors record indoor and outdoor air temperature and humidity, indoor air quality (contaminants in parts per billion), air flow, energy use, sorbent performance, and system operating conditions. These are securely connected to the Internet through wireless data transmission, and presented in a data dashboard for easy understanding. Connect directly, or through BACnet or LoRa.

## HLR Economics

- Significant first cost CapEX saving
- Peak load saving routinely **exceed 40%**
- Annual HVAC energy saving 20-40%

## Customer Average Energy Savings using YORK EcoAdvance HLR1000E

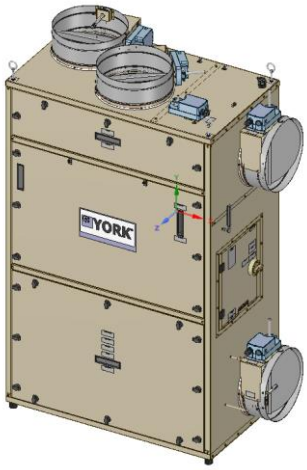


## Conducting and Reporting the Results of a CFD Simulation Airflow Analysis for HLR1000E Unit

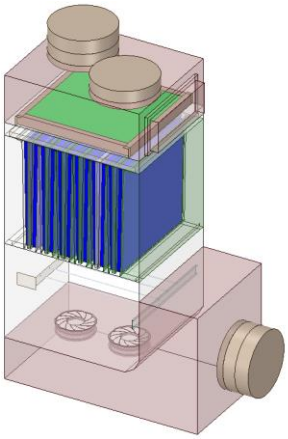
- Objective is to achieve a high level of credibility and confidence in the results from CFD performed as part of the design and air flow analysis and predict airflow pattern in the HLR1000E Unit.

- Credibility and confidence are obtained by demonstrating acceptable levels of error and uncertainty as assessed through verification and validation.

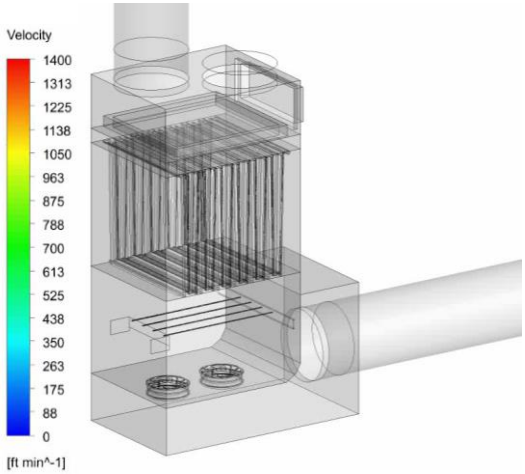
- Identified flow path and pressure zones in different components of the HLR unit



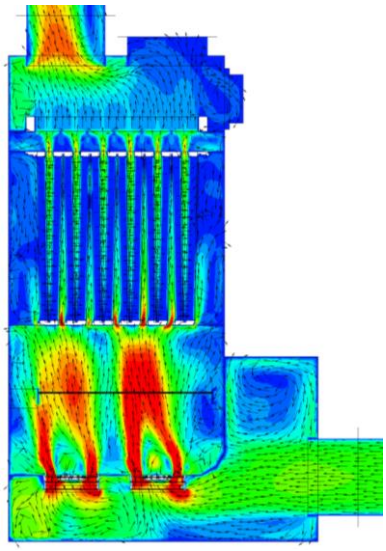

HLR_1000E



CFD Model - HLR_1000E




Stream Lines - animation



Velocity Vectors

## Results & Conclusions

### Results

**Model – HLR 1000E- Results**

| CFD Calculation Pressure Drop | | |
|---|---|---|
| Filter | 0.0923 inch wg | 22.96Pa |
| Cartridges Compartment | 0.6388 inch wg | 158.96Pa |
| *CFD Domain | -0.1352 inch wg | -33.65Pa |

### Conclusion

- Pressure drop across the filter assembly is 0.0923 inch wg
- Pressure drop across the Cartridges Compartment is 0.6388 inch wg
- Pressure drop across the CFD domain is -0.1352 in. wg
- The flow rate from Fan 1 is calculated as 385.7 CFM
- The flow rate from Fan 2 is calculated as 364.3 CFM

LEED O+M: Existing Buildings | v3 - LEED 2009

# Indoor air quality procedure

EQpc68 | Required



**Intent**
To contribute to the comfort and well-being of building occupants by establishing minimum standards for indoor air quality (IAQ).

**Requirements**
This prerequisite is available for pilot testing by the following LEED rating systems and building types:

New Construction

Office
Multi-family Residential Lodging
Warehouses

Retail NC (excluding restaurants)
Schools (excluding laboratories within school buildings) Commercial Interiors
Retail CI (excluding restaurants)
Existing Buildings Operations and Maintenance

Office
Retail (excluding restaurants)
Multi-family Residential
Lodging
Schools (excluding laboratories within school buildings)
Warehouses

Project types not listed above that are interested in pursuing this path, should contact USGBC before registration. See below for more information.

Note: The following Pilot Credit modifications apply to this prerequisite:

Introductory phone call between project teams pursuing this path and GBCI reviewers.
Project teams pursuing this pilot prerequisite will be required to fulfill all prerequisite requirements. Unlike with other pilot credits, documenting that a pilot credit is in need of major revision and in unachievable in its current form will not demonstrate compliance for IEQp1.
No ID points will be awarded.

If a project team registers and submits documentation noting that space in the project fails testing (chemical or perceived), corrective action must be taken until the project meets all requirements; it will not be acceptable to pursue the Ventilation Rate Procedure in IEQp1 once evidence of not meeting the pilot requirements is submitted. If, however, a project team decides that this path is too costly or otherwise onerous prior to submission, they may go back and use the traditional IEQp1 path.

BD+C and ID+C projects will still need to meet local code requirements for ventilation if they differ from the IAQP.

Meet the minimum requirements of ASHRAE Standard 62.1-2007, Sections 4 through 6, Ventilation for Acceptable Indoor Air Quality (with errata). Determine the minimum outdoor air intake flow for mechanical ventilation systems using the In-door Air Quality Procedure, or a local equivalent, whichever is more stringent.

Combining the IAQP and VRP is not an acceptable means of compliance with this pilot prerequisite.

Prohibit smoking in the building.

Meet the following requirements for ventilation systems designed in accordance with Section 6.3 Indoor Air Quality (IAQ) Procedure:

1. Contaminant Sources. Identify the outdoor sources, indoor sources, and the expected emission rate for each of the contaminants and mixtures of concern listed in Table 1. Additionally, confirm that the top 10 contaminants by concentration in the building, as identified by mass spectrograph analysis, are included in Table 1. If they are not already included in Table 1, list them.

2. Contaminant Concentration. Refer to Table 1 for maximum allowable concentration limits for each contaminant of concern.

3. Perceived Indoor Air Quality. At least 80% of observers or occupants must determine the perceived indoor air quality to be “acceptable” using a Subjective Evaluation.

4. Design Approach. If adjustments will be made to the outdoor air flow rate, use mass balance analysis. Determine minimum outdoor airflow rates per steady-state mass-balance in Appendix D of the standard. Measure system level airflow rates before and after modifications are made.

5. Non-Dilution Air Cleaning Technology. If non-dilution air cleaning technology is utilized, use air cleaning technology consisting of sorptive active agents, in accordance with ASHRAE Standard 145.2-2011, Laboratory Test Method for Assessing the Performance of Gas-Phase Air-Cleaning Systems: Air Cleaning Devices. If electronic air cleaning technology is pre-existing, continuous ozone monitoring shall be provided.
   Electronic air cleaning cannot be used as a means of chemical contaminant control.

6. Air Testing. Conduct contaminant-level testing for each of the contaminants of concern as follows:

   1. Each contaminant of concern shall be measured using the test methods in Table 1. If the top 10 contaminant concentrations are not listed in Table 1, separately mitigate these contaminants or provide a ruling by a cognizant health body that they have no known adverse health impact. Testing is to be completed during time of anticipated peak contaminant loading by an appropriately accredited professional. Use current versions of ASTM standard methods or ISO methods. The number of sampling locations depends on the size of the building and number of ventilation systems, but must include the entire building and all representative space uses.

   2. All measurements within each location shall demonstrate compliance with the maximum allowable concentration limits per Table 1. For each sampling point where the concentration exceeds the limit, take corrective action and retest for the noncompliant contaminants as the sampling points. Repeat until all requirements are met.

3. Provide testing frequency as follows:

   For initial certification, the testing must occur within the performance period.
   For recertification, the testing must occur no less frequently than every two years. Project teams may test more frequently at their discretion.
   Construction projects within an existing building must comply with the requirements under this prerequisite for ID+C projects.
   Any adjustments to outside air volumes required to comply with the maximum allowable concentration limits must be implemented within the performance period. Outside air measurements at the affected air handling units must confirm the adjustments.

4. Confirm complete implementation of maintenance plans for the following contaminants or document status of "no further remediation" required:

   Asbestos Containing Materials (ACMs)
   Lead
   Radon
   Mold

7. Subjective Evaluation. Distribute a seven-point scale questionnaire to at least 30% of the space/building occupants as described in IEQ Credit 2.1 Occupant Comfort – Occupant Survey. The questionnaire is to be designed to address perceived air quality particularly focusing on odors and irritation responses.

8. Maintenance Program. Implement and maintain an HVAC system maintenance program to ensure the proper operations and maintenance of HVAC components as they relate to outdoor air introduction and exhaust. Include any non-dilution methods used.

9. System Testing. Test and maintain operation of all building exhaust systems, including bathroom, kitchen and parking exhaust systems.

## Table 1.

| Contaminant Compound (CAS#) | Concentration Limit (μg/m3) | Test Method |
|---|---|---|
| Volatile Organic Compounds (VOCs) | | |
| Acetaldehyde 75-07-0 | 140 | ISO 16017-1, 2; ISO 16000-3, 6; ASTM D6345-10 |
| Benzene 71-43-2 | 60 | |
| Carbon disulfide 75-15-0 | 800 | |
| Carbon tetrachloride 56-23-5 | 40 | |
| Chlorobenzene 108-90-7 | 1000 | |
| Chloroform 67-66-3 | 300 | |
| Dichlorobenzene (1,4-) 106-46-7 | 800 | |
| Dichloroethylene (1,1) 75-35-4 | 70 | |
| Dimethylformamide (N,N-) 68-12-2 | 80 | |
| Dioxane (1,4-) 123-91-1 | 3000 | |
| Epichlorohydrin 106-89-8 | 3 | |
| Ethylbenzene 100-41-4 | 2000 | |
| Ethylene glycol 107-21-1 | 400 | |
| Ethylene glycol monoethyl ether 110-80-5 | 70 | |
| Ethylene glycol monoethyl ether acetate 111-15-9 | 300 | |
| Ethylene glycol monomethyl ether 109-86-4 | 60 | |
| Ethylene glycol monomethyl ether acetate 110-49-6 | 90 | |
| Formaldehyde 50-00-0 | 33 | BS-ISO 16000-3, 4; ASTM D5197; BS ISO 16000-4 |
| Hexane (n-) 110-54-3 | 7000 | ISO 16017-1, 2; ISO 16000-3, 6; ASTM D6345-10 |
| Isophorone 78-59-1 | 2000 | |
| Isopropanol 67-63-00 | 7000 | |
| Methyl chloroform 71-55-6 | 1000 | |
| Methylene chloride 75-09-2 | 400 | |
| Methyl t-butyl ether 1634-04-4 | 8000 | |
| Naphthalene 91-20-3 | 9 | |
| Phenol 108-95-2 | 200 | |
| Propylene glycol monomethyl ether 107-98-2 | 7000 | |
| Styrene 100-42-5 | 900 | |
| Tetrachloroethylene 127-18-4 | 35 | |
| Toluene 108-88-3 | 300 | |
| Trichloroethylene 79-01-6 | 600 | |
| Vinyl acetate 108-05-4 | 200 | |
| Xylenes-total 108-38-3, 95-47-6, and 106-42-3 | 700 | |

| Inorganics | | |
|---|---|---|
| Carbon Monoxide | 9 | ISO 4224 |
| Ozone | 147 (0.075 ppm) | ISO 13964; ASTM D5149-02 |
| Particulate Matter PM2.5 | 15 | ISO 7708 |
| Ammonia | 200 | NIOSH Manual of Analytical Methods |
| Carbon Dioxide | 700 above outdoor ppm | EPA compendium infared |

Submittals

**General**

REGISTER FOR PILOT ACP 68

Participate in the LEED user pilot credit forum

Complete the feedback survey:

CREDITS 1-27

CREDITS 28-38

CREDITS 39-41

CREDITS 42-56

CREDITS 57-67

## EBOM specific

In addition to the above, meet the following additional requirements:

## Establishment

1. Provide a copy of the building maintenance plan implementing a regular IAQ Performance Method compliant with this Pilot Prerequisite. Describe the ventilation maintenance program, including a description of the periodic checks and scheduled maintenance performed, and whether the checks are manual, based on a building automation system, or both.

2. Confirm that the project team has performed or overseen tests in all project building exhaust systems during the performance period to verify proper function.

## Performance period

1. Documentation provided must confirm that required performance period miles-tones have been completed within the stated performance period for the project building.

2. If adjustments are made to the outdoor air flow, provide a table listing system level air flow rates before and after adjustments are made.

## Additional questions

Would the team apply this method to another building in the future? Why/why not? How did the cost of this method compare to the cost of the Ventilation Rate Procedure?

## Background Information

Subjective evaluation - Panel

Panel participants may be regular occupants of the project building, visitors to the building (i.e. customers of a retail establishment), or individuals with no connection to the project building. Composition of the panel in this regard is at the discretion of the project team.

Responses are to be collected via anonymous methods either written or electronic. The Perceived Indoor Air Quality test is considered "passing" if 80% or more of the panel renders the space "acceptable" at each interval. If less than 80% of the panel renders the space "acceptable", appropriate corrective actions must be implemented to correct the deficiency. Corrective actions must be implemented within six (6) months of
the conclusion of the panel observations.
Subjective evaluation – Questionnaire

The questionnaire is to be designed to address perceived air quality particularly focusing on odors and irritation responses. The responses shall be tabulated. Respondent answers of -1, -2, or -3 on the seven- point scale will be considered as dissatisfied. If more than 20% of respondents are dissatisfied, appropriate corrective actions must be implemented during the performance period.

For EB: O+M projects, at least one occupant survey must be conducted during each monitoring period.

Space sampling for testing

Randomly select spaces to be tested, ensuring that each occupiable space type is adequately represented. Utilize HERS sampling methodologies for multi-family and lodging projects or APPA sampling methodologies for offices, retail, schools, warehouses, and existing buildings.

1. Minimum area and space counts noted in the applicable sampling methodology MUST be met.

    1. For HERS sampling procedures, randomly select one in seven (1 in 7) substantially similar spaces. Each sample group would consist of identical spaces, one out of every seven of which are to be tested. A minimum of three tests must be conducted in each sample group.

    2. For APPA, randomly select locations totalling at least 10% of the gross floor area of the building and 10% of the total count of substantially similar spaces provided at least five (5) spaces of each space type are included. For any space types with less than five (5) spaces, include all spaces of that type.

    2. Note: different occupiable space types may be combined into common groups if the contaminants and mixtures of concern within those space types are expected to be the same with similar emission rates and the spaces are served by the same ventilation system.

For purposes of determining how many test locations are required, the following shall govern:

1. Testing must occur in at least one location per ventilation system, per occupiable space type. The location(s) selected for testing must represent the worst-case zone(s) where the highest concentrations of contaminants of concern are likely to occur.

    1. For offices, retail, schools, lodging, multi-family residential, and existing buildings, testing must occur within areas no larger than 5,000 square feet. For warehouses or large open spaces within other building types (i.e. ballrooms in lodging, gymnasiums in schools, etc.) a limit of 50,000 square feet may be used. If there is evidence that the air within the space is well-mixed and sources of contaminants of concern are uniform, project teams may test a single location within that space. Evidence would consist of one of following:

    1. Engineering verification of HVAC system with uniform ventilation distribution, and uniform source of contaminants within that space.

    2. Tracer gas analysis showing uniform air distribution, and initial contaminant measurements showing uniform levels of contaminants of concern.

2. Real-time sensors may be used to identify the worst-case zones for contaminants of concern; however, final testing results must be measured using the protocols below. Real-time sensor testing is not acceptable for final testing results.

3. Locations selected may be served by more than one ventilation system provided that each ventilation system serving the location is designed in accordance with Section 6.3.

**Additional Resources**

1. Reference to CHiPS database of contaminant generation rates
2. Spreadsheet Calculator for compliance purposes
3. Flow chart of compliance steps
4. Example Surveys
5. CEC/LBNL report, "Balancing energy conservation and occupant needs in ventilation rate standards for "Big Box" stores in California: predicted indoor air quality and energy consumption using a matrix of ventilation scenarios". It is available here

**BacNET BAS Point List**

The unit will be sense the following 14 points

1. Indoor CO2
2. Indoor Temperature
3. Indoor humidity
4. Indoor tVOC
5. Output Co2
6. Output temp
7. Output humidity
8. Outside temp
9. Outside humidity
10. Supply temp
11. Supply humidity
12. Cartridge temp
13. Cartridge Pressure
14. Fresh air damper.

Not pursuing this pilot but have a comment you'd like to share with USGBC?

Click here to submit your comment



## Indoor Environmental Quality: Indoor Air Quality (IAQ)

| | | |
|---|---|---|
| **Traditional Path** | | |
| Prerequisite | Minimum IAQ Performance | Required |
| Prerequisite | Environmental Tobacco Smoke Control | Required |
| Credit | Enhanced IAQ Strategies | 2 |
| Credit | Low - emitting Materials | 3 |
| Credit | IAQ Assessment (Air Testing) | 2 |
| Credit | Construction indoor air quality management plan | 2 |
| **Alternate Path** | | |
| Prerequisite | New LEED Pilot Credits EQpc68: Indoor Air Quality Performance (IAQP) | 9 credits |