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APPLICATION POTENTIAL OF LIQUID DESICCANT INSTALLATIONS IN HAWAII

Task 7

Prepared For
Hawaii Natural Energy Institute

Prepared By
Sustainable Design & Consulting LLC & HNEI

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HNEI
Hawai'i Natural Energy Institute
University of Hawai'i at Mānoa

DESICCANT DEHUMIDIFICATION TO SUPPORT ENERGY EFFICIENT SPACE CONDITIONING SYSTEMS FOR HAWAII

PROJECT PHASE 1: DESIGN STUDY AND PROJECT SITE SELECTION

Project Deliverable No. 2:

" Identify Application Potential of Liquid Desiccant Installations in Hawaii "

Prepared for

Hawaii Natural Energy Institute

RCUH P.O. #Z10143891

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ABBREVIATIONS

AC	Air-conditioning
AHU	Air-handling Unit
ASHRAE	American Society of Heating, Refrigerating, and Air-Conditioning Engineers
COP	Coefficient of performance
DOAS	Dedicated Outdoor Air Supply
DP	Dew point
DEAC	Direct Evaporative Air Coolers
DEC	Direct evaporative cooler
EAC	Evaporative Air Cooling external source of energy (Q)
HNEI	Hawaii Natural Energy Institute
HR	Humidity Ratio
HVAC	Heating Ventilation Air Conditioning
IEAC	Indirect Evaporative Air Coolers
LD	Liquid Desiccant
IEC	Indirect Evaporative Cooler
LiCl	Lithium Chloride
LCST	Lower Critical Solution Temperature
OA	Outdoor (or outside) Air
PV	Photovoltaic System, also solar-PV Power System
RH	Relative Humidity
SHR	Sensible Heat Ratio
SDC	Sustainable Design & Consulting LLC
SI	International System of Units
VAC	Vapor-Compression Air Conditioning
WBT	Wet-bulb temperature
VAV	Variable Air Volume

UNITS

atm	Atmosphere pressure
BTU	British Thermal Unit
°C	Degree Celsius
CFM	Cubic feet per minute
°F	Fahrenheit
fpm	Feet per minute
kJ	kIlo Joule
MPa	Mega Pascale

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SECTION 1 – EXECUTIVE SUMMARY AND RECOMMENDATION

This report is the Project Deliverable 2 "Identify Application Potential of Liquid Desiccant Installations in Hawaii". This report is the second part of a series of reports investigating and proposing the feasibility of using liquid desiccants to develop an innovative hybrid space conditioning system for Hawaii's climate. The proposed space conditioning system separates sensible from latent heat removal through liquid desiccants in lieu of the conventional cooling coil dehumidification. Since the cooling coils or other sensible cooling technologies do not have to provide below-dew-point surfaces for condensation based humidity removal, as in conventional HVAC, overcooling of spaces can be virtually ruled out.

Precise dehumidification of outdoor air can be achieved, to a level that is deemed optimum for both the specific indoor use and occupant preference. The proposed system will keep indoor temperatures at a higher level than is customary in buildings with conventional HVAC. This saves energy, provides indoor thermal comfort, has elements of adaptive comfort and opens the door to use a range of building technologies and design features, which provide elements of good IEQ (Indoor Environmental Quality).

Section 2 of this report discusses IEQ, which is linked, along with temperature, ventilation, and humidity controls, to occupant comfort and optimized individual performance. The proposed hybrid space conditioning system has twin goals - to provide good IEQ, and to yield significant electric energy savings. Providing a good indoor environment depends on a range of aspects that goes beyond satisfactory thermal comfort, which is typically at the heart of good HVAC design and operation.

The literature postulates different types of IEQ aspects that constitute the overall indoor environmental experience. For the discussion of this report, and with the focus on assessing the feasibility of the proposed alternative space conditioning system for use in Hawaii, a specific range of aspects of indoor environmental quality (IEQ) is considered. The range of relevant IEQ aspects is illustrated in Figure 1.1. Three groups were established, each consisting of multiple IEQ criteria. Each group consists of individual IEQ criteria with similar characteristics of utility and importance, measured either by means of established metrics or as more subjective means.

An important requirement of good space conditioning, especially for the hot and humid climate in in Hawaii, is the avoidance of humidity related problems. Among a wider range of humidity related problems is the occurrence of mold from indoor dampness. While implementing more energy efficient technologies in buildings, the precise control of humidity is getting more important. Energy efficiency in buildings, for example, is often linked to increased sealing of buildings and a combined ventilation and cooling HVAC. Both building technologies render precise and effective humidity control more challenging. This is because indoor spaces in well-sealed and insulated buildings do not need to receive the amount of cooling that is required in conventional buildings. Since all-air cooling and ventilation is linked in conventional HVAC systems, ventilation rates and the connected humidity removal might be lower than required. The proposed system with the dedicated liquid desiccant based humidity control, separating latent heat from sensible load removal, will provide effective means to avoid such humidity related problems.

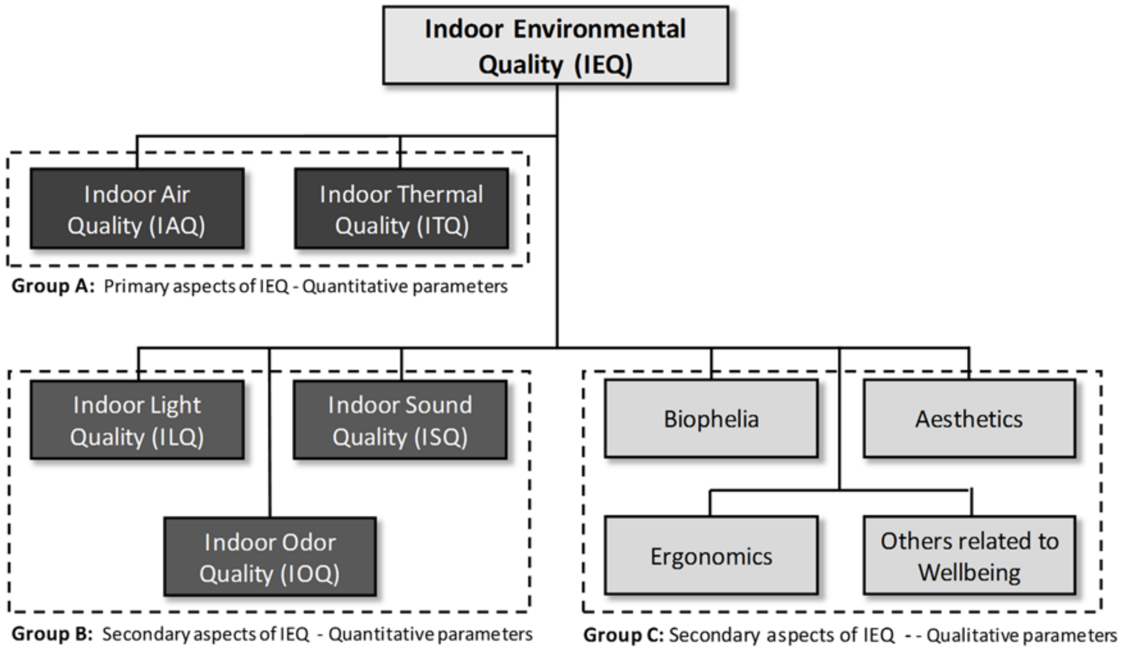


Figure 1.1: Interrelationship of aspects of IEQ (see also Figure 2.1.1)

Section 3 presents and discusses four indoor conditioning technologies which are presently used in Hawaii. Section 3 also describes the proposed hybrid system based on liquid desiccant dehumidification. The four presently used space conditioning systems are:

- System (A) – Natural ventilation
- System (B) – Natural ventilation (with mechanically induced indoor air movement):
- System (C) – Mechanical ventilation:
- System (D) – Full, conventional HVAC:

System (E) - the proposed hybrid system, is compared with the four systems, Systems (A) through (D).

Section 4 investigates the performance of the five space conditioning systems (A) through (E) regarding providing good energy savings and at the same time establishing good indoor environmental quality. For the quantitative assessment of the performance, a multi-tiered ranking system was developed that assigned individual ranking weights to the different IEQ aspects and the potential of energy savings. The comprehensive ranking procedure involved multiple layers to arrive at an overall score for the five space conditioning systems (A) through (E). The assignment of weights for the various parameters in the ranking framework was done subjectively, while considering the goals of the proposed innovative space conditioning system and the relative importance of energy savings and IEQ. Figure 1.2 shows the derived overall performance scores of systems (A) through (E). The results of the assessment suggest that the proposed hybrid space conditioning system (System E) has the best overall score and therefore the best combined performance regarding IEQ and energy savings.

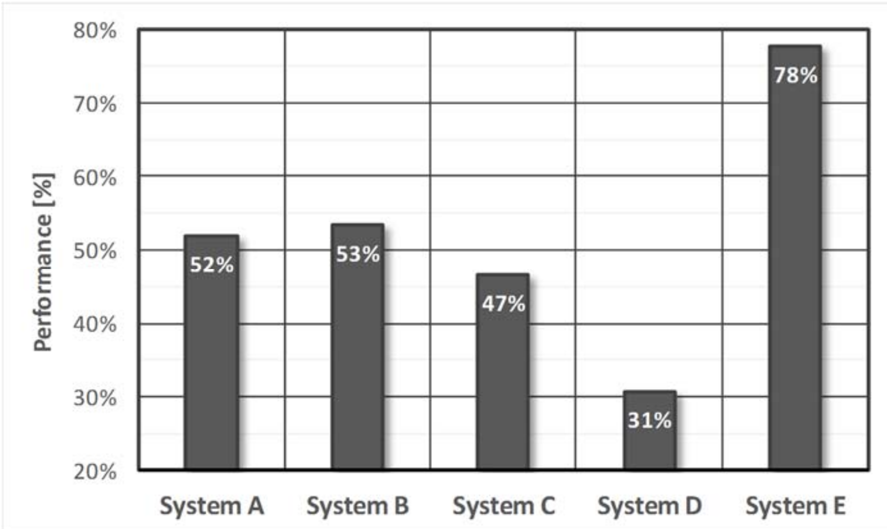


Figure 1.2: Figure 4.4.2: Overall ranking scores of System A through E

The overall score indicates the level of performance when both providing high energy savings and good IEQ are considered in a comprehensive assessment framework.

(See also Figure 4.4.2 in Section 4)

Since the two main assessment parameters of the overall performance are energy savings potential and providing good indoor environmental quality, a sensitivity analysis was performed that gauged the overall score as a function of importance to energy savings. In this assessment, the importance of energy savings ranged from 0% and 100%. The importance of good IEQ was expressed as the complementing value to the importance of energy savings. Therefore, when the importance of energy savings was 100%, 50% and 0%, the importance of creating good IEQ was the complementing 0%, 50% and 100%, respectively. Figure 1.3 shows the results of the sensitivity analysis for the Systems (A) through (E). In this assessment System E, the proposed hybrid space conditioning systems achieves by far the best performance over the full range of importance of energy savings.

Section 5 provides a brief discussion of special requirements for IEQ in schools. The initial focus of this research project was the use of innovative space conditioning systems in educational facilities. Children and young adults have a different physiological and emotional response to indoor IEQ impacts than adults. The discussion in Section 5 recommends that increased efforts must be employed to provide good IEQ for schools, since most established standards for the different aspects of IEQ were derived from studies with adults and for office building.

Section 6 presents information material that was developed in preparation for meeting with stakeholders of the Hawaii Department of Education (DoE). The initial focus of the research project was the use of the proposed hybrid space conditioning system in educational facilities, such as classrooms and libraries.

Section 7 reports the results of six site visits to institutional and commercial buildings which utilized unique space conditioning processes and technologies. One of the visited locations was in California, while the rest of the visited sites were on O'ahu. Each building visited represented a different type of system representing viable methods for inclusion in the proposed hybrid system (System E). The visits with and feedback from operators and occupants provided the authors with an understanding of how different candidate HVAC and space conditioning technologies are performing in real world conditions. This knowledge will assist the project team to derive the best system architecture for the proposed hybrid space conditioning system, which is in the end an integration of established technologies into a system that is optimized for use in Hawaii.

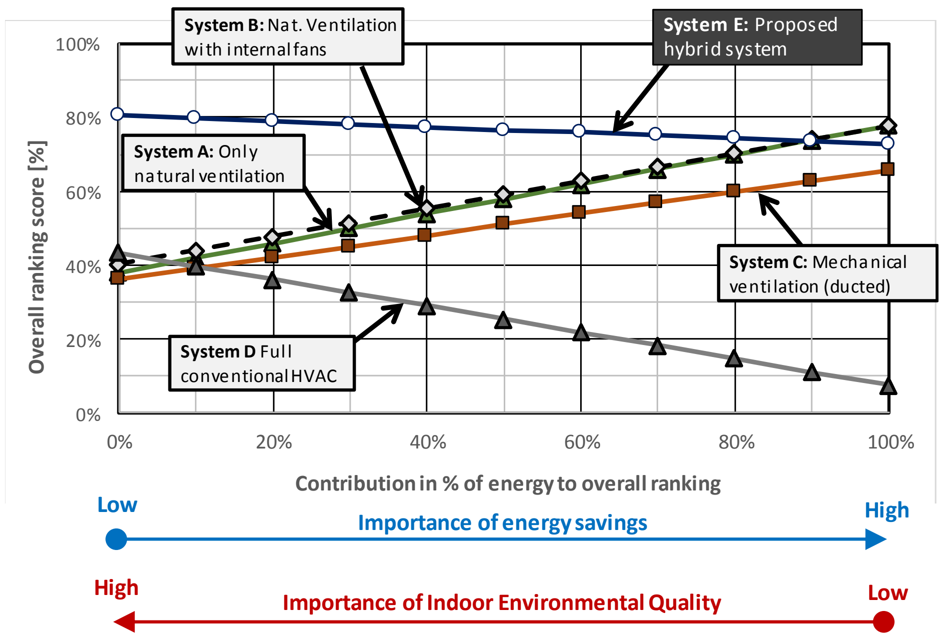


Figure 1.3: Relationship between the contribution of energy savings potential to overall ranking score

(See also Figure 4.5.1 in Section 4)

SECTION 2 - REVIEW OF INDOOR ENVIRONMENTAL QUALITY

On average, people spend about 90% of their time indoors (NIBC, 2017). The issue of indoor environmental quality is becoming more important as buildings are more effectively sealed, thus effectively isolating indoor space from the climatic rhythm of the external natural environment. In the past, buildings have been somewhat open to the outside environment, allowing outside air to enter the building for ventilation and temperature control. Therefore, indoor environment was able to mirror external climate. But as modern life increasingly centers around indoor activities, most people have adapted to the indoor realm as their "natural" environment. In order to satisfy the human need for affinity to the natural world, inside the built environment, natural conditions can be emulated, and these enhance health, productivity and the human experience.

Implementing effective sealing of the building, such as net zero, severs the direct link to the outside environment and creates its own indoor climate conditions. These indoor conditions are helpful when harsh outside climate conditions exist, but the same conditions can also be detrimental and can sometimes lead to unintended unhealthy conditions.

Efforts to increase sealing building envelopes have become an established practice to lower energy use. Significant infiltration of cold or hot air has negative effects on the building's energy consumption for heating or cooling, respectively. While the energy use through a sealed building envelope can have a positive effect on the energy consumption in buildings, reduced ventilation as a result of less infiltration also brings less connection with natural climate conditions. Designing indoor spaces to mimic the positive aspects of natural climate succeeds in providing healthier and more comfortable environmental conditions.

2.1 Concept of Indoor Environmental Quality (IEQ)

Indoor Environmental Quality (IEQ) is referred to as the state of an indoor environmental condition, which is establish by a combination of several physical and emotional response conditions. While definitions of indoor environmental quality may differ in regard to what conditions are included in the overall IEQ experience, the following aspects are commonly accepted:

- Indoor Air Quality (IAQ) refers to the level of high quality indoor air.
- Indoor Thermal Quality (ITQ) refers to the level of occupant's thermal experience.
- Indoor Light Quality (ILQ) refers to the quality of light sources.
- Indoor Sound Quality (ISQ) refers to the acoustic comfort experienced by the occupant
- Indoor Odor Quality (IOQ) refers to the occupant's perception of air quality based on their sense of smell

In addition, other IEQ characteristics include:

- Biophelia, the human affinity to nature.
- Aesthetics, the aspect of incorporating beauty in design.

- Ergonomics, the aspect of adapting indoor objects and spaces in an efficient way to accommodate the occupant's capabilities.

Figure 2.1.1 illustrates the interrelationship of aspects of IEQ. For the following discussion of IEQ, the different aspects are assigned to three groups:

- Group A includes two aspects, which have the greatest influence on IEQ, Indoor Air Quality (IAQ) and Indoor Thermal Quality (ITQ), usually also referred to as thermal comfort. Both aspects can be readily quantified with standard parameters.
- Group B includes three aspects, which have somewhat less influence on IEQ, Indoor Light Quality (ILQ), Indoor Sound Quality (ISQ), and Indoor Odor Quality (IOQ). Parameters of ILQ and ISQ can be readily qualitied with standard parameters, while IOQ is a more subjective measure.
- Group C includes three IEQ aspects and "others". These IEQ aspects are based on individual experience and cannot be readily qualified with standard parameters.

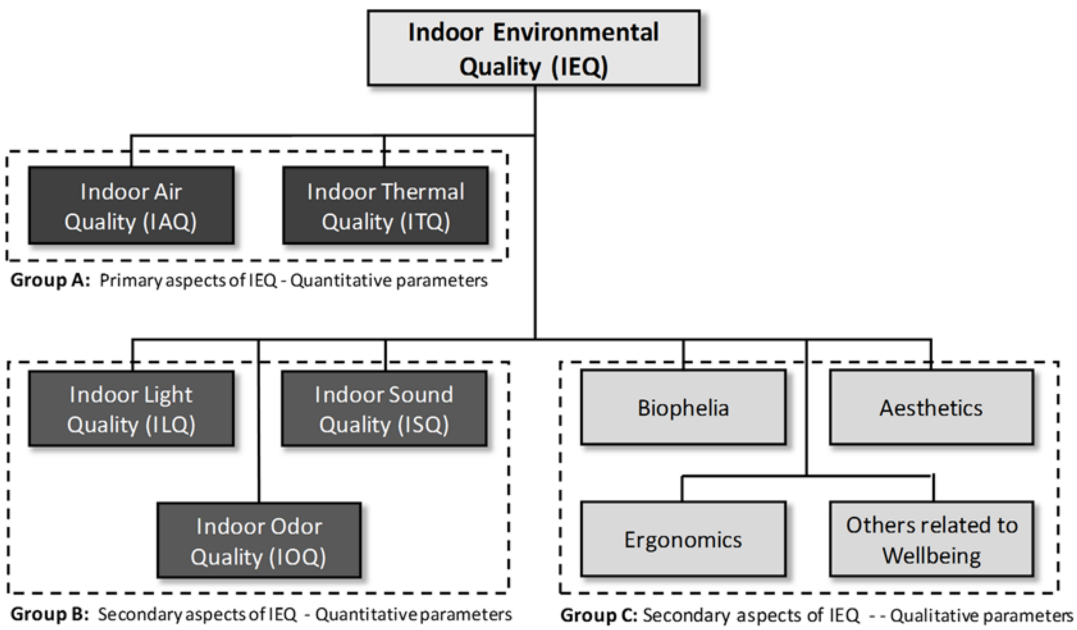


Figure 2.1.1: Interrelationship of aspects of IEQ

2.2 Indoor Air Quality (IAQ)

According to the EPA clean air is a critical component to our health. Air pollution is the number one environmental cause of premature mortality. Indoor Air Quality (IAQ) describes air quality within buildings, as it relates to the health and comfort of building occupants.

Indoor air pollutants contribute to reduced health and comfort of building occupants. A person breathes an average of 15,00 liters of air (WELL, EPA) every day. This large volume of inhaled air means that even well diffused air pollutants from distant sources are potentially harmful to building occupants. Effects can be immediate or long-term.

Immediate effects can be experienced from a single exposure or repeated exposures to a pollutant. Effects include irritation of the eyes, nose, and throat, headaches, dizziness, and fatigue. Immediate effects are usually short-term and treatable, by simply eliminating the person's exposure to the source of the pollution, assuming it can be identified. The effect of immediate effects depends on several factors including age, preexisting medical conditions, and the person’s individual sensitivity. Long term effects might become apparent only after repeated periods of exposure. Long-term effects can cause more severe health consequences including respiratory diseases, heart disease and cancer. Therefore, just based on health costs alone, mitigation of air quality problems is prudent even if no effects on occupants are noticeable.

The level of Indoor Air Quality is affected by the interaction of external and internal sources and processes. The following four main factors can contribute to problems in IAQ:

- <u>Pollutant source:</u> Sources of air contamination can either be indoor or outdoor.
- <u>HVAC:</u> IAQ problems arise if the HVAC systems cannot control the spread of pollutants, and/or control required temperature and humidity levels.
- <u>Pathways:</u> Pollutants can be transported or introduced along pathways of the airflow. The pathways represent conduits for pollutants, where the transport driving forces are either mechanically generated or naturally occurring wind or buoyancy pressure differentials.
- <u>Occupants:</u> Building occupants react differently to air pollutants, and it is important to consider increased susceptibility in certain applications, such as hospitals, elderly care facilities or schools.

<u>Pollutant sources</u>: Indoor air contaminants can be released within the building or be introduced from the outside. The following sources can be distinguished:

External sources which enter the building:

- Contaminated outdoor air containing fugitive dust, industrial pollutants, general vehicle exhaust
- Emissions from nearby sources, such as vehicles whose exhaust can enter from adjacent parking lots or roads, odors from waste, building ventilation discharged from the same or adjacent buildings
- Vapor or gas pollutant at the site, such as radon or pollutants from previous site use, or chemicals used in landscaping

Moisture in building assemblies:

- Excessive moisture levels in the building envelope, leading to mold growth which is hard to repair.
- Intrusion of moisture from leaks in the envelope and roof, rain penetration through leaky windows

HVAC related internal sources:

- Dust, dirt of growth inside ductwork, microbiological growth on cooling coils and drip pans
- Improper use of biocides, sealants, and/or cleaning compounds
- Leakage of refrigerants

Non-HVAC equipment

- Gaseous emissions from office equipment, indoor processes, or mechanical equipment

Human Activities

- Emissions from personal activities, including smoking, cooking, body and cosmetic odor
- Emissions from housekeeping activities, including cleaning materials and procedures, emissions from stored supplies or trash, fugitive dust from vacuuming
- Maintenance activities, including microorganisms in mist from improperly maintained HVAC components, volatile organic compounds from paint and adhesives

Building Components and Furnishings:

- Dust accumulation of textured surfaces and shelves
- Emissions from microbiological growth on furniture, surfaces with condensate and poorly maintained drains
- Outgassing of volatile organic or inorganic compounds used in furnishings and building components

<u>HVAC system:</u> A properly designed and operated HVAC system is a significant effect on IAQ in conditioned spaces. In respect to IAQ the HVAC system has three main functions:

- Providing indoor thermal quality (ITQ) through temperature and humidity control. ITQ will be discussed in detail in a separate section. Regarding IAQ extreme humidity levels in the air can create problems. Very high or low relative humidity can create discomfort and stimulate health risks. High relative humidity can promote growth of mold and mildew
- Providing adequate volumes of outdoor air to meet ventilation requirements. Providing too little volume would violate ventilation rates prescribed by code; providing too much can result in equipment problems and too high fan energy demand.
- Removal of odors and contaminants contained in the indoor air through pressure control, filtration, and exhaust fans. Another strategy of for controlling odors and contaminants is to dilute them with outdoor air. This approach only works if there is a consistent and adequate flow of outdoor supply air that is effectively mixed with indoor air.

<u>Pollutant pathways and driving forces of indoor air movement:</u> Airflow in buildings is driven by pressure differentials, which are either mechanically generated or occur naturally through cross ventilation and buoyancy processes. Pollutants are transported along the streamlines of the moving air flow, which is referred as “pathways”. Air flow can also be initiated or influenced by human activities. The HVAC system is generally the main driving force for air movement though the buildings. Building components and space outfitting interact to affect the distribution of contaminants. Air flow that is

maintained by the HVAC fan, and which typically flows between supply diffusers and return air openings, can be diverted or obstructed by partitions, walls, and furnishings, and redirected by openings that provide pathways for air movement.

Pressure differentials are either mechanically generated or occur naturally from cross ventilation or buoyancy result. Pressure differentials move airborne contaminants from areas of relatively higher pressure to areas of relatively lower pressure through any available openings. Flow rates are determined by the magnitude of the pressure differentials, which are the driving forces, and the pressure losses, which create obstacles to moving air along the pathway. Movement of people can cause movement of pollutants through induced air flow, since entrained pollutants are then distributed by the air flow. Some of the pathways that include doors and windows are not static, and closing and opening them affect the air flow field. Depending on unintended leakage rates of the building envelope air movement patterns can be different than planned. This in turn can cause arbitrary air flow throughout ventilation zones or create stagnant air pockets, both processes can negatively affect IAQ.

The moving indoor air is the transport mechanism for indoor air pollutants. The following flow patterns can create problems maintaining good IAQ:

- Poor local circulation in a space containing the pollutant source can impede effective removal or dissipation of the pollutant.
- Air movement into adjacent spaces which have lower pressure can transport pollutants in an undesirable way, to more densely occupied spaces.
- Recirculation of air within the zone containing the pollutant source or in adjacent zones where return systems overlap can redistribute pollutants rather than removing them from the spaces.
- Air movement into the building through either infiltration of outdoor air or reentry of exhaust air can deteriorate IAQ.
- Even if over pressurizing in a mechanically ventilated space is a design goal to avoid pollutants from entering the building through leaks in the envelope, locations of intermittent lower pressure relative to the outside can occur, which would allow pollutants to enter the building in an uncontrolled manner.

<u>Building occupants</u> are people who spend extended time periods, such as full workdays or full days in school, in a building. Temporary building occupants, such as customers or visitors, can have different tolerances and expectations from those who spend their entire workdays in the building. Groups of occupants with elevated susceptibility to the effects of indoor air contaminants include allergic or asthmatic individuals, and people with respiratory disease or with suppressed immune systems. People with heart disease may be more affected by exposure at lower levels of carbon monoxide than healthy individuals and children may be have higher risk of respiratory illnesses.

Varying sensitivity to a particular IAQ can lead to considerably differences in reactions among occupants, with significant problems in one group while other surrounding occupants have no ill effects. When a smaller percentage of occupants, or a single occupant, experiences symptoms, the reason could be that problems occur because one indoor location receives the bulk of the pollutant dose. In other cases, complaints may be widespread. Symptoms can also be caused by other factors, not necessarily due to air quality deficiencies. Interrelated indoor deficiencies, such as thermal discomfort, improper lighting, noise, vibration, overcrowding, ergonomic stressors, and job-related psychosocial problems (such as job stress) can produce symptoms that are similar to those associated with poor air quality.

The following are known indoor phenomena which are attributed to poor air quality:

Sick building syndrome (SBS) describes instances when building occupants experience acute health and comfort effects that are more prevalent the longer they spend in the building. In these cases, no specific illness or cause may be identified but the symptoms may be localized in a particular room or zone or may be widespread throughout the building. A wide range of symptoms have been associated with SBS, including respiratory complaints, irritation, and fatigue. Air samples often fail to detect high concentrations of specific contaminants. SBS can occur by a combination of the effects of multiple pollutants at low concentrations of environmental stressors such as overheating, poor lighting, noise, or by ergonomic or job-related psychosocial stressors.

Building-related illness (BRI) occurs through exposure to the building air, where symptoms of diagnosable illness are identified, such as allergies or infections, and where these can be directly linked to certain air pollutants. Examples are *Legionnaire's disease* and *hypersensitivity pneumonitis* which can have serious, even life-threatening consequences.

2.3 Indoor Thermal Quality (ITQ)

ITQ, also referred to as "thermal comfort", is the condition of satisfaction with and subjective experience of the thermal conditions of the ambient indoor environment. It is understood that thermal satisfaction is linked to thermal neutrality, this means the absence of thermal discomfort.

The body maintains thermal neutrality by rejecting excess thermal energy from metabolism to the environment. In warm climates, effective body heat rejection is an absolute must for healthy bodily functions. Heat rejection in the built environment can occur through a combination of the following major four heat transfer mechanisms:

- <u>Convective heat transfer</u> is through a transfer of heat energy to adjacent air, where the air is in direct contact with the body surface. The thickness and flow conditions of the surface layer, e.g. boundary layer, can either impede or enhance the magnitude of heat transfer. A thin and turbulent surface boundary layer is a smaller barrier to heat transfer than a wider laminar. Clothing acts as barriers to heat transfer. Increased air movement across the body surface increases heat transfer. Therefore, fans are frequently used to induce a cooling effect. Another important aspect to control heat transfer is the temperature difference between the surface and the ambient air.
- <u>Evaporative heat exchange</u>: Heat is exchanged between body and the ambient air by means of evaporation of perspiration on the body surface. Evaporative heat losses are very effective, because a phase change from liquid to vapor is involved, with high evaporative energy

requirements, and therefore significant energy transfer rates. Evaporative heat transfer is augmented by air movement over the body. Evaporative heat transfer requires a humidity differential between body surface and the moist air, and evaporation rates are higher with lower the relative humidity of the ambient air. Evaporative heat transfer is ineffective in air at humidity saturation.

- Radiative heat transfer is the process of heat energy transfer from warm to cold surfaces, through the action of infrared radiation. The main driving forces which constitute the magnitude of radiative heat transfer is the temperature difference between surfaces that exchange heat, the emissivity of surface material and the relative orientation of surfaces to each other. Differently from convective and evaporative heat transfer, radiative heat transfer rejects heat from the body to the ambient air as well as to ambient object surfaces. Radiative heat loss is regarded as the least invasive heat transfer experience, provided that temperature differentials between the body and are not high. Radiative heat loss through large indoor surfaces that are actively held at a few degrees below the body temperature are the basis for radiant ceilings.
- Conductive heat transfer is the exchange of heat energy when the body is in direct contact with objects. Typically heat transfer between the body and air is attributed to convective heat loss, but conduction also plays a role. The driving force of conductive heat loss is the temperature difference between the bodies in direct contact. Materials between bodies function as impeding insulators to heat flow, with a wide difference in their insulating or heat conductive properties.

The overall heat loss from the body is almost always a combination of the main processes indicated above, where the three processes of convective, evaporative and radiative heat rejection are the most common and effective. Regarding comfort, humans prefer a “good” mix of heat loss mechanisms, where the mix is based on personal preferences.

Another aspect of the human experience of thermal comfort is based on a transient rather than stable thermal climate. Interestingly, thermal conditions can best be detected when external thermal stimuli are not stable but changing. Thus, the individual experiences a deviation from thermal discomfort as a positive thermal experience. A change to decrease a negative experience of thermal conditions is experienced as relief, and vice versa. For example, when a person experiences the cooling effect when entering a cooled space from the hot outside it is a very satisfying experience. After a while, when the body has adjusted to the cooler environment, the experience of improving the thermal experience ceases, and the same thermal environment that initially provided relief from thermal discomfort is no longer regarded as a strongly thermal stimulus. This phenomenon can be described as “thermal boredom” (Kwock, 2015) where unchanging thermal conditions lose their potential of thermal relief.

Thermal comfort models have been developed which provide quantification of expected comfort levels for conditioned spaces and naturally ventilated spaces:

- For conditioned spaces, such as spaces that have mechanical cooling and humidity control, the Predicted Mean Vote (PMV) model is the most recognized method to describe the level of comfort. The PMV is based on objective heat loss data and subjective experimental data of the occupant's response to thermal conditions.

- For naturally ventilated spaces, e.g. for spaces that do not have forced mechanical ventilation, cooling or dehumidification, the adaptive comfort model has been developed. This model of predicting thermal experiences correlates an acceptable operative temperature to longer-term temperature trends outdoors and the fact that humans adjust to their thermal environment which they become accustomed to.

The two models are described in more details below.

The PMV model incorporates six factors for thermal comfort, four of them are factors of thermal comfort that represent the space, and are therefore applicable to all occupants in that space. Two of which represent individual thermal factors that a dependent on the occupant's clothing and physical activity. The six factors of thermal comfort are specified in the ASHRAE Standard 55:

Four factors of thermal comfort that represent the space:

1. Air temperature is the temperature of the air surrounding the occupant and is measured with a dry-bulb thermometer. Air temperature is the significant parameter for convective heat transfer.
2. Mean radiant temperature (MRT) is the average surface temperatures of objects surrounding the occupant, with which the occupant can exchange heat by radiative heat transfer. The MRT is measured indirectly with a globe thermometer or directly by measuring the surface temperature of contributing objects and applying a transfer function. MRT is an important factor for radiant heat transfer.

   Note: The weighted average of air temperature and MRT is referred to as operative temperature.

3. Air speed is the rate of air movement at point in the space. Typically, air speed is defined as a non-directional property. The air speed is measured with an anemometer.
4. Humidity is the representative humidity, or moisture, content in the surrounding air. Humidity can be measured with appropriate instruments, historically a wet bulb thermometer, and can be expressed as wet bulb temperature or absolute humidity. In combination with the air temperature (e.g. dry bulb temperature) humidity can also be expressed as relative humidity.

Two factors of thermal comfort that represent the individual occupant, or a representative value for a specific group of occupants:

5. Metabolic rate is the rate of transformation of chemical energy into mechanical work or heat by metabolic activities. The higher the activities the higher the values of metabolic rate quantified as the relative factor "met" of a certain standard activity.

6. Clothing insulation is the resistance to heat rejection created by the clothing. The value of clothing insulation is defined as the relative quantity as "clo". Lighter clothing has a smaller value of "clo".

The value for PMV in a specific space and for a specific occupant or occupant which is representative for a group of occupants is calculated by using the numerical values of the six aspects. PMV can either be positive or negative, indicating too warm or cold thermal conditions, and can be expressed from –3 to +3 corresponding to the categories "cold," "cool," "slightly cool," "neutral," "slightly warm," "warm," and "hot." ASHRAE 55 describes that an acceptable PMV should be in the order of -0.5 to + 0.5. Figure 2.3.1 shows a correlation of PMV to the predicted percentage of dissatisfied (PPD) value. The PPD index is an experimentally derived quantitative prediction of the percentage of thermally dissatisfied people.

Elevated air speeds can provide the perception of temperature reductions, while the operative temperature, e.g. the average of air and mean radiant temperatures, and relative humidity remains the same. The temperature reduction is based on increased convective and evaporative heat loss, through the decreased convective surface film resistance and enhanced evaporation rate, respectively. Figure 2.3.2 shows a relationship between air speed and temperature rise. The temperature rise is defined as the value by which the operative temperature can be raised while causing the same thermal perception at 0 air speed. In Figure 2.3.2 the minimum air speed is indicated as 30 fpm, which is the threshold of occupants to detect air movements.

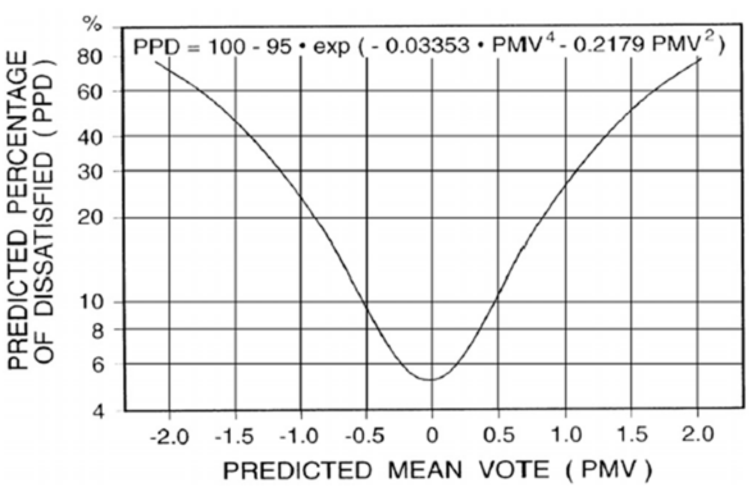


Figure 2.3.1: Predicted percentage dissatisfied (PPD) as a function of predicted mean vote (PMV).
Source: ASHRAE

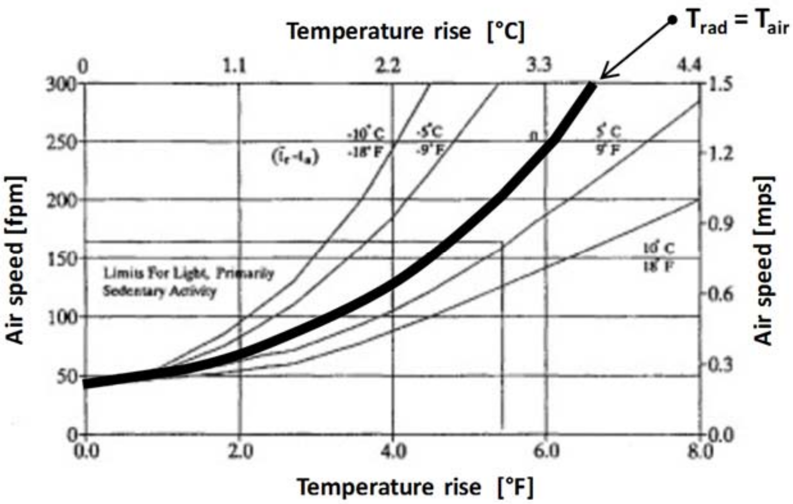


Figure 2.3.2: Temperature rise as a function of air speed
Source: ASHRAE

The solid thicker graph represents the case when the air temperature (T_{air}) is the same as the radiant temperature (T_{rad}); hence **$T_{air} = T_{rad}$**

Local thermal discomfort aspects: By definition the PMV and PPD represent general thermal comfort. In addition to PMV and PPD the ASHRAE 55 standard also defines several local thermal discomfort conditions. As per ASHRAE 55 the conditions of local discomfort requirements must only be met when the representative occupant meets the following two criteria:

- Have clothing insulation (Icl) less than 0.7 clo
- Are engaged in physical activity with metabolic rates below 1.3 met

The four aspects of local discomfort, which must be simultaneously met are as follows:

Radiant temperature asymmetry is the difference between the surface radiant temperature in opposite directions. The asymmetries are quantified in vertical and horizontal radiant temperature planes, this means upward and downward directions and all horizontal directions. The maximum permissible dissatisfied value is 5%. Figure 2.3.3 shows the predicted percentage of dissatisfied occupants for radiant temperature asymmetry as a function of different vertical and horizontal radiant surface combinations.

Draft is unwanted local cooling from elevated air movement and occupants are most susceptible when thermal sensation is “cool” (e.g. negative PMV). This especially applies when the occupant’s metabolic rate and clothing insulation are low. The level of discomfort depends on the air speed, air temperature, the metabolic activity, and the clothing insulation. When thermal sensation is neutral to slightly cool, this means within the comfort envelope range of ±0.5 PMV and operative temperatures below 72.5°F, average air speeds should not exceed 30 fpm. Any higher air speeds provoke the negative thermal sensation of “draft”. The maximum percent dissatisfied due to draft should be below 20%.

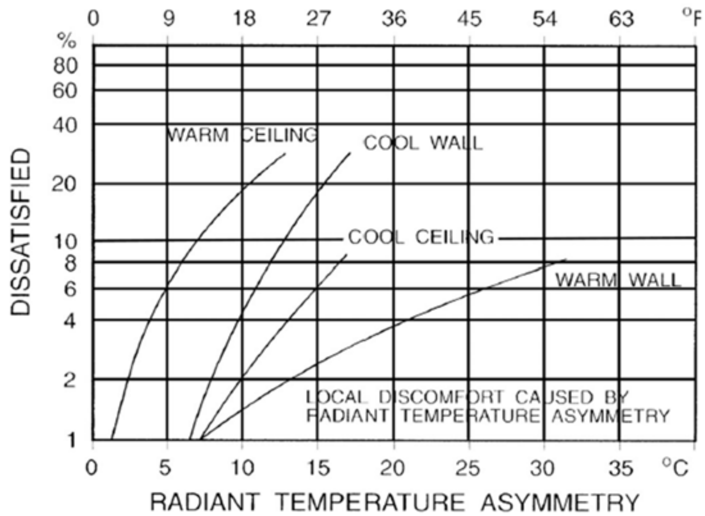


Figure 2.3.3: Local thermal discomfort caused by radiant asymmetry.
Source ASHRAE

Vertical air temperature difference is defined as thermal air stratification, with the air temperature at the head level being warmer than that at the ankle level. Such thermal stratification may cause thermal discomfort. Figure 2.3.4 indicates the expected percent dissatisfied due to the air temperature difference where the head level is warmer than the ankle level. The maximum allowable percent dissatisfied is 5%.

Floor surface temperatures, which are too warm or too cool, can cause thermal discomfort. Figure 2.3.5 shows the predicted percentage dissatisfied occupants due to floor temperature based on people wearing lightweight indoor shoes. The maximum allowable percent dissatisfied occupants by warm or cold floors is 10%.

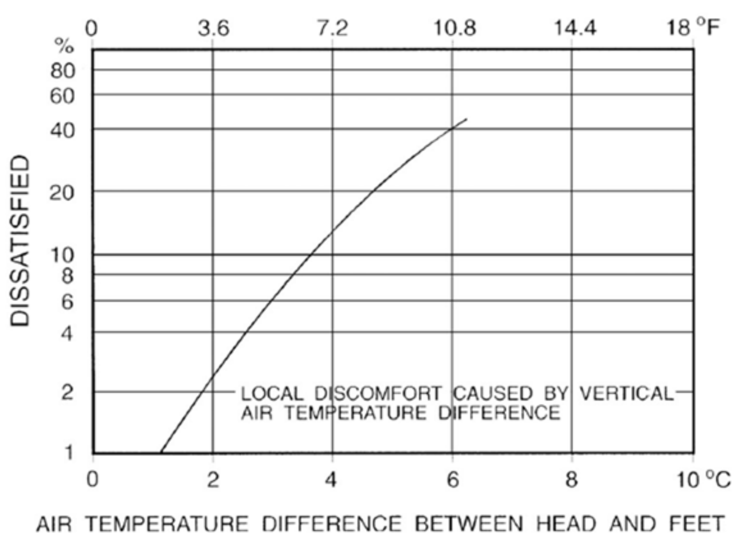


Figure 2.3.4: Local thermal discomfort caused by vertical temperature differences.
Source ASHRAE

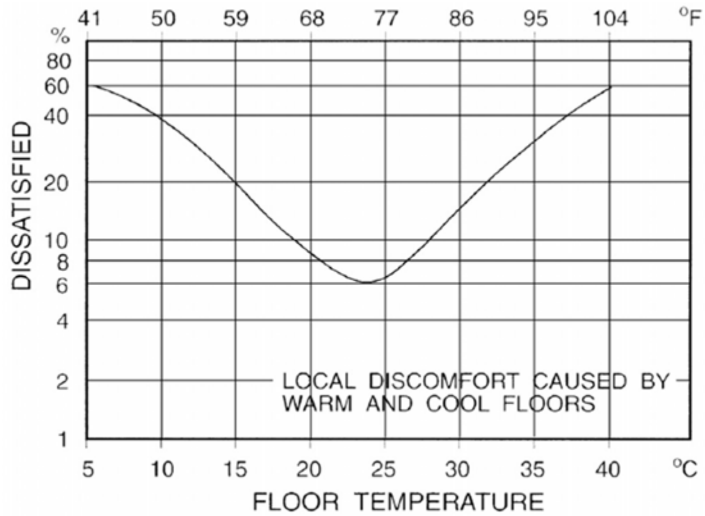


Figure 2.3.5: Local discomfort caused by warm and cool floors. Source ASHRAE

The Adaptive Comfort model was developed for naturally ventilated spaces, where no mechanical cooling and dehumidification is used. Under the adaptive model, occupants are accustomed to the external climatic conditions, and will freely choose appropriate clothing when they expect to be in an indoor climate that mirrors the external environment. This means that occupants living in a warm climate will use lighter clothing if they can expect a similar indoor thermal environment. The adaptive mode also considers some degree of freedom of using operable windows, fans to provide local (and not ducted) enhanced air speed, and operating shades to lower solar gain.

The adaptive model correlates longer term and averaged external air temperatures with internal operative temperatures. The model stipulates that people being subjected to longer periods of warm temperature can more easily tolerate higher indoor temperature. ASHRAE 55 states that the adaptive model defines acceptable thermal environments only for occupant-controlled naturally conditioned spaces that meet all the following criteria:

- There is no mechanical cooling system (e.g., refrigerated air conditioning, radiant cooling, or desiccant cooling) installed. No heating system is in operation.
- Representative occupants have metabolic rates ranging from 1.0 to 1.3 met.
- Representative occupants are free to adapt their clothing to the indoor and/or outdoor thermal conditions within a range at least as wide as 0.5 to 1.0 clo.
- The prevailing mean outdoor temperature is greater than 50°F and less than 92°F.

Figure 2.3.3 shows the allowable adaptive indoor temperature (e.g. the indoor operative temperature) as a relationship between of long term external air temperatures. Compliance of the adaptive standard applies when the indoor operative and prevailing mean outdoor air temperatures are within the 80% band. The prevailing mean outdoor air temperatures is calculated by taking average daily temperatures over a period which is longer than seven days and shorter than 30 days.

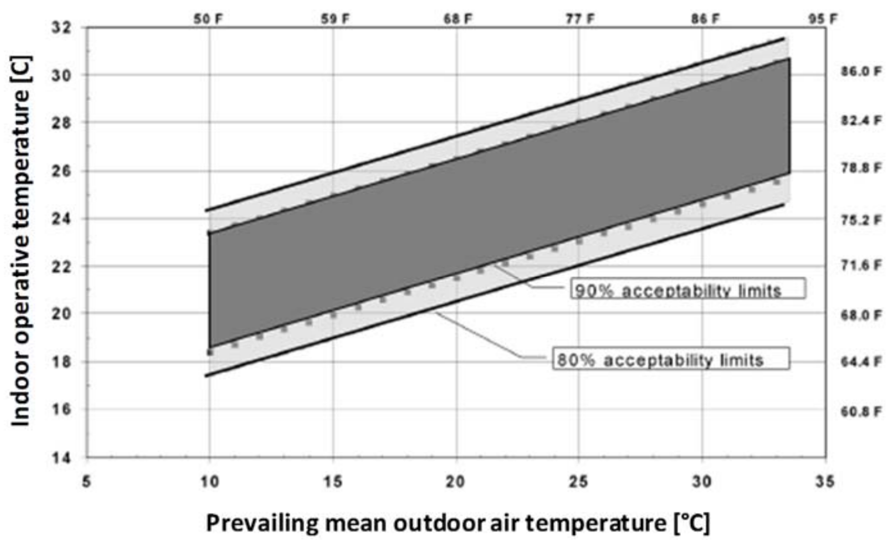


Figure 2.3.2: Acceptable operative temperature (to) ranges for naturally conditioned spaces. Source: ASHRAE

2.4 Humidity Control

The control of humidity in the building is important to maintain a healthy and comfortable indoor environment and avoid damaging effect on building structure, material and equipment. Scientific evidence has established a direct link between excess moisture (dampness) and mold in buildings. Mold has adverse health outcomes, particularly asthma and respiratory symptoms. Apart from health implications excess moisture in buildings can lead to costly maintenance and repair of the building structure and decreased performance of building systems. Excessive humidity can trigger undesirable chemical and physical reactions in indoor material s, such as increased out-gassing of building materials, especially as formaldehyde, which outgasses more than 2-times when humidity levels increase by 35% (WELL standard)

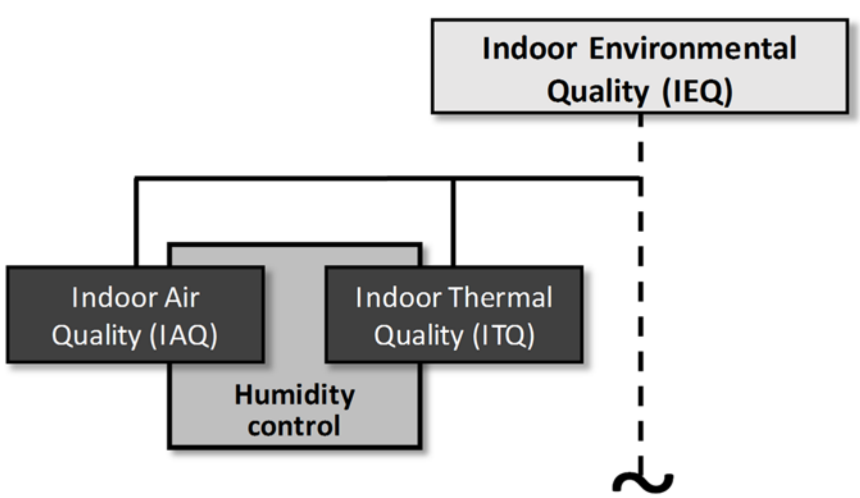


Figure 2.4.1: Importance of humidity control for IAQ and ITQ

Refer also to Figure 2.1.1 for the entire structure of aspects that establish IEQ

Since humidity induced effects overlap the two most important aspects of IEQ, Indoor Air and Indoor Thermal Quality, humidity related effects on the indoor environment are discussed below separately. Figure 2.4.1. indicates the importance of adequate indoor humidity control as an important issue that concerns both IAQ and ITQ, of thermal control.

Excessive humidity can have serious effects on a range of building integrity and indoor environmental quality. Some major effects include:

- Biological growth, especially fungi, can have a significant detrimental effect on the IAQ and the occupants.
- Electrochemical corrosion of metal equipment, including HVAC, electronics, structural framing etc.
- Discoloration, such as staining, of building materials and finishes
- Volume changes, such as swelling, warping and shrinkage, which can cause structural failure or deterioration of appearance.
- Chemical deterioration and dissolution of building materials, including gypsum, ceiling tiles, wood and textile products, etc.

Straube (2002) suggests that moisture related problems occur due to a combination of conditions, including:

1. Existence of a moisture source
2. A route, or pathway, that the moistures travels, in its different physical phases
3. Presence of a driving force that causes moisture movement
4. The building material is susceptible to moisture damage

Straube (2002) points out that it is next to impossible to entirely eliminate any one of the four conditions. For example, it is not feasible to avoid all humidity sources and only choose materials that are not susceptible to humidity problems. It is more feasible to address two or more of the conditions in an integrated moisture management and risk-avoidance strategy.

Figure 2.4.2 illustrates the basic moisture balance of an indoor space. Figure 2.4.2 indicates that sources of humidity can be external or internal. Humidity can be stored safely in liquid, solid and gaseous materials, if a safe humidity storage capacity is maintained. The process of humidity storage includes that humidity is taken up and released by the material. Moisture sinks can be either external of internal. Internal sinks are, however, only transient sinks, since moisture is eventually rejected from the internal to the external sinks.

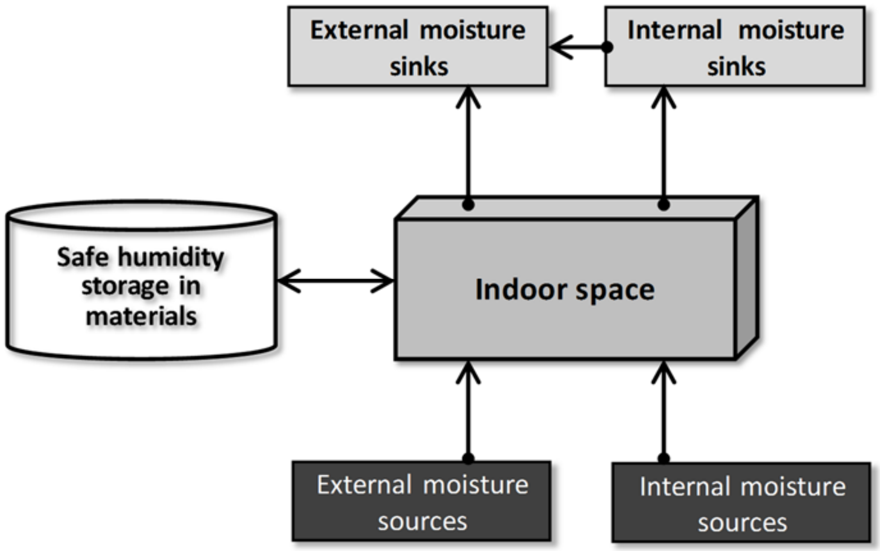


Figure 2.4.2: Basic Humidity balance

When intake and output of humidity is balanced over time humidity related problems can be avoided.

As expressed in equation 2.4.1, a neutral steady state balance exists if balance between the amounts of intake (wetting) and output (drying) moisture is maintained and moisture related problems are basically avoided. Equation 2.4.2 shows a shorter-time situation with internal storage and release of moisture by means of suitable materials. Provided that a safe humidity storage capacity of the materials can be maintained, differences in humidity intake and output rates can be tolerated.

$\mathbf{H_{In\ SS} - H_{out\ SS} = 0}$ Balanced steady state of humidity (Equation 2.4.1)

$\mathbf{h_{In\ SS} - h_{out\ SS} - Sh_{stor} = 0}$ Balanced mass flow rates of humidity (Equation 2.4.2)

Where:

$Hum._{In\ SS}$ = Amount of humidity entering into the space
$H_{out\ SS}$ = Amount of humidity leaving the space
$\mathbf{h_{In\ SS}}$ = Rate of humidity entering the space
$\mathbf{h_{out\ SS}}$ = Rate of humidity leaving the space
$\mathbf{Sh_{stor}}$ = Rate of humidity stored in materials (release is negative value)

Straube (2002) suggests that most moisture control strategies try to reduce the moisture intake, by increasing the airtightness and vapor resistance of the enclosure. Imperfections of such measures are all but certain and the designer cannot rely only on source reduction. More recent design paradigms give more attention to drying potential and safe storage capacity of building materials. The author provides a versatile framework of major wetting and drying processes, humidity storage and moisture transport mechanisms. The proposed framework, shown in Figure 2.4.3, can be used to identify comprehensive moisture management during operation of building. Construction related humidity processes are not considered.

The three major moisture sources depicted in Figure 2.4.3 are:

1. Liquid water from precipitation or plumbing leaks: Rain and walls receive large amount of precipitation. Therefore, even small leaks can cause significant moisture related problems, as literally hundreds of gallons can be discharged into a building.
2. Water vapor from exterior sources and from interior activities and processes: External and internal water vapor sources can be problematic as leaks for water, although the magnitude of moisture involved is much smaller than with water leaks. External water vapor sources are through intentional supply air ventilation or unintentional air leaks through the building envelope and ducts. Internal water vapor sources vary significantly in size and type; some typical sources of interior moisture sources are presented in Table 2.4.1.
3. Liquid and vapor from the soil adjoining the building: Soil can be a significant source of moisture which enters the building through basement, foundation and ground floors. Liquid water can directly drain through leaks and cracks. Liquid water can also enter through capillary actions through porous materials.

Liquid water and water vapor move under different flow mechanisms and driving forces.

The four transport mechanisms referred to in Figure 2.4.3 are presented hereafter in the order of most to least efficient:

Liquid water gravity flow: Gravity flow occurs in the presence of a hydraulic gradient. Gravity flow is the most significant and powerful means of moisture transport. A large quantity of water can enter the building through cracks, pipes, leaks and macro-pores in the building envelope. The openings for gravity flow must be large enough to overcome resisting capillary forces. If water enters the building through gravity, it can have very detrimental effects on the building structure and materials. Flashings are a common way to avoid gravity flow induced water from entering the building.

Liquid water capillary flow: Liquid water is moved through porous material through capillary actions. The smaller the pores the higher are the driving forces. Capillary transport rates of water are typically small but important to consider when the building touches large source liquid water, such as soils or if there are rain-wetted surfaces. A capillary barrier can be installed between the driving force and the capillary flow. Such a barrier can be a gravel layer below the concrete slab.

Water Vapor convection: Vapor convection transports water vapor as part of air flow. Convection is much more efficient than vapor diffusion in moving volumes of water into and throughout the building. Vapor is transported in and out of the building through ventilation air. Unintentional convective transport of vapor of into the building air is through leaks and cracks in the building envelope; this is the largest source of moisture inside the building enclosure after rainwater penetration. Therefore, effective air barriers of the envelope, including careful sealing of all duct penetration of the envelope, are important mitigation measures.

Water vapor diffusion: Vapor transport through diffusion moves water vapor from regions of high to low concentration. The driving force is vapor pressure differences. Vapor diffusion moves water vapor through air within porous material. If vapor diffuses through the building envelope it may condense on colder surfaces. This detrimental diffusion and subsequent accumulation of condensed water can be mitigated with vapor barriers that stops water diffusion.

Types of indoor moisture source	Moisture generated indoors	
	lbs / day	gpd
People (evaporation per person)		
sedate	1.1	0.13
heavy work	2.6	0.32
average	11	1.32
Dishwashing	1.1	0.13
Avg. bathing per person	0.9	0.11
Avg. shower (each)	2.2	0.26

Moisture generated by selected types of moisture sources

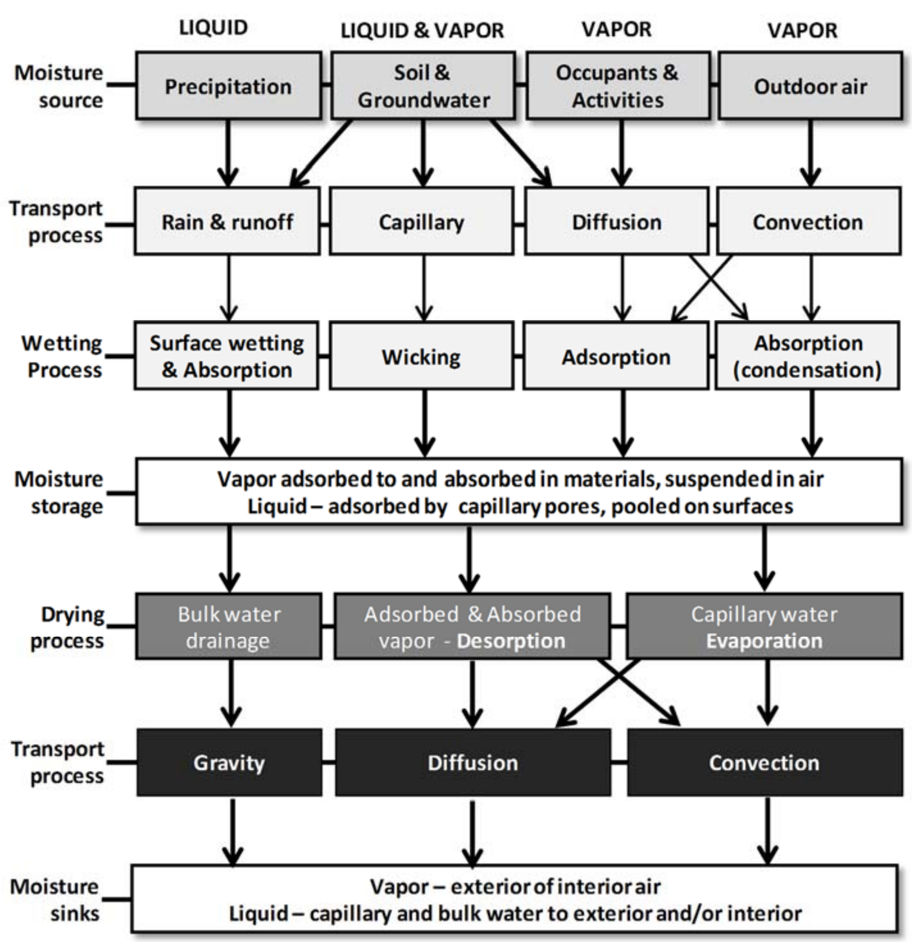


Figure 2.4.3: Humidity framework (Straube, 2002; Modified by the author)

2.5 Humidity Interactions of Air-Quality and Thermal Comfort

Several humidity related problems for air quality and thermal comfort have been briefly discussed in Sections 2.2 and 2.3, respectively. Humidity can have different impacts on air quality and thermal comfort. The following examples should illustrate the importance of considering humidity in a way that includes different impacts.

As discussed in Section 2.3, humidity is one of several aspects of determining the expected percentage of dissatisfied people. The PMV, and thus PPD value can be readily determined with the CBE ASHRAE 55 online tool. As an illustrative example, six indoor thermal conditions are used to calculate the PMV and thus determine if these conditions are consistent with the ASHRAE 55-2013 standard. The input parameters and results for the six example cases are shown in Table 2.4.2 and Figure 2.4.4. Figure 2.4.5 shows an optimum range of humidity in terms of IAQ.

Figure 2.4.4 states that, according to ASHRAE 55, satisfactory thermal comfort (e.g. acceptable PMV values) can be achieved for a temperature range even at very high and low humidity levels. Figure 2.4.5 indicates, however, that humidity related IAQ problems increase outside the optimum humidity range of 30 to 55%. This conflicting information is due to the fact that the PMV calculation assumes only thermal heat loss properties, whereas the IAQ related optimum humidity range considers health issues, based on humidity ranges that create detrimental microbiological and chemical processes.

Table 2.4.2: Example cases A through F of humidity levels in thermal comfort

			Cases					
			A	B	C	D	E	F
Input	Operative temperature	°F	80	80	72	73	77	87
	Air speed	fpm	20	20	20	20	20	20
	Relative humidty	%	90%	95%	95%	50%	15%	15%
	Metabolic rate	met.	1.1	1.1	1.1	1.1	1.1	1.1
	Clothing level	clo	0.5	0.5	0.5	0.5	0.5	0.5
Results	PMV	[-]	0.49	0.54	-0.35	-0.53	0.4	0.47
	PPD	%	10%	11%	7%	11%	8%	10%
	Sensation		neutral	slightly warm	neutral	slightly cool	neutral	neutral
	Complies with ASHRAE 55	Yes/No	Yes	No	Yes	No	Yes	Yes

Cross-effects of IAQ and thermal comfort: In cases of impaired air quality, occupants tend to be less willing to accept marginal or unsatisfactory thermal conditions. Fang (1999) presented a strong relationship between air quality and acceptance of thermal conditions. Fang suggested that moisture and relative humidity play a role in the perception of air quality, since moisture in the air can lead to oxidation and chemical reactions by hydrolysis and decomposition, including enzymatic digestion by molds. Figure 2.4.6 indicates that occupant perception depended on the enthalpy (heat content) of the air. Air that is dry is typically perceived as “more pleasant” than air that is moist.

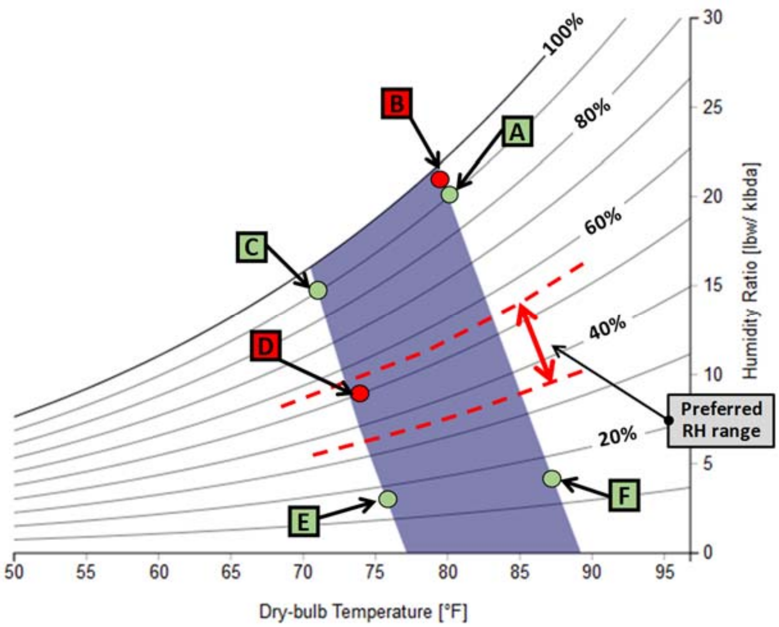


Figure 2.4.4: Example cases A through F of humidity levels in thermal comfort (source Health Canada)

The base figure is a scree shot of the CBE online toon for ASHRAE 55 compliance
The cases A through F are illustrative examples to explain how high and low humidity rates are still meeting the PMV criteria for thermal comfort (ASHRAE 55)

The Preferred (“optimum”) range of RH is taken between 35% and 55%.

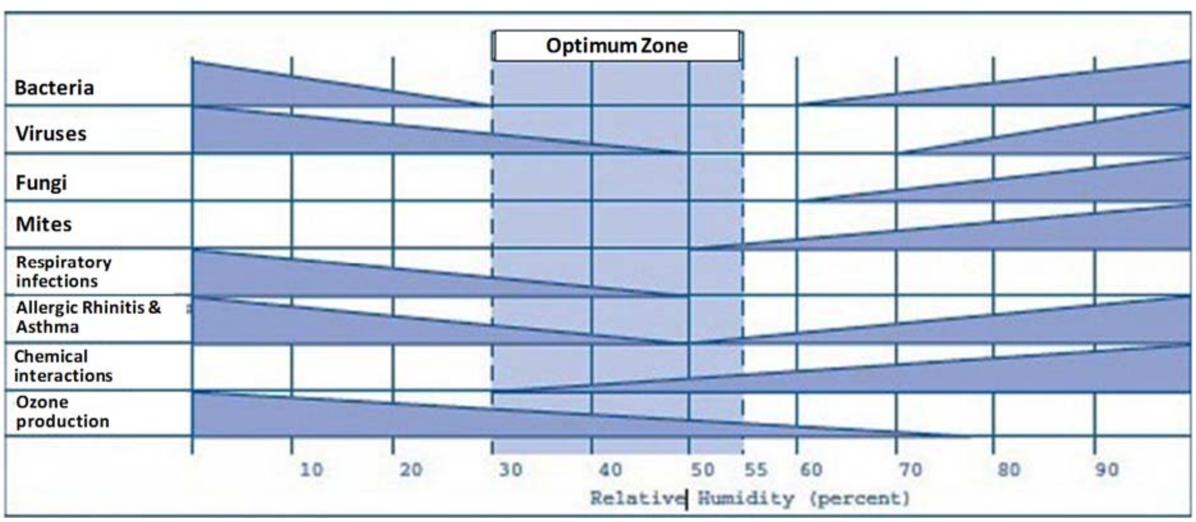


Figure 2.4.5: Optimum indoor humidity levels to safeguard IAQ

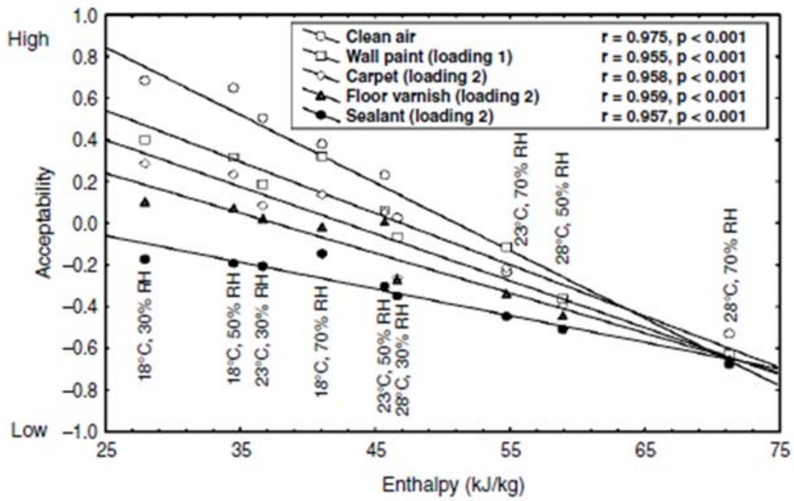


Figure 2.4.6: Acceptability of air quality as a function of enthalpy (heat content) and odorous sources. SOURCE: Fang, 1999

For this discussion, the data presented of Fang was used for a further analysis. The input values and results are presented in Table 2.4.3 and Figures 2.4.7 through 2.5.10. Six indoor comfort states, depicted in Fangs graph (Figure 2.4.6) were assigned the identifiers 1 through 6. The six states are Figure 2.4.7. The PPD values was calculated using the CBE AHDRAE 55 tools and the acceptability level was derived from Fang's data. Table 2.4.3 indicates the results of PPD and acceptance. Figure 2.4.7 shows the thermal comfort conditions of states 1 through 6. Figure 2.4.8 overlays the six comfort states on the psychrometric chart of the CBS online AHSRAE 55 calculator. Figures 2.4.9 and 2.4.10 compare the calculated PPD and observed occupant's acceptance values for the clean-air baseline for 28 °C and 23 °C.

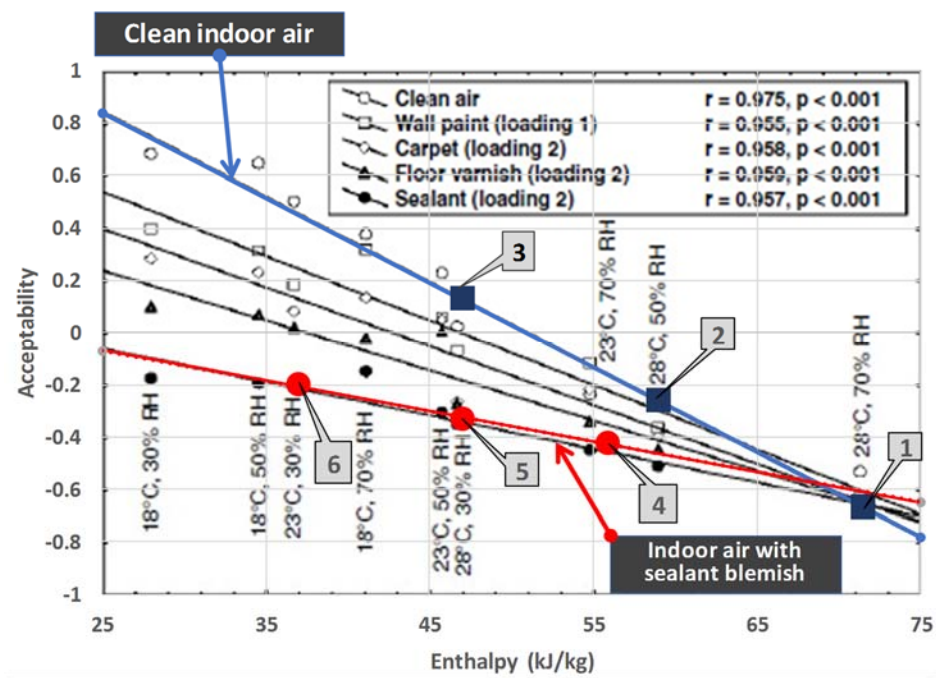


Figure 2.4.7: Six indoor comfort states overlaid with Fang data

The indoor states 1 through 6 correlate thermal conditions and acceptability during different air quality

Table 2.4.2: The indoor states 1 through 6

			Cases					
Thermal comfort			1	2	3	4	5	6
Input	Operative temperature	°C	28	28	28	23	23	23
	Air speed	m/s	0.1	0.1	0.1	0.1	0.1	0.1
	Relative humidty	%	70%	50%	30%	70%	50%	30%
	Metabolic rate	met.	1.1	1.1	1.1	1.1	1.1	1.1
	Clothing level	clo	0.5	0.5	0.5	0.5	0.5	0.5
Thermal comfort								
Results	PMV	[-]	0.57	0.39	0.21	-0.35	.-48	-0.62
	PPD	%	12%	8%	6%	7%	10%	13%
	Sensation		slightly warm	neutral	neutral	neutral	neutral	slighty cool
	Complies with ASHRAE 55	Yes/No	**No**	**Yes**	**Yes**	**Yes**	**Yes**	**No**
Acceptability acording to Fang 1999								
	Clean air		-67%	-26%	13%			
	Highest measure air pollutant case					-43%	-33%	-20%

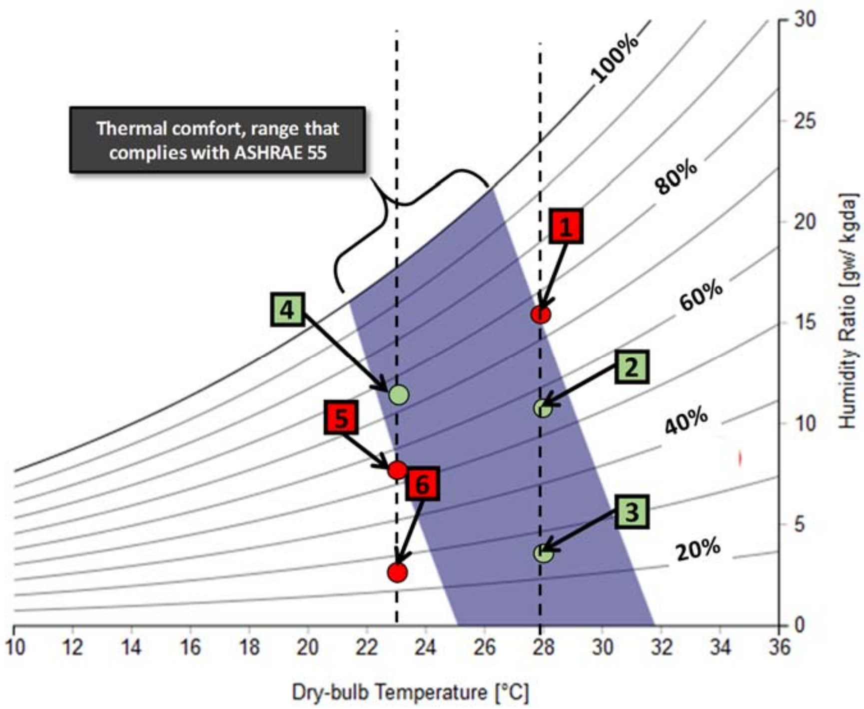


Figure 2.4.8: The indoor states 1 through 6 – thermal comfort illustration

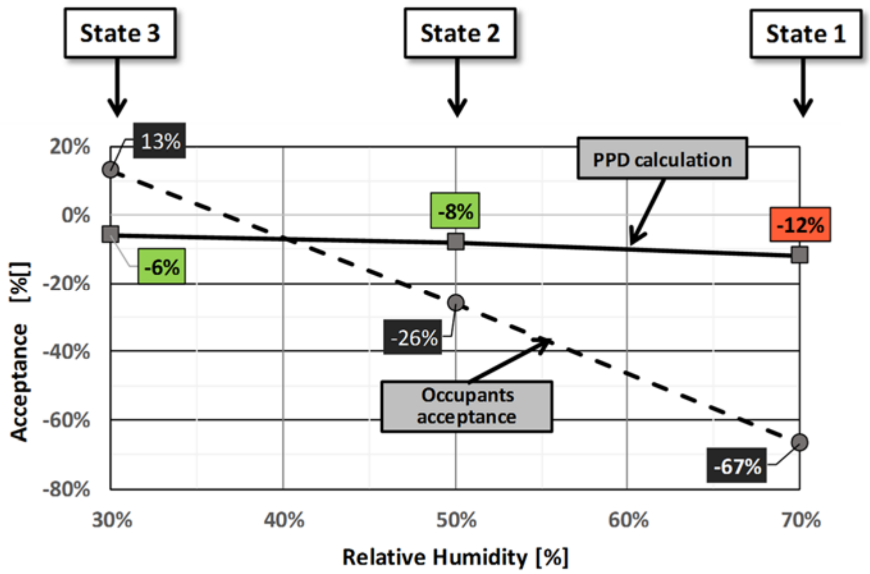


Figure 2.4.9: Comparison of calculated PPD and observed occupants' acceptance values for the clean-air baseline **for 28 °C**

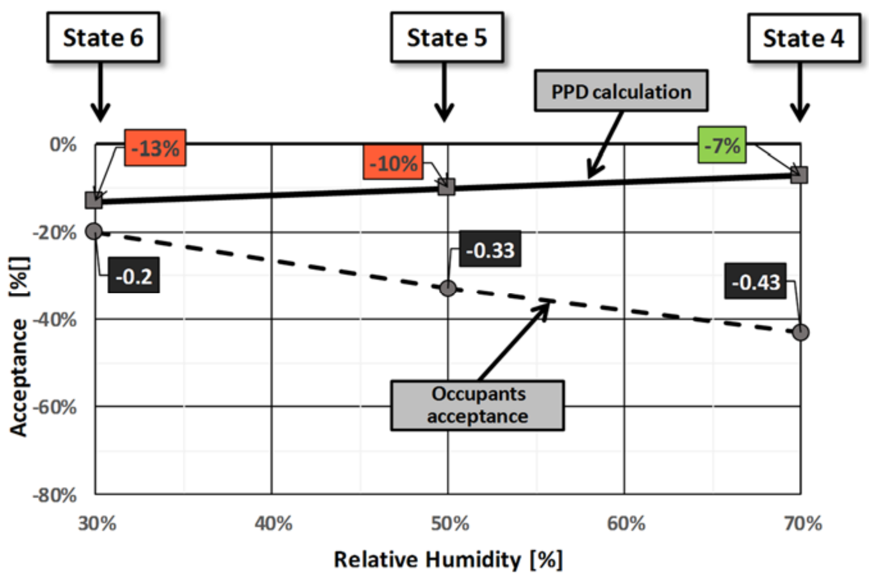


Figure 2.4.10: Comparison of calculated PPD and observed occupant acceptance values for the clean-air baseline **for 26 °C**

In Figure 2.4.11, the observed acceptance values for different relative humidity and air temperatures are indicated. According to Fang's data, the following relationships can be stated:

- Occupant acceptance is a strong function of relative humidity; acceptance is higher in lower relative humidity conditions, given a constant air temperature.
- Low air quality significantly decreases occupant acceptance
- Lower air temperatures increase occupant acceptance.

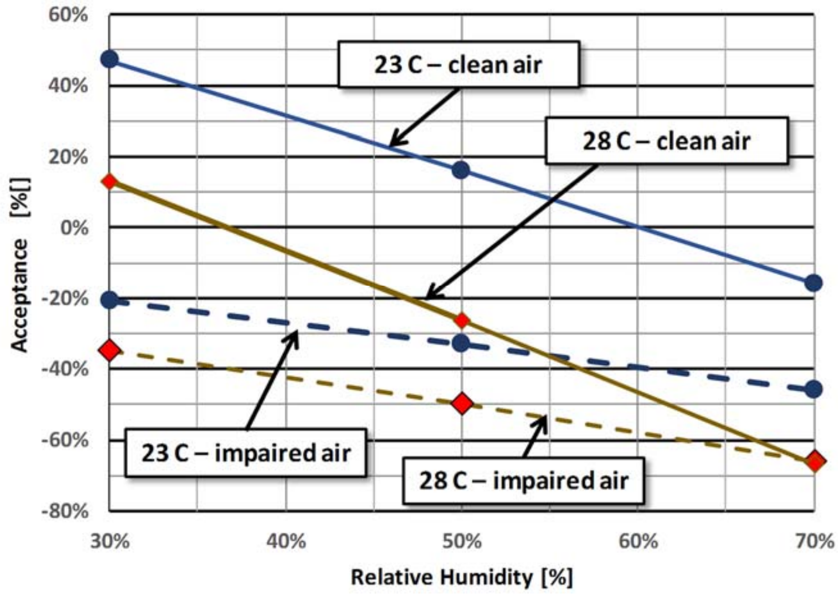


Figure 2.4.11: Comparison of observed occupant acceptance values different temperature and air qualities

The results strongly suggest that air-quality has a significant effect on the acceptance of indoor thermal conditions. Even at marginal thermal comfort conditions, as defined by PPD and the ASHRAE 55 comfort standards, low indoor humidity levels can result in higher occupant acceptance.

2.5 Impacts of Indoor Mold

EPA (2017a) suggests that molds are part of the natural environment, and the various types of mold can be found everywhere, indoors and outdoors. Mold can become a problem when it begins growing indoors. The key to mold control is moisture control. Mold growth occurs when spores settle on wet or damp spots and begin growing. Molds have the potential to cause health problems, both immediate and long term. Inhaling or touching mold or mold spores may cause allergic reactions in sensitive individuals. Allergic responses include hay fever-type symptoms, such as sneezing, runny nose, red eyes, and skin rash. Molds can also cause asthma attacks in people with asthma who are allergic to mold. Beside significant effects on the health of building occupants, molds can also deteriorate indoor material.

The World Health Organization (WHO) in a 2009 published study (WHO, 2009) describes microbial pollution as a key element of indoor air pollution, which is caused by hundreds of species of bacteria and fungi, in particular filamentous fungi (mold), growing indoors when sufficient moisture is available. The WHO findings provide scientific evidence on health problems associated with building moisture. The investigation concluded that the most important means for avoiding adverse health effects is the prevention (or minimization) of persistent dampness and subsequent microbial growth on interior surfaces.

WHO reports that the presence of many biological agents in the indoor environment is due to dampness and inadequate ventilation. Excess moisture on almost all indoor materials leads to growth of microbes, such as mold, fungi and bacteria, which subsequently emit spores, cells, fragments and volatile organic compounds into indoor air. Moreover, dampness initiates chemical or biological degradation of materials, which also pollutes indoor air. An important determinant of dampness and biological growth in indoor spaces is ventilation, and occupants of damp or moldy buildings are at increased risk of respiratory symptoms, respiratory infections and exacerbation of asthma. The report (WHO, 2009) suggests that the conditions that contribute to the health risk were summarized as follows:

- The prevalence of indoor dampness varies widely within and among countries, continents and climate zones. It is estimated to affect 10–50% of indoor environments worldwide. In certain settings, such as coastal areas, the conditions of dampness are substantially more severe than the national averages for such conditions.
- The amount of water on or in materials is the most important trigger of the growth of microorganisms.
- The dust and dirt normally present in most indoor spaces provide sufficient nutrients to support extensive microbial growth. While mold can grow on all materials, selection of appropriate materials can prevent dirt accumulation, moisture penetration and mold growth.
- Microbial interactions and moisture-related physical and chemical emissions from building materials may also play a role in dampness-related health effects.
- Building standards and regulations regarding comfort and health do not sufficiently emphasize requirements for preventing and controlling excess moisture and dampness.
- Most moisture enters a building in incoming air, including that infiltrating through the building envelope or that resulting from the occupants' activities.
- Allowing surfaces to become cooler than the surrounding air may result in unwanted condensation. cold water plumbing and cool parts of air-conditioning units can result in surface temperatures below the dew point of the air and in dampness.
- Persistent dampness and microbial growth on interior surfaces and in building structures should be avoided or minimized, as they may lead to adverse health effects.
- Indicators of dampness and microbial growth include the presence of condensation on surfaces or in structures, visible mold, perceived moldy odor.
- Management of moisture requires proper control of temperatures and ventilation to avoid excess humidity, condensation on surfaces and excess moisture in materials. Ventilation should be distributed effectively throughout spaces, and stagnant air zones should be avoided.
- Building owners are responsible for providing a healthy workplace or living environment free of excess moisture and mold, by ensuring proper building construction and maintenance.
- The presence of many biological agents in indoor environments is attributable to dampness and inadequate ventilation. Excess moisture on almost all indoor materials leads to growth of microbes, such as mold, fungi and bacteria, which subsequently emit spores, cells, fragments and volatile organic compounds into indoor air. Moreover, dampness initiates chemical or biological degradation of materials, which also pollute indoor air.

WHO reports that several widely acknowledged global trends contribute to problems associated with increased exposure to dampness and mold:

- Increase use of energy conservation measures that are not properly implemented (tightened building envelopes, ventilation deficits, improper insulation);
- Urbanization (migration, building type and density, urban degradation, housing availability and social inequity);
- Climate change (increasing frequency of extreme weather conditions, shifting of climate zones); and the quality and globalization

Figure 2.5.1 shows the complex processes that constitute a health hazard, and links sources of water / excessive moisture to biological growth and physical and chemical degradation, as well as emission of hazardous biological and chemical agents.

Effects of dampness on the quality of the indoor environment

EPA (2017a) and WHO (2009) suggest that Indoor environments contain a complex mixture of live (viable) and dead (nonviable) microorganisms, fragments thereof, toxins, allergens, volatile microbial organic compounds and other chemicals. The indoor concentrations of some of these organisms and agents are known or suspected to be elevated in damp indoor environments and may affect the health of people living or working there. In addition, dampness is an indicator of poor ventilation, which may result in increased levels of a wide range of other potentially harmful indoor pollutants (see Chapter 3). Excess moisture may also result in increased chemical emissions from building materials and floor covers.

According to WHO (2009), fungi are ubiquitous eukaryotic organisms, comprising an abundance of species. They may be transported into buildings on the surface of new materials or on clothing. They may also penetrate buildings through active or passive ventilation. Fungi are therefore found in the dust and surfaces of every house, including those with no problems with damp. Once fungi are indoors, fungal growth can occur only in the presence of moisture, and many fungi grow readily on any surface that becomes wet or moistened; that is, virtually all fungi readily germinate and grow on substrates in equilibrium with a relative humidity below saturation

Fungi also need nutrients, which may include carbohydrates, proteins and lipids. The sources are diverse and plentiful, ranging from plant or animal matter in house dust to surface and construction materials (such as wallpaper and textiles), condensation or deposition of cooking oils, paint and glue, wood, stored products (such as food), and books and other paper products. Nutrients are therefore generally

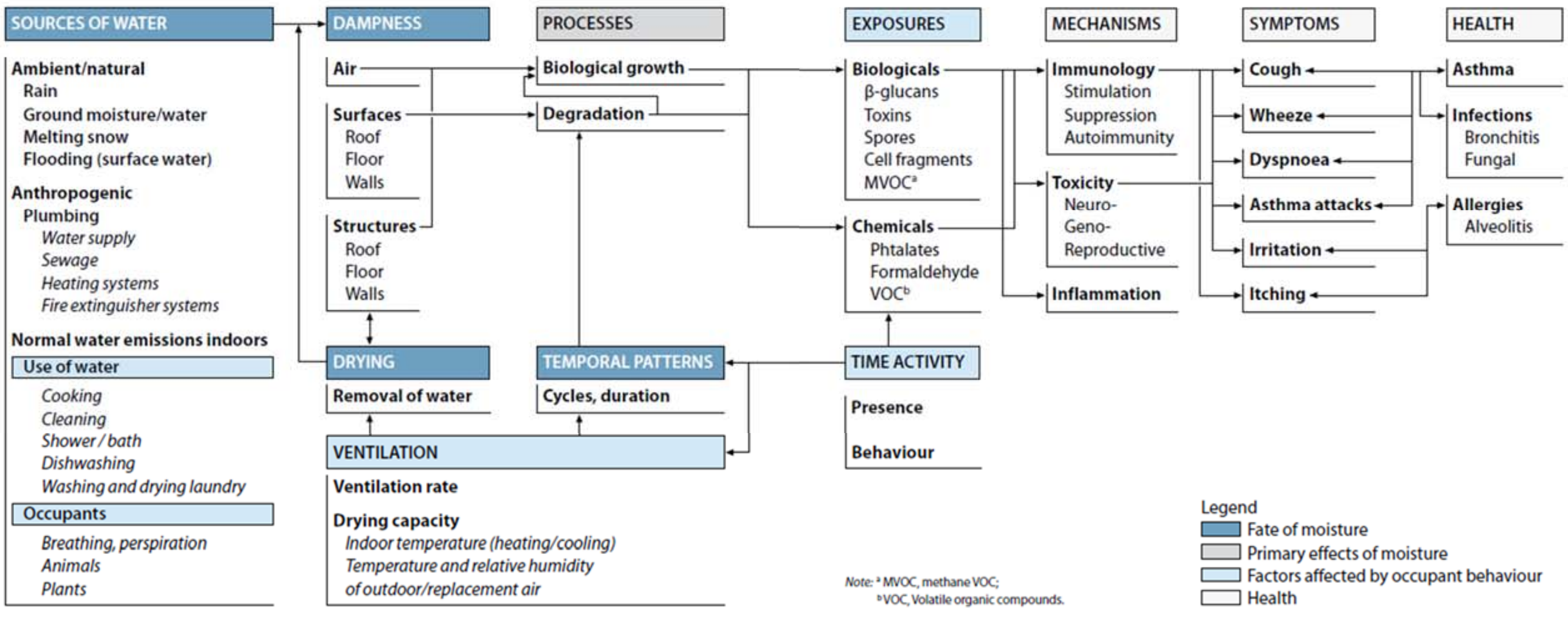


Figure 2.5.1: Pathways linking sources of dampness with health

not a limiting factor for indoor fungal growth. In fact, fungi are known to grow even on inert materials such as ceramic tiles and can obtain sufficient nutrients from dust particles and soluble components of water. As most indoor fungi grow within temperature ranges of 10–35 °C, common indoor temperatures are also not a limiting factor; however, although temperature and nutrients are not critical, they may affect the rate of growth

Fungi not only have adverse effects on health but also cause considerable damage to buildings, the wood-rotting fungi being particularly destructive to (wooden) building structures.

Moisture control, ventilation and the need for dehumidification

WHO (2009) suggest the following concerns relative to moisture control, ventilation and HVAC:

- In non-residential buildings and in hot climates, ventilation is often integrated with air-conditioning, which complicates the operation of these systems.
- The prevalence of symptoms of the sick-building syndrome has been associated with the characteristics of the HVAC. The prevalence of such symptoms was higher in air-conditioned than in naturally ventilated buildings, independent of humidification.
- Better hygiene, commissioning, operation and maintenance of air-handling systems is particularly important in reducing the negative effects of heating, ventilation and air-conditioning systems. Thus, moisture and microbial contamination – not only in the building structure or surfaces, but also in heating, ventilation and air-conditioning systems – has adverse health effects.
- Exposure to pollutants in indoor air generated by indoor activities and emitted from indoor materials or ventilation systems can have a variety of effects with a broad range of severity, from the perception of unwanted odors to cancer.
- Ventilation dilutes the concentrations of (or disperses) airborne viruses or bacteria that can cause infectious diseases. Thus, higher ventilation rates reduce the prevalence of airborne infectious diseases
- Some microorganisms can grow on cooling-coils and in drip pans, as well as air humidifiers and cooling towers, thus causing respiratory diseases or symptoms, such as legionnaires disease and humidifier fever.
- Low ventilation rates (10 l/s) per person are associated with significantly higher occurrence of one or more health outcomes or with worse perceived air quality in office. Larger ventilation rates (approximately 20–25 l/s per person) are associated with a significant decrease in the prevalence of symptoms of sick-building syndrome or with improved perceived air quality in office environments.
- Improved ventilation can improve occupant task performance and productivity in an office environment.
- Ventilation rates of up to 9 l/s per pupil in schools improve performance in school.
- Indoor humidity is influenced by ventilation rates. Ventilation usually reduces indoor moisture levels. Very high indoor humidity is associated with increased growth of microorganisms such as mold and bacteria.

- Relative humidity greater than approximately 40% - 50% increases indoor dust mite levels.
- Important considerations of mold problems include insufficient dehumidification by HVAC systems, which may result in levels of interior humidity that are high enough to cause mold to grow on furniture, walls, ceilings or HVAC components.

2.6 Indoor Light Quality (ILQ)

As people are spending more and more time inside the built environment, the quality of light becomes more important. All living and work spaces require a high quality of light to promote productivity and wellbeing. Natural light should be a significant source of illumination, with artificial light present to provide additional light sources. Problems occur when artificial light is used at the exclusion of natural light. The type and quality of light has a significant effect on human health and the level at which occupants can perform their different duties.

The quantity of light provided to occupants should neither be too little nor too much. Too little can make it difficult to perform work or essential task, too much light can cause unwanted and even harmful glare. Light is typically referred to as a small range of the electromagnetic spectrum, e.g. the visible spectrum. Wave frequencies adjacent are on the higher and lower margins of the visible spectrum the UV and IR. Both can be harmful to the human eye.

Light sources: The following typical artificial light sources (e.g. lamps) are as follows:

Incandescent lamps provide light through electricity flowing through a tungsten filament. These lamps have a lower electrical efficiency and shorter life than other lamps.

Fluorescent lamps create light through low-pressure UV discharge, which is transformed into visible light by specific coating at the interior of the encapsulating glass containment.

High-intensity discharge lamps, create light through a discharge arc inside a specific vapor container.

Light-emitting diode (LED) lamps have semiconductor devices that emit visible light. LEDs are very energy efficient and have a long life.

Lighting in the built environment can be classified as ambient, task and accent lighting. Figure 2.6.1 shoes the three types of indoor lighting.

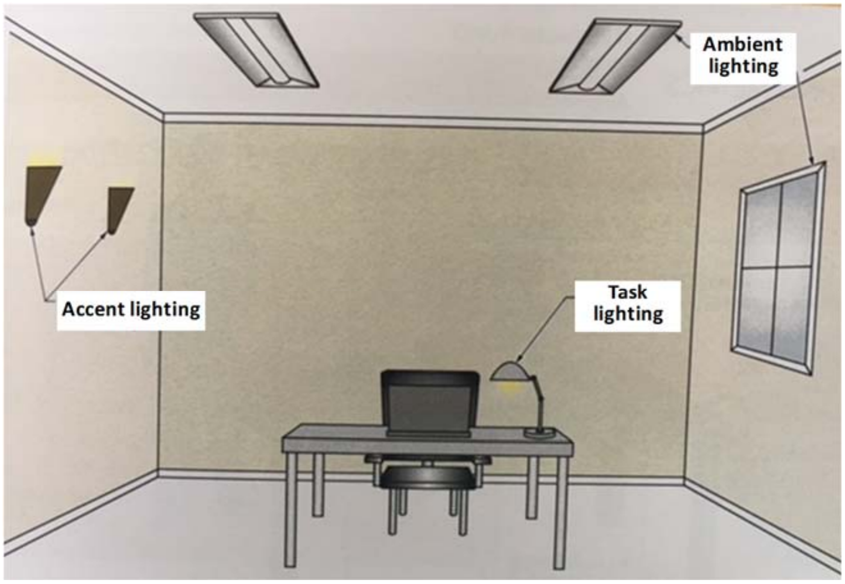


Figure 2.6.1: Three type of lighting in the built environment
Sources: WELL, 2017 – modified

Ambient lighting, is considered general lighting and is the main source of non-directional illumination. Ambient must provide enough light intensity for safe movement but not too much to cause visual discomfort. Typically, ambient light control is integrated with daylight control, to maintain sufficient light levels.

Accent lighting focusses on particular areas or objects. It usually represents a small portion of the overall lighting.

Task lighting provides increasing illuminance to better accomplish a specific function. Besides illuminance level contrast is important. Typically, task lighting is controlled by the occupant. Task lighting can augment the ambient lighting, thereby reducing the energy requirements.

Light metrics: Light can be quantified by the color temperature of the light, the intensity of the lamp output, reception of the occupant and flicker.

The color temperature is a descriptor of the “warmness” of the light, ranging from warm (1,000 K) to cold (>8,000 K). Warmer light colors have more red and yellow shades and cooler light colors have more blue shades. Figure 2.6.2 shows a color temperature scale, indicating the range of color temperatures provided by the different light sources.

Light intensity: Figure 2.6.3 illustrates the four light intensity parameters.

- Luminous flux is the total luminous output, given in the unit lumens. The overall emittance of the light source is given off in all directions. It is measured in LUMENS.

- Luminous intensity, is the visual intensity provided by the lights source in a specific direction. It is quantified as CANDELA.
- Illuminance is the light incident on a given surface. It is given as LUX or FOOTCANDELS measured in LUMENS per ft^2 or LUMENS per m^2 , respectively.
- Luminance is the value at of how bright the surface will appear to the occupant. It is measured in CANDELAS per m^2 .

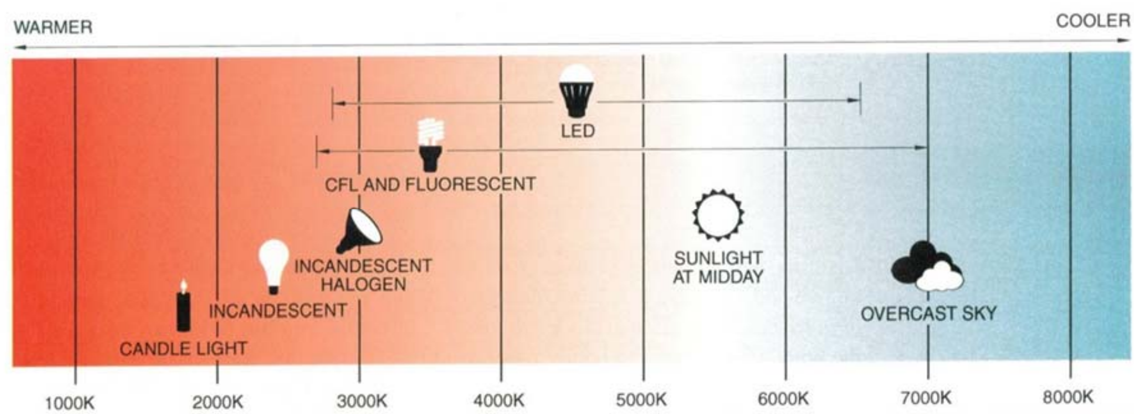


Figure 2.6.2: Color temperature scale, indicating the range of color temperatures provided by the different light sources (WELL, 2017)

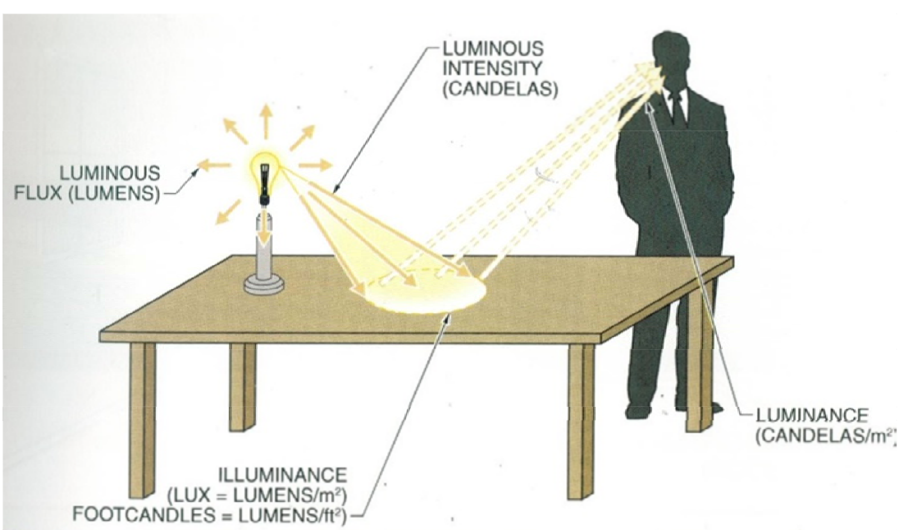


Figure 2.6.3: Illustration of the different light intensity metrics (WELL, 2017)

Light flicker is a visible fading or modulation between cycles displayed by a light source. Voltage fluctuation change the intensity of the output. Light flicker can be an inherent dilemma of video displays as well as of several types of lamps. Light flicker is an undesirable circumstance, causing discomfort, affecting productivity, or even safety.

The following main features determine the suitability of the indoor lighting to contribute to good IEQ:

Light volume: Sufficient light must be provided to occupants for their type of work and indoor activity. Standards have been developed to quantify sufficient light levels. Ambient light levels have to sufficient enough to allow for most tasks, and additional lighting has to be available if the occupant requires it for productivity.

Glare is excessive brightness in regard to the light source, reflection from surface or contrast. Glare decreases the comfort level and lowers the quality of visual perception. Glare from lamps can be mitigated with shielding. Solar glare is mitigated with appropriate shading, light shelves, or other more sophisticated measures.

Color quality: Inadequate color rendering can negatively affect occupant comfort. Indoor color rendering is quantified as the color rendering index (CRI) which is a measure of appearance of 8 to 14 colors under a specific light source in comparison to the appearance of a black body source of the same surface temperature.

Daylighting is a building design approach to expose occupants to sufficient natural light, without incurring negative effects such as soar gain or glare. Daylighting requires sufficiently large and appropriate openings in the building envelope and internal reflective surfaces to create effective internal lighting. Objectives of daylighting are to increase occupant comfort while reducing energy demand from lighting, when artificial light levels can be reduced or replaced. The quality of daylighting must satisfy two metrics, spatial daylight autonomy and annual sunlight exposure. Spatial daylight autonomy quantifies the portion of indoor space that receives sufficient daylight, measured in percent of the entire indoor space. Annual sunlight exposure gives a metric of the percentage of space that received a threshold lighting level of at least 250 hours in the year.

2.7 Indoor Sound Quality (ISQ)

Excessive noise can harm the activity and wellbeing of building occupants; sounds can be distracting and disruptive to work or relaxation. Noise can be so disruptive and harmful to effect human health; surpassing threshold noise levels can create acute pain. Noise at lower levels can still negatively affect the occupant's comfort and lower ability to perform. Acoustic problems are a leading source of dissatisfaction within the environmental conditions of an office. WELL (2017) suggests that noise is ubiquitous, and policies, technologies and practices should be implemented to achieve a quieter acoustical environment and minimize the occupants to exposure to harmful and unnecessary sound.

Noise is quantified by the sound level, which is based on pressure variations generated by the sound source. The metric for sound level is the decibel (dB), where the most suitable metric is that of the A-weighted decibel (dBa), since it reflects the human perception of sound in regard to octave band frequency.

Noise can be categorized in external and internal noise sources.

External noise is referred to as “environmental noise”, arising from the increasingly mobile and modern world, with noise sources coming mainly from machines and transportation systems, motor vehicles engines, aircraft, and trains. Urban planning which does not place sufficient emphasis on noise abatement and control can exacerbate noise pollution. In many communities, noise laws and ordinances establish admissible noise levels, typically based on land use criteria.

Managing external noise in the built environmental is through effective noise infiltration mitigation measures, such as high-performance windows and wall construction. External noise is an inherent shortcoming of naturally ventilated buildings, since the building envelop must be opened to achieve high rates of naturally occurring ventilation. In order to achieve satisfactory indoor sound quality, external noise intrusion is typically limited in accordance to the use of the indoor space.

Internally generated noise: Occupants are negatively affected by interior noise, generated by occupants, HVAC and other mechanical building systems, as well as from office equipment. Mitigation of excessive interior sound includes source and propagation control and includes the following:

<u>Acoustic planning and mechanical equipment:</u> Indoor spaces should be designed to establish loud and quiet zones. Acoustic source control should be implemented to mitigate indoor noises, such as generated by HVAC and other mechanical equipment. The metric of generated noise is the noise criteria (NC), where allowable NC should be limited in accordance with the types of use of the indoor spaces. For example, conference rooms should have a significantly lower allowable NC than open office space and lobbies.

<u>Reverberance time mitigation:</u> Reverberance time is the time, measured in seconds, required for sound to decay. It is quantified as the number of seconds it takes a sound to decay by 60 dB from its original level. Reverberation time is usually quantified as a single value although it is frequency dependent. Therefore, a more precise description would be in terms of frequency bands. The shorter the reverberance time, the better the indoor sound quality. Long reverberance time can cause excessive sound levels and decrease occupant comfort. The level of sound level decay depends on sound-absorptive characteristic of floors, ceiling, walls and interior decorations and furniture.

<u>Sound reducing surfaces</u> can be used to lower excessive sound transmissions. Sound reduction surfaces are typically used on ceilings and walls. The metric for sound reduction is the noise reduction coefficient (NRC), with a NRC range from 0 to 1.0, where 0 indicates total sound reflection and 1 total sound absorption. Table 2.7.1 provides NRC values for common building materials:

Table 2.7.1: NRC values for common building materials (WELL, 2017)

Building material	Noise reduction coefficient (NRC)
Acoustic tile	0.5 to 0.9
Brick	0.02 to 0.05
Carpet	0.3 to 0.55
Concrete	0.05 to 0.2
Cork tiles	0.7
Glass	0.05 to 0.1
Gypsum boards	0.05
Interior furnishing	0.3 to 0.6
Marble	0.0
Polyurethane foam	0.3
Semi rigid fiberglass	0.75
Steel	0.0 to 0.1
Wood	0.05 to 0.15

Sound barriers impede sound transmission through walls and doors and between adjacent rooms. Sound barriers block the transmission of sound waves by avoiding air gaps and by adding sound insulation.

Sound masking: Interestingly, while excess noise negatively affects occupants, ambient silence can also be a distraction and comfort impairment, but it is not an issue impairing health. When the indoor space is significantly quiet, any small noise can be disturbing and the sense of privacy can be reduced. The appropriate mitigation measure is sound masking, which is a low-level background noise, such as emitted from electronic devices.

2.8 Indoor Oder Quality (IOQ)

Odor and fragrance basically describe the same physical property, which is the presence of chemical compounds in the air that humans experience as olfactory sensation. Odor and fragrance are referred to as negative and positive sensations, respectively. Odors from cleaning substances, off-gassing material, personal hygiene substances and food sources can cause occupant discomfort, including headaches and eye, nose and throat irritation.

An odorant is defined as a substance, which can cause an olfactory reaction. (Powers, 2007) Odor is defined as the emotional reaction to the sensation produced by the olfactory organs. The detection of odor often requires only very minute concentration in the air. Powers (2007) suggested that the threshold of experiencing a smell are low, often in the parts per billion (ppb) or parts per trillion (ppt) range. The range of detection to the perception of maximum intensity of a smell is quite narrow, with a concentration only 10 to 50 times above the detection threshold value often being the maximum intensity that can be detected by humans. The contrast to other sensory systems such as light is striking, where maximum intensity of light is about 500,000 times that of the threshold intensity, and a factor of 1 trillion is observed for hearing. Because of this small range from threshold to maximum intensity, smell is often experienced as a sensation of being present or absent. Often, a 50% percent detection of an odor by a sample group of observers is defined as the threshold.

Powers (2007) describes five properties that quantify the sensation of smell:

1. Intensity
2. Duration
3. Frequency
4. Character
5. Degree of offensiveness

The sensation of smell and the experience of odor is very subjective, and humans react to odor in different ways. The individual odor experience is based previous experience, relationship to the odor-producing function and the sensitivity of the individual to that smell. There are, however, objective conditions and environmental properties, such as temperature, humidity and wind movement, that affect the volatility of the odor producing compounds.

While experiencing smell sensation, most humans tolerate a strong smell for a short time, as long as they are subjected to the smell infrequently. But the tolerance level is very subjective, and might change significantly among a sample group. The three properties intensity, duration and frequency can be measured, while character and degree of offensiveness are more subjective, although there are certain smells which are uniquely offensive, such as foul smells. As a result, regulatory procedures often include concentration, frequency, and duration as part of compliance standards. From individual experience, exposure time is an essential metric in expecting negative smell experience.

In the indoor environment discomfort from odor can negatively affect occupant wellbeing and productivity. The most common odor mitigation measure is the separating of the occupants from the source of the smell (WELL, 2017). This includes the following:

Negative pressurization: Mechanical ventilation devices can be used to create negative air pressures in spaces that contain odor sources. The pressure differentials prevent odor migration from spreading into the higher-pressure spaces. Negative pressurization is an effective measure to curb odor migration inside indoor spaces, but can require significant ventilation equipment and energy consumption.

Interstitial spaces are unoccupied spaces which are located between rooms with odor sources and regularly occupied spaces. Such space can contain mechanical and other utility systems, or have no other function as separating two or more spaces.

Vestibules have a long tradition in architectural to provide a representative separation between internal and external space in the building. Regarding to a more functional use of vestibules in modern buildings, vestibules have an "air lock" function, as they reduce air infiltration to the building or between internal zones by having only one set of doors open at any given time.

Self-closing doors have automatic mechanism to close after a certain time. This prevents air from flowing between indoor spaces.

2.9 Additional Aspects Affecting IEQ

This section presents several aspects which affect the indoor environmental quality (IEQ). These aspects are only briefly introduced. They represent a collection of primarily emotional individual responses which affect the perception of quality of wellbeing inside the built environment. The selected aspects are not meant to be all-encompassing. These aspects typically have a lower effect on IEQ than the aspects discussed on sections 2.2. through 2.8. These aspects can nevertheless play an important factor on the individual experience of indoor wellness and comfort, and they can serve as authenticating factors in the individual occupants' perception of other IEQ aspects.

With respect to the aspects affecting Indoor Environmental Quality (IEQ,) the following are considered in this section:

- Biophilia, the human affinity to the natural world
- Aesthetics, the aspect of incorporating art and beauty in design
- Ergonomics, the aspect of adapting indoor objects and spaces in an efficient way to accommodate the occupant's capabilities.

Biophilia is the instinctive predisposition of humans to connect with nature and other forms of life. In practicing biophilia in architectural design, natural elements are introduced in the design of the built environment. Much of the contemporary design shuts out nature, by sealing the building envelope to increase energy efficiency in lieu of opening up the envelope. Occupants, however, can greatly benefit from proximity and connection to the natural environment, even if this connection is limited by representative indoor elements. Indoor environment that lacks biophilic elements are perceived a cold and sterile. A reduced perception of the natural environment can reduce occupant's comfort and content. On the other hand, additions of biophilic designs can increase the acceptance of overall indoor comfort and wellness, and in turn increase the productivity of indoor work.

The WELL standard suggests the following indoor features to achieve some level of biophilic design:

- Incorporation of nature in the design, an effort to use environmental elements, natural light and an appropriate layout that foster the incorporation of nature.
- Nature interaction, a building feature that provides for sufficient opportunity for human nature interactions. This feature is important for both the interior and the exterior.
- Biomimicry, the imitation of natural and biological in the design of structures and materials.

- Indoor Biophilia, including such design elements as potted plants and vegetated atriums or courtyards. Contemporary biophilic designs also include vegetated walls (green walls).

Aesthetics in design can be described as introducing art and beauty in the indoor space. Measures that can be taken to implement beauty and art are the following:

- Using appropriate room width to ceiling height ratios, rather than staying with a constant ceiling height, and promoting the use of larger windows to provide external views.
- Using art work that is distinctive, such as sculptures or paintings to stimulate visual experience.
- Creating spaces that have a spatial identity, such as zones that use a unifying design or corridors that have visual anchors, such as art work or windows.

Ergonomics, the design approach of adapting objects, spaces and processes to accommodate occupant capabilities, to foster safety and efficiency. Good ergonomic design strategies include safe and comfortable internal layouts that are pleasing to the visual experience of occupants. Supportive ergonomics also includes providing comfortable and adjustable workstations as well as flexibility in seating arrangements.

2.10 Concluding Remarks - Aspects of Indoor Environmental Quality

The discussion in sections 2.2 through 2.9 suggests that indoor environmental quality (IEQ) entails several important aspects, all woven in a comprehensive and interrelated system of mutual enforcement and mitigation.

The present discussion about the contributing aspects of indoor environmental quality (IEQ) is not generic in nature, but is centered on the merits of an innovative space conditioning and ventilation system. The innovative approach includes the separation of latent and sensible heat removal, and the use of liquid desiccants for energy efficient humidity control. Figure 2.10.1 illustrates the interrelationship of the different aspects on IEQ as they are evaluated for the application of the innovative space conditioning and ventilation technology.

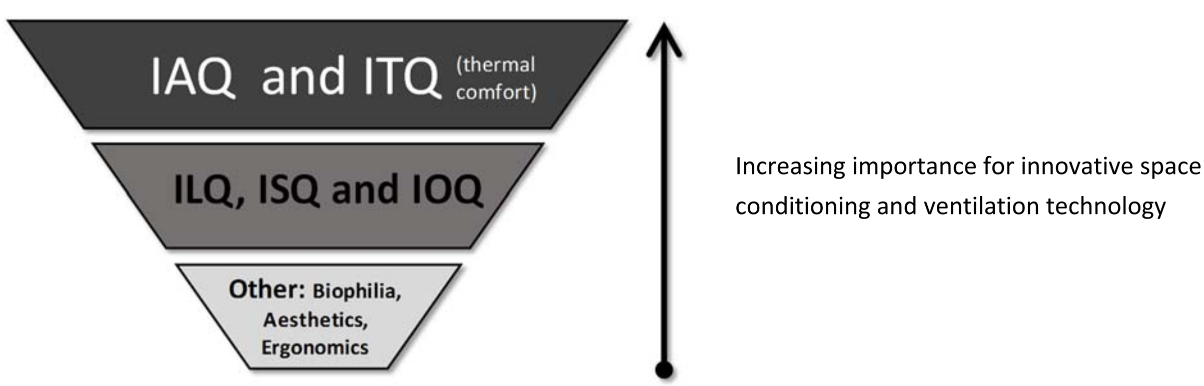


Figure 2.10.1: Increasing importance of aspects of IEQ as they relate to innovative space conditioning and ventilation

As is illustrated in Figure 2.10.1, the significance of different IEQ aspects decrease as they are applied to evaluating shortcomings of indoor spaces ventilation, cooling and dehumidification.

For the discussion in this report, and in order to develop an evaluating framework with quantitative metrics, IEQ aspects discussed in previous sections are divided into three tiers with decreasing importance.

At the top, in the first tier and the highest importance. are the two IEQ aspects of Indoor Air Quality (IAQ) and Indoor Thermal Quality (ITQ), the latter also being referred to as thermal comfort. These two IEQ aspects are directly affected by the performance of the innovative space conditioning and ventilation technology, and largely provide the metrics to determine the innovative technology performance.

In the second tier, with a lesser importance relative to the innovative space conditioning and ventilation technology, are Indoor Light Quality (ILQ), Indoor Sound Quality (ISQ) and Indoor Odor Quality (IOQ). ILQ is directly affected by the sealing of the space and possibly limiting the access to daylighting for the occupants. On the other hand, increasing daylighting through larger windows and openings in the building envelope can increase thermal gain. ISQ can be negatively affected by opening the building envelope. Likewise, Indoor Odor Quality can be negatively affected by opening the building envelope and removing indoor air barriers. Thus, the performance of the innovative space conditioning and ventilation technology is affected by these second tier IEQ aspects.

The third tier has the smallest effect on the performance of the innovative space conditioning technology. The effect of these third tier IEQ aspects is at the individual experience level, but these aspects can nevertheless have a significant effect on how the IEQ is experienced by the building occupants.

In practical terms, however, biophilia could impose direct effects since larger plants and the associated irrigation as well as possible water features can add to the internal humidity load.

SECTION 3 – PERFORMANCE: SPACE CONDITIONING TECHNOLOGIES FOR HAWAII

This section discusses generic performance of space conditioning technologies which are used or are planned for Hawaii.

3.1 Types of Space Conditioning – Present Applications

Figure 3.1.1 depicts the different types of space conditioning and ventilation systems which are being used in Hawaii and summarizes their main functions. Figure 3.1.1 also illustrates how the proposed innovative space conditioning and ventilation systems compare to the different functions of the presently used systems.

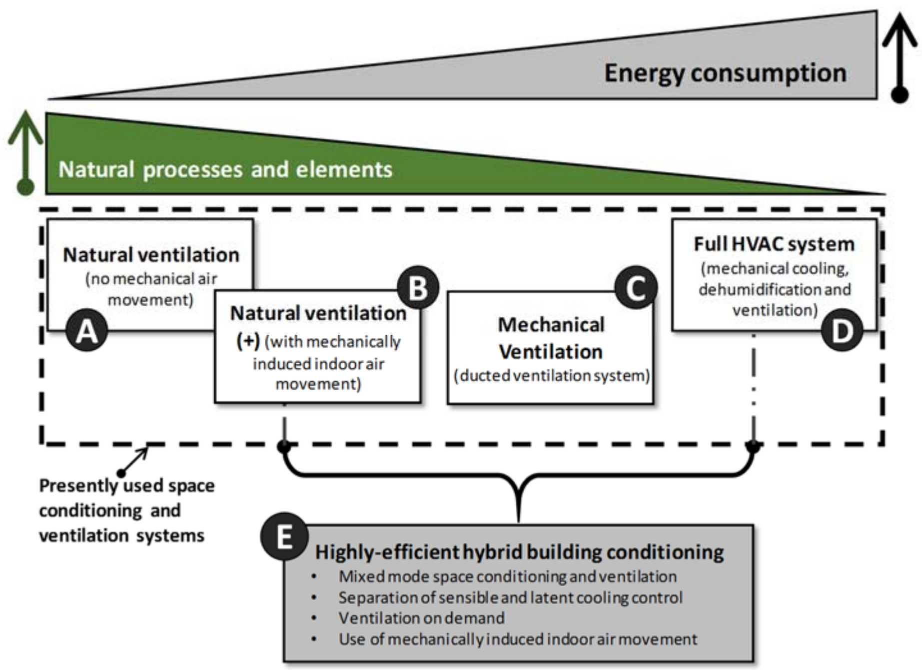


Figure 3.1.1: Presently used space conditioning and ventilation systems and the proposed innovative system

The systems depicted in Figure 3.1.1 are described as follows:

<u>System (A) – Natural ventilation</u> <u>(no mechanically induced air movement):</u> The indoor space ventilated entirely with natural driving forces, which means cross ventilation and/or stack effect. Cross ventilation is due to a wind induced pressure differential, where the air is moved between locations from high to low pressure areas. The magnitude of the pressure differential and the pressure losses incurred by internal air flow determines the magnitude of the air movement. The stack effect is a buoyancy induced air flow which occurs through a density differential between warm and cold air volumes, with the warmer air having a lower density. Figure 3.1.2 illustrates the working process of natural ventilation.

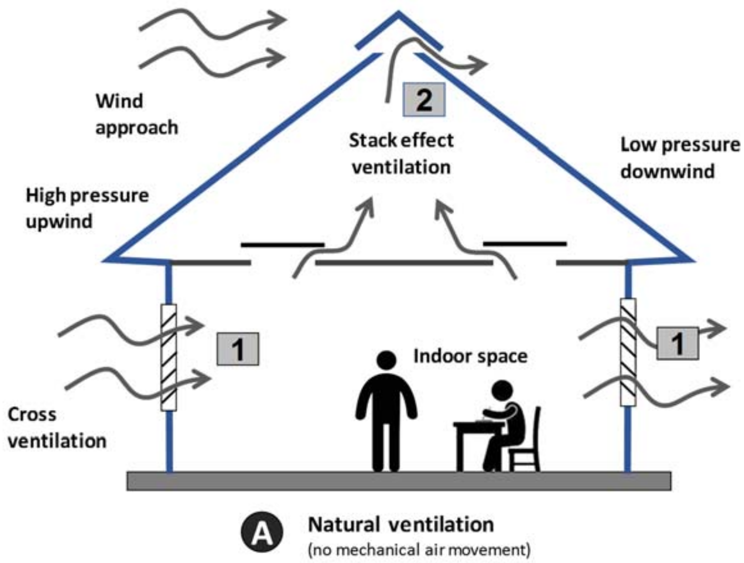


Figure 3.1.2: Working principle of System (A) - natural ventilation (without mechanically induced air movement

Building component ([x]) that support natural ventilation without mechanical fan power are described in more detail in Table 3.1.1.

[1] Safety, pest management, sound and solar gain protection of windows and openings
[2] Opening to support stack effect

Table 3.1.1: Properties of natural ventilation; System (A) in Figure 3.1.2

No.	**Function / Process / Property**	**Performance**
A	Working principle of ventilation	Air movement through the indoor spaces is driven by naturally occurring wind and temperature differences
	• Mechanically induced	NO
	• Wind / buoyancy induced	Yes, either cross ventilation or stack effect
B	Working principle of cooling / dehumidification	
	• Type cooling	Naturally induced: Cooling is provided by freely flowing external air through the indoor spaces. The flowing air removes heat energy by convection.
	• Type dehumidification	Naturally induced: Removal of internally generated or stored humidity only be drier external air flowing through the indoor spaces.
C	Energy demand	Low, and none for mechanical ventilation, cooling and dehumidification.
D	Equipment demand	[1] Requires limited equipment for openings in the building envelope (i.e. bug screen, security bars) for security and pest repellent; sound abatement if possible; shades to lower solar gain [2] The stack effect requires openings at a high point of the building to vent the warmer air and induce a buoyance driven air flow through the indoor spaces.
E	Type of main shortfalls	Natural ventilation is dependent on external and naturally occurring wind and climate conditions, heat rejection of indoor heat not always effective; dehumidification only

Table 3.1.1: Properties of natural ventilation; System (A) in Figure 3.1.2

No.	Function / Process / Property	Performance
		sufficient if sufficient volumes of dry external air can be passed through the indoor spaces and vapor pressure differentials between the ventilation air and the humidity sources are sufficient

System (B) – Natural ventilation (with mechanically induced indoor air movement): This process of space conditioning is very similar to System (A)– Natural ventilation (no mechanically induced air movement) since the ventilation of the spaces is still dependent on wind and buoyancy induced pressure differential. The difference from System (A) is that System (B) uses mechanical fans to create localized air movements inside the indoor space. These air movements provide occupants with some degree of additional sensible cooling, which is due to increased convective and evaporative thermal losses from the body. Figure 3.1.2 illustrates the working process of natural ventilation.

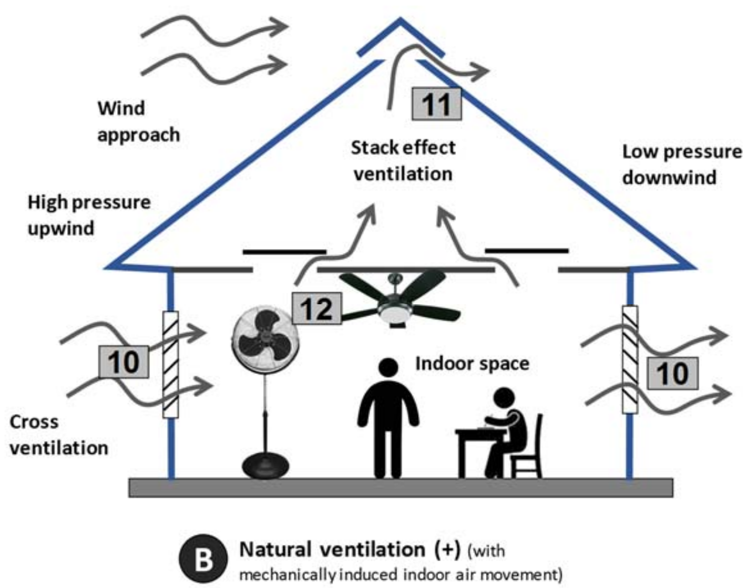


Figure 3.1.3: Working principle of System (B) - natural ventilation (with mechanically induced indoor air movement)

Building component ([x]) that support natural ventilation with mechanically induced indoor air movement are described in more detail in Table 3.1.2.

[10] Safety, pest management, sound and solar gain protection of windows and openings
[11] Opening to support stack effect
[12] Indoor fans, ceiling, standing or personal comfort fans

Table 3.1.2: Properties of natural ventilation; System (B) in Figure 3.1.3

No.	Function / Process / Property	Performance of specific system components
A	Working principle of ventilation	Air movement through the indoor spaces is driven by naturally occurring wind and temperature differences
	• Mechanically induced	NO

Table 3.1.2: Properties of natural ventilation; System (B) in Figure 3.1.3

No.	Function / Process / Property	Performance of specific system components
	• Wind / buoyancy induced	Yes, either cross ventilation or stack effect
B	Working principle of cooling / dehumidification	
	• Type cooling	Naturally induced: Cooling is provided by freely flowing external air through the indoor spaces. The flowing air removes heat energy; additional cooling is provided by increased air movement of the occupants. This increased air movement increases convective and evaporative het loss from the human body
	• Type dehumidification	Naturally induced: Removal of internally generated or stored humidity only be drier external air flowing through the indoor spaces
C	Energy demand	Low, and none for mechanical ventilation, cooling and dehumidification. Some minor electric demand for ceiling fans.
D	Equipment demand	[10] Requires limited equipment to openings in the building envelope (i.e. bug screen, security bars) for security and pest repellent; sound abatement if possible; shade to lower solar gain [11] The stack effect requires an opening at a high point of the building to vent the warmer air and induce a buoyance driven air flow through the indoor spaces. [12] Fans that induce indoor air movement, this includes: • ceiling fans, which provide increased air speed over a larger portion of the space • Standing or personal comfort fans which provide directional air movement towards the occupant.

Table 3.1.2: Properties of natural ventilation; System (B) in Figure 3.1.3

No.	Function / Process / Property	Performance of specific system components
E	Type of main shortfalls	Natural ventilation is dependent on external and naturally occurring wind and climate conditions, rejected of indoor temperature not always effective; dehumidification only sufficient if sufficient volumes of dry external air can be passed through the indoor spaces and vapor pressure differentials between the ventilation air and the humidity sources is sufficient. The increased air movement for cooling is dependent on personal preferences and can be differently experienced by occupants, either as positive or negative comfort.

System (C) – Mechanical ventilation: This process of space conditioning uses mechanical fans to supply pressure differentials and therefore pressure driving forces for air movement through indoor spaces. The external air is not cooled and dehumidified.

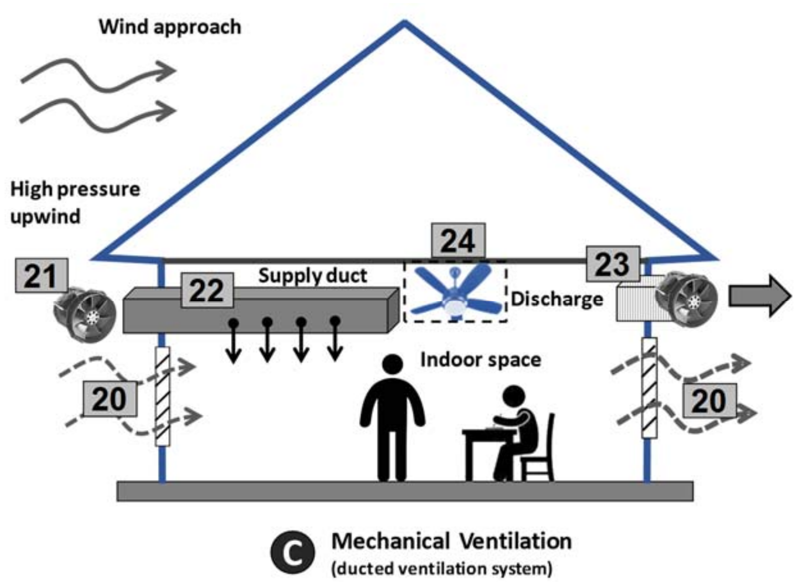


Figure 3.1.4: Working principle of System (C) - mechanical ventilation
Building component ([x]) that support mechanical ventilation are described in more detail in Table 3.1.3.

[20] Protection of windows and openings; means to open and seal windows
[21] Mechanical ventilation fans to provide supply air
[22] Supply air ducts; filters for air supply
[23] Options: discharge ventilation fan to remove air from the space
[24] Optional ceiling fans

Table 3.1.3: Properties of mechanical ventilation; System (C) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
A	Working principle of ventilation	Air movement through the indoor spaces is driven by mechanical means
	• Mechanically induced	Yes
	• Wind / buoyancy induced	Optional, if outside climate conditions allow natural ventilation processes can be used
B	Working principle of cooling / dehumidification	
	• Type cooling	Naturally induced cooling: Cooling is provided by forced air through the indoor spaces. The flowing air removes heat energy; additional cooling is provided by increased air movement of the occupants. This increased air movement increases convective and evaporative heat loss from the human body; magnitude of cooling can be regulated the air volume flowing through the indoor spaces
	• Type dehumidification	Naturally induced dehumidification: Removal of internally generated or stored humidity only be drier external air flowing through the indoor spaces; dehumidification is NOT provided by mechanical ventilation.
C	Energy demand	Medium for mechanical ventilation fans; fan energy demand is dependent on the required pressure differential for ventilation and the ventilation rates
D	Equipment demand	[20] Building envelope has to be sealed to avoid excessive infiltration through gaps and leaks, which can cause humidity induced problems inside walls and enclosed spaces; windows have to be sufficiently air tight to lower associate pressure losses and infiltration; windows should be opened to allow natural ventilation if external climate allows, windows need to have mechanical mechanism to allow ready operation and closing of windows. [21] The air supply fan creates the required pressure for ventilation driving forces. [22] The air duct(s) distribute supply air to the indoor spaces; different zones can be supplied

Table 3.1.3: Properties of mechanical ventilation; System (C) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
		independently; air filters can be implemented inside the supply ducts [23] If ventilation includes multiple zones discharge, ducts have to be implemented; optional is the ventilation fan that discharges air from the indoor spaces, thereby creating a lower pressure in the building. [24] **Optional** are ceiling fans that increase the cooling through internal air movement; the ducted ventilation does typically not provide the required air speed through the indoor spaces that would create additional cooling effect.
E	Type of main shortfalls	Mechanical ventilation requires significant fan power to move the supply air through the building; ducts have to be added to supply different zones, the operation of fans is sometimes noisy; if a mixed mode ventilation is desired the windows have to be mechanically operated to provide a sealed envelope and avoid shortcuts in ventilation air streamlines

System (D) – Full, conventional HVAC: This process of space conditioning uses mechanical fans and cooling coils to provide ventilation and cooling / dehumidification, respectively. The external air is cooled and dehumidified using vapor compression cooling equipment. Since the internal air is cooled, dehumidification is required to lower indoor humidity levels.

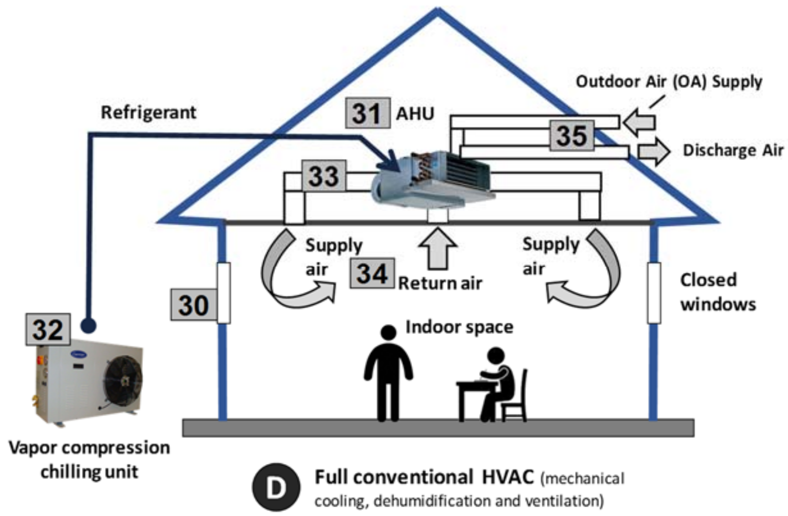


Figure 3.1.5: Working principle of System (D) – Full, conventional HVAC

Building component ([x]) that full, conventional HVAC are described in more detail in Table 3.1.4.

[30] Building envelope and windows must be sealed
[31] Air handling unit (AHU) with cooling coils and ventilation fans
[32] Mechanical cooling, vapor compression
[33] Internal air distribution ducts
[34] Induced flow of cooled and dehumidified air through indoor spaces
[35] Supply and discharge air ducts

Table 3.1.4: Properties of Full, conventional HVAC; System (D) in Figure 3.1.5

No.	Function / Process / Property	Performance of specific system components
A	Working principle of ventilation	Air movement through the indoor spaces and cooling & dehumidification is through mechanical means
	• Mechanically induced	Yes
	• Wind / buoyancy induced	No
B	Working principle of cooling / dehumidification	
	• Type cooling	Mechanical cooling; return and outside air is forced over cooling coils by fans; this provides the required ventilation rates and removes sensible loads from the indoor air supply.

Table 3.1.4: Properties of Full, conventional HVAC; System (D) in Figure 3.1.5

No.	Function / Process / Property	Performance of specific system components
	• Type dehumidification	Mechanical dehumidification: Removal of internally generated or stored humidity by means of cooling coil based drying. Returned indoor air of outdoor supply air is forces to flow over cooling coils which are operated below air dew point, thereby causing condensation of the air born humidity on the cooling coils and removal of humidity as liquid condensate.
C	Energy demand	High energy demand for mechanical cooling and fans. In Hawaii climate, mechanical cooling must remove a high magnitude of latent load (e.g. dry the warn and g=humid external air.
D	Equipment demand	[30] Building envelope and windows must be sealed: Sealing of the enveloped must satisfy several objectives: • Envelope and opening must provide sufficient building tightness and insulation to control heat gain through accidental infiltration, conductive heat transfer and solar radiation • Envelope must provide sufficiently tight vapor seal to avoid condensation of outside air inside interstitial spaces [31] Air handling unit (AHU) with cooling coils and ventilation fans: AHUs have internal fans that drive the air across cooling coils held at a below dew-point temperature (in a split system the evaporator coil). This cools the air and causes the humidity to condensate. [32] Mechanical cooling, vapor compression, is the conventional method of providing cooling capacity. [33] Internal air distribution ducts distribute the cooled and dehumidified air to various internal zones. [34] Induced flow of cooled and dehumidified air through indoor spaces removes sensible and latent load from the indoor spaces. [35] Supply and discharge air ducts establish the connection to the outside air. Fresh outside air is admitted and mixed with circulated return air. The same amount of air is discharged from the indoor space as are introduced to it.

Table 3.1.4: Properties of Full, conventional HVAC; System (D) in Figure 3.1.5

No.	Function / Process / Property	Performance of specific system components
E	Type of main shortfalls	Mechanical cooling, dehumidification and ventilation requires high electric power to drive the ventilation fans and provide the cooling. Especially in humid climates the conventional HVAC system has shortcomings in balancing the basic need for HVAC that are • Ventilation and the supply of fresh outside air • Cooling to provide comfortable operative air temperatures inside the indoor spaces • Dehumidification to control the indoor humidity levels. Besides unfavorable energy and power demands for the mechanical ventilation and cooling equipment, conventional HVAC often causes unsatisfactory IEQ and humidity problems.

3.2 Proposed Highly-efficient Hybrid Building Conditioning (System E)

This section introduces the proposed highly-efficient hybrid building conditioning system. While several system components have been individually used in Hawaii, the system components have not been used in the proposed integrated fashion. Figure 3.2.1 illustrates the proposed highly-efficient hybrid building conditioning and the basic process is described in Table 3.2.1. The following are the main objectives of the proposed system:

- Separate sensible from latent heat load removal. Avoid the challenges and shortcomings of conventional HVAC systems which, because of cooling coil dehumidification, cannot be optimized for the three basic space conditioning functions, which are ventilation with outside air, removal of sensible heat and removal of latent load.
- Avoid overcooling of indoor spaces caused by cooling coils that operate to condense humidity in the indoor air.
- Improve humidity control, by controlling energy efficient dehumidification independently of sensible cooling.
- Utilize solar heat or process (waste) heat for latent and sensible heat removal.
- Reduce overall energy consumption for space condition and provide aspects of IEQ that support the wellness and comfort of building occupants.

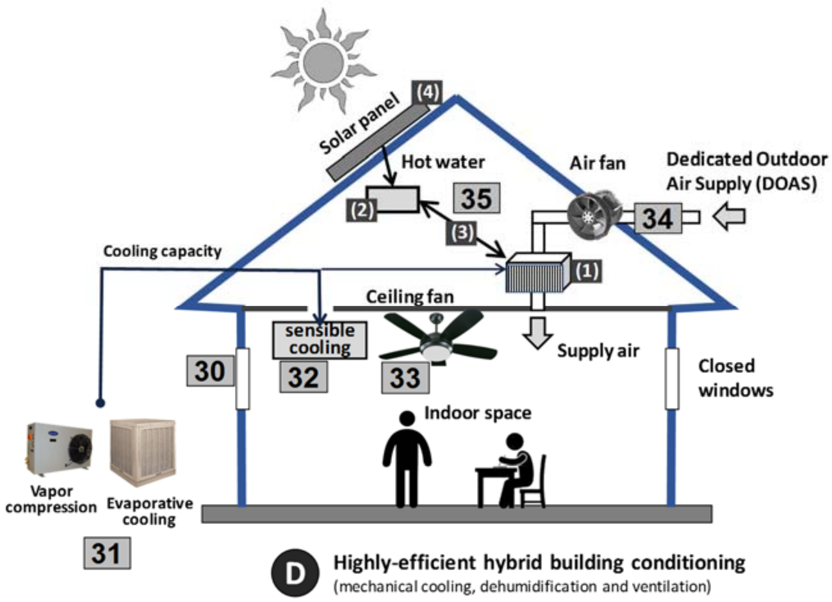


Figure 3.2.1: Working principle of System (E) – Highly-efficient hybrid building conditioning

Building component ([x]) that support the proposed Highly-efficient Hybrid Building Conditioning system are described in more detail in Table 3.2.1.

[30] Building envelope and windows are sealed but can be opened to allow natural ventilation
[31] Cooling capacity by vapor compression or evaporative cooling
[32] Sensible cooling
[33] Ceiling fans
[34] Dedicated outdoor air supply
[35] Liquid desiccant system

Table 3.2.1: Properties of mechanical ventilation; System (E) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
A	Working principle of ventilation	Air movement through the indoor spaces and cooling & dehumidification is through mechanical means, a Dedicated Outdoor Air System (DOAS) is used that limits the quantity of conditioned air through the indoor spaces
	• Mechanically (mainly)	Yes, typically the indoor spaces are ventilated by fans
	• Wind / buoyancy (optional)	Yes; optional; in the mixed-mode ventilation strategy, natural ventilation can occur when outside climatic conditions are favorable
B	Working principle of cooling / dehumidification	
	• Type cooling	<u>Mechanical cooling</u>; cooling can be accomplished by dedicated sensible cooling devices, such a fan coils, chilled beams, and radiant surfaces (radiant ceiling or walls); the cooling capacity can either be provided by vapor

Table 3.2.1: Properties of mechanical ventilation; System (E) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
		compression or by evaporative cooling units. The advantage of the sensible cooling devices is that the heat sink can be at raised temperatures (e.g. above dew point). This avoids overcooling of the indoor spaces.
	• Type dehumidification	Desiccant dehumidification: Removal of internally generated or stored humidity is be means of liquid desiccant devices. The humid air is passed through an open cycle of liquid desiccant and humidity is removed by absorption into the liquid desiccant concentration. During the absorption process the liquid desiccant solution decreases in concentration. The liquid desiccant solution is regenerated by heating the desiccant to a point when vapor pressure differentials between descant and scavenging are is sufficiently high enough to cause desorption of water vapor from the desiccant liquid solution.
C	Energy demand	Energy demand is from ventilation fans and from vapor compression or from evaporative cooling for mechanical cooling and fans. Solar heat is preferred to regenerate the liquid desiccant solution. Evaporative cooling is preferred over vapor compression. Since the amount of supply air is significantly recued in the DOAS, fan energy consumption can also be reduced.
D	Equipment demand	[30] Building envelope and windows must be sealed: Sealing of the enveloped must satisfy several objectives: • Envelope and opening must provide sufficient building tightness and insulation to control heat gain through accidental infiltration, conductive heat transfer and solar radiation • Envelope must provide sufficiently tight vapor seal to avoid condensation of outside air inside interstitial spaces • If natural ventilation is used as an option, windows have to have an efficient way to operate. [31] Cooling capacity is provided vapor compression or by evaporative cooling; other cooling technologies might be applicable in the future. Evaporative cooling is efficient when the external (or process) air has a low enough relative humidity. In the typical Hawaii climate,

Table 3.2.1: Properties of mechanical ventilation; System (E) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
		this is often not the case. A suitable strategy of energy recovery is the use of the building air discharge, since this has a low enough relative humidity. [32] Sensible cooling can be carried out by reducing the air temperature through passing air of cold surface (fan coils) or by providing cooler surfaces (radiant cooling). The advantage of this form of sensible heat removal is that cooling does not have to produce the cold temperatures for cooling coil dehumidification. Since no phase change occurs under this form of sensible heat removal the chillers can run at higher temperatures, thereby being significantly more energy efficient [33] Ceiling fans are an efficient and low impact process to provide additional sensible heat removal from human bodies. Ceiling fans are not often used in fully air-conditioned spaces since at lower air temperatures the increased air speed produced by ceiling fans is experienced as annoying draft. In the proposed highly-efficient hybrid building conditioning indoor air temperatures are held at a higher range than in spaces that are conditioned with conventional HVAC [34] Dedicated outdoor air supply (DOAS) system can readily control the amount of air that is provided to the space. The DOAS system is a 100 % supply air system, this means no internal recirculation, the air volume can be controlled by controllable fans and dampers. [35] Liquid desiccant system: The liquid desiccant system removed the latent load and precisely controls the indoor humidity level. The system components elements of the desiccant system, as shown in Figure 3.2.1 are as follows: [35-1] The desiccant conditioner (or absorber) provides contact surfaces between the liquid desiccant solution and the supply air for mass transfer of humidity. Due to vapor pressure differentials water vapor in the air migrates to the desiccant surface, where it is absorbed by the liquid desiccant. The latent heat liberated in the conditioner is removed by an internal heat sink (cooling). [35-2] The desiccant regenerator (or desorber) provide contact surfaces between the heated desiccant

Table 3.2.1: Properties of mechanical ventilation; System (E) in Figure 3.1.4

No.	Function / Process / Property	Performance of specific system components
		and a lower temperature scavenger air flow for mass transfer. The desiccant inside the regenerator is heated to increase the vapor pressure. The process heat for the regenerator is provided by solar panels. [35-3] The liquid desiccant solution flows between the conditioner and the regenerator, thus transporting water volumes to the outside and thereby reducing the humidity. Concentrated desiccant, e.g. desiccant that has padded though the regenerator, can be stored to serve as an efficient form of energy storage. The stored concentrated desiccant can thus provide solar based dehumidification during a period of no solar gain in the panels. [35-4] Hot water, derived from solar panels, provides the process heat for desiccant regeneration. As an alternative to the storage of concentrated desiccants, hot water can also be stored and used during off-solar hours to provide dehumidification. The storage of hot water rather than concentrated desiccant has significantly smaller energy density, therefore requiring a larger liquid storage volume and insulated water storage tanks.
E	Type of main shortfalls	The system is innovative and requires willingness and openness by operate a mechanical system with advanced technology and controls. Due to the innovative nature of the technology and system integration some system components have a higher cost than conventional technologies, because of lacking present economy of scale.

Several of the components of the proposed hybrid building conditioning system have already been implemented in Hawaii, however not in the combination as in the proposed integrated space conditioning system.

No.	Component / technology	Reported experience
1	Separation of sensible and latent heat removal	Installations have been completed in Hawaii. With very few exemptions cooling coil dehumidification applications were used to remove humidity from the air
2	Evaporative cooling	Hawaii's typical climate is not well suited to the use of evaporative cooling for indoor cooling, because of the consistently high relative humidity. The use of cooling towers for process heat rejection is however widespread and proven. Using the discharge of dried indoor air for evaporative cooling is a proven technology and has been used in Hawaii. The use of phase change provides for a much higher cooling capacity than sensible air cooling.
3	Sensible heat removal with chilled beams	Chilled beams have been used in Hawaii in several installations. The chilled beam applications provided additional sensible cooling to conventional HVAC systems. The experience of performance has been mixed. Ranging from fully to partly satisfied.
4	Liquid desiccant dehumidification	There have been several liquid desiccant installations in Hawaii to provide additional dehumidification capacity to the conventional HVAC system for supermarkets. The systems have had operational problems, which was mainly based on a suboptimum design and performance for the liquid desiccant conditioner and regenerator. A new design for liquid desiccant conditioner and regenerator has shown much better performance characteristics than the previous designs. Both solar heat and heat derived from propane gas has been used for the process heat in the regenerator.
5	Dedicated outdoor air supply (DOAS)	DOAS systems have been used in Hawaii where 100 % outdoor air supply is required.
6	Ceiling fans for boosted cooling capacity	The use of ceiling fans is widespread in Hawaii. Newer ceiling fans designs have a significantly lower energy demand and provide a comfortable air movement

SECTION 4 - EVALUATING IEQ PERFORMANCE FOR SPACE CONDITIONING APPLICATIONS

This section evaluates and ranks the performance of the five space conditioning technologies presented in Section 3 in regard to Indoor Environmental Quality (IEQ) and energy saving potential.

4.1 Developing Ranking Framework

As discussed in Section 3, the IEQ experience of occupants in an indoor space is affected by a number of aspects; some of these aspects are strongly interrelated and affect how occupants are experiencing other aspects. As discussed in Section 3, for example, thermal comfort can be positively or negatively affected by the quality of indoor air. For example, the Indoor Sound Quality (ISQ) in a space can be affected by how tight the envelope can be configured or what sound abatement can be installed to keep out external noise. Systems A through E have inherently different potentials of keeping outside noises out, since natural ventilation relies on an open building envelope to allow outside ready entrance into the building and offer little pressure losses. On the other side, conventional HVAC needs to seal the building to lower warm and moist air intrusion.

While a wide range of IEQ aspects determines the overall IEQ experience, only a smaller subset has to be considered when comparing the present indoor space conditioning (Systems A - E). Aspects that need to be considered in the comparison are limited to those which rely on certain space condition technologies, process and building elements. Therefore, aspects which are similar for all systems are not included in the comparative ranking of alternatives. In addition, energy savings potentials of Systems A through E are used for the ranking. Figure 3.1.1 illustrates the selection of the ranking criteria out of a larger pool of IEQ aspects and combining these with rankings criteria of energy savings potential. Table 4.1.1 provides an overview of IEQ aspects and energy savings opportunities for the comparison.

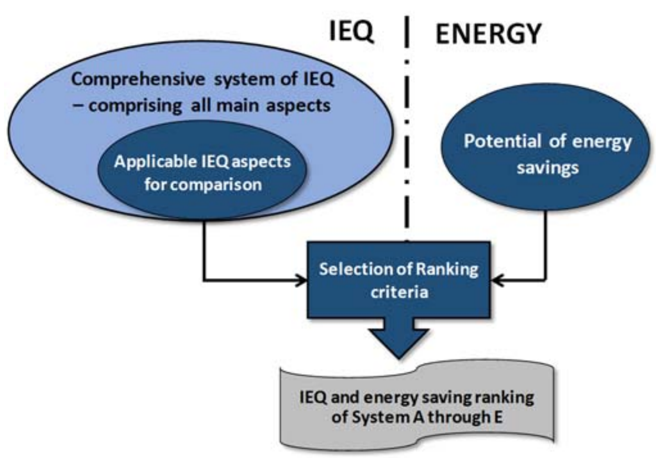


Figure 4.1.1: Evaluation and Ranking Framework

The ranking criteria for Systems A through E include metrics of performance for IEQ and Energy savings. For IEQ performance, only selected aspects are considered, with differential effects across systems.

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
A	**IAQ - Indoor Air Quality**		
	Pollutants sources:		
1	External sources: fugitive dust and other air born pollutants	Avoidance of dust entering indoor spaces	Install filter to keep dust out
2	Humidity entering space from the outside (other than through windows and other constructed opening in the envelope)	Avoidance of uncontrolled entry into interstitial spaces of the building	Install effective vapor barrier and well sealing moveable windows and openings
3	Humidity from interior sources	Can cause health issues; can accumulate in building material and cause structural damages	Manage internal humidity and avoid unnecessary humidity sources
4	HVAC related - dust, dirt or microbiological growth since ductwork, on cooling coils, etc.	Humidity related micro bacterial growth can cause problems	Efficient humidity control on and inside HVAC components avoids excess humidity; remove growth
5	Internal pollutants; gaseous emissions from office equipment	Emissions can cause health problems	Efficient dilution through sufficient ventilation air flow; keep problematic office equipment out or inside a dedicated space that is separated from regularly occupied spaces

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
	Pathways		
6	Continuous ventilation by mechanical means	Ventilation is created by mechanical fans which can be in operation all the time; pollutant can be introduced continuously	Readily controlled ventilation rates ensure good dilution of indoor pollutant and transport of pollutant to the outside
7	Intermittent ventilation by natural means	Ventilation rates are generated by intermittent natural driving forces.	Cannot control intermittence ventilation
8	Extent of recirculation of indoor air	When excess air is recirculated inside space indoor pollutants can spread	Avoid excessive recirculation, add extra filters to avoid higher concentration of pollutants
9	Accidental infiltration through the envelope	Polluted air can be introduced through gaps and leaks in the building envelope	Sealing the envelope with effective barrier
10	Opportunity of shortcuts and poorly ventilated spaces	Air circulation be trapped by inefficient air renewal	Establish good and open pathways and control distribution of indoor air
B	**ITQ – Indoor Thermal Quality** (thermal comfort)		
	Control PMV comfort index:	Ability to continuously establish good PMV	
1	Control operative temperature	Control air temperature and radiant temperature to remain in targeted range	Have means to control air and radiant temperature
2	Control humidity level	Humidity level affects to some extent	Have ability to control humidity

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
3	Control Air speed	Ability to provide additional sensible cooling through increased air speed over the body	Install ceiling fans or other comfort fans if the air flow through the room is not sufficient.
4	Clothing insulation	Lighter clothing insulation enables less cooling	Promote occupants to dress in accordance to climate
5	Control local thermal discomfort	Control uniform air and radiant temperature and control floor temperature	Good ventilation and avoidance of air stratification
6	Overcooling	Avoid overcooling	Provide means to provide air in good temperature range; reheat if required
7	Add adaptive comfort where applicable	Adaptive comfort is based on occupant ability to adjust expectations of indoor thermal climate depending on external climate	Appropriate to apply in space that are naturally ventilated, or which have elements of natural ventilation
C	**Humidity control**		
1	Keep internal humidity in good range	Optimum range is between 35% and 55% to avoid health problems and mitigate humidity related problems with building materials	Control humidity sources and provide effective dehumidification
2	Energy requirements for humidity control (electric energy)	Use electric energy to operate dehumidification devices	Use of vapor compression systems and cooling coil based dehumidification
3	Using other energy sources for humidity control	Ability to use solar thermal or process (waste_ heat sources	Use of desiccant dehumidification devices
4	HVAC related problems of humidity control	Conventional humidity related problems are condensation and microbiologic growth on cold surfaces or in ducts	Control HVAC system components to avoid unwanted condensation and related health and material problems

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
D	**ILQ - Indoor Light Quality**		
1	Access to natural light - Daylighting	Humans prefer natural light	Have sufficient envelope openings to allow natural light penetration and provide an open space layout to provide sufficient indoor propagation of natural light
2	Lighting quantity and quality	Good indoor lighting is essential for occupant well-being and productivity	Select adequate lights and adjust internal layout to promote selection of good lighting
3	Glare reduction	Avoid glare through appropriate fenestration	Provide shades, light shelves to cut down on glare and direct solar gain
E	**ISQ**		
1	Controlling external noise intrusion into indoor spaces	External noises progressing into the indoor space can cause indoor discomfort	Eliminating external sound sources from intruding into the indoor space by implementing external barriers to sound
2	Controlling internal noise	Internal noise sources and propagation should be mitigated	Eliminate internal noise from equipment by minimizing noise producing equipment
3	Sound barriers	Sound source can be isolated by internal barriers	Install effective sound barriers and reduce internal reverberance time by appropriate space layout
F	**IOQ**		

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
1	Controlling external odor	Outdoor odors cause discomfort	Eliminating external odor sources from intruding into the indoor space by implementing external barriers to air movement
2	Controlling internal odor through barriers	Indoor odor sources can cause discomfort	Install effective sound barriers between spaces that have odor problems
G	**Biophilia**		
1	Provide affinity to natural environment for occupants inside spaces	Humans enjoy being surrounded by natural elements	Provide opportunities for occupants to experience natural environment
H	**Aesthetics**		
1	Creating zones that have a spatial identity	Human enjoy being inside beautiful spaces which have spatial identity	Provide access to outside view and provide a good layout for spatial identity
I	**Energy consumption**		
1	Use of electrical energy for ventilation	Mechanical systems are used to ventilate indoor spaces	Identify energy saving opportunities to save on fan power
2	Use of electrical energy for cooling	Mechanical systems are used to cool indoor spaces	Identify energy saving opportunities to save on vapor compression
3	Use of electrical energy for Dehumidification	Mechanical systems are used to dehumidify indoor spaces	Identify energy saving opportunities to save on cooling coil dehumidification

Table 4.1.1: List of aspects used in ranking IEQ and energy saving performance of Systems A through E.

No.	Description	Properties and problems	Mitigation or Implementation
4	Use of renewable (solar) energy	Ability to use renewable (solar) energy reduces the demand for electric energy and reduces carbon footprint	Use regeneration of liquid desiccants using solar or waste heat sources
5	Energy savings from adaptive thermal comfort	Under the adaptive comfort model occupants adjust their behavior, including clothing, to the external climate conditions	Use naturally ventilated space to promote adaptive comfort experiences
6	Thermal energy storage	Ability to store thermal energy for off-solar exposure hours of operation	Use either liquid desiccant or hot water storage
7	Ability to save lighting energy through daylighting	Ability to use natural light sources to a large extent	Provide open building envelope to admit natural lighting, without incurring excess solar heat gain and annoying glare

4.2 Selecting Ranking Criteria and Ranking of Individual Criteria

The final ranking criteria are selected from the larger pool of applicable aspects presented in Table 4.1.1. The specific ranking statements for the criteria and the level to which the Systems A through F comply to the intent of the specific ranking statement of each criterion are listed in Table 4.1.2. The following discrete weights are assigned to the level at which the Systems A through F comply to the ranking statements.

Level of compliance to ranking statement	Identifier	Percentage assigned in ranking
Ranking statement of criterion of **not satisfied at all**	**1**	0%
Ranking statement of criterion is a **somewhat below average satisfied**	**2**	25%
Ranking statement of criterion is **on average satisfied**	**3**	50%
Ranking statement of criterion is **somewhat above average satisfied**	**4**	75%
Ranking statement of criterion is **fully satisfied**	**5**	100%

Table 4.2.1: Ranking criteria definition and ranking of Systems A through F

No.	Ranking statement of ranking criterion	ranking weight for criterion category	System A Pure natural ventilation	System B Nat. Ventilation with internal fans	System C Mechnical ventilation (ducted)	System D Full conventional HVAC	System E Proposed hybrid system
A	**IAQ**						
a	Ability to minimize intrusion of external pollutants	15%	**1**	**1**	**3**	**4**	**4**
b	Ability to prevent humidity intrusion through the envelope	10%	**2**	**2**	**3**	**3**	**4**
c	Ability to control favorable humidity inside the indoor spaces and avoid dampness	25%	**3**	**3**	**2**	**4**	**5**
d	Ability to prevent HVAC related IAQ problems (microbiological growth)	15%	**5**	**5**	**3**	**2**	**4**
e	Ability to guarantee continuous ventilation	15%	**3**	**3**	**5**	**5**	**5**
f	Ability to lower recirculation of internal air and avoid repollution	10%	**4**	**4**	**3**	**3**	**3**
g	Ability to avoid accidental infiltration through the envelope	10%	**2**	**2**	**3**	**3**	**4**
	sum of ranking for criterion category >>	100%	**48%**	**48%**	**51%**	**64%**	**83%**

Table 4.2.1: Ranking criteria definition and ranking of Systems A through F

No.	Ranking statement of ranking criterion	ranking weight for criterion category	System A Pure natural ventilation	System B Nat. Ventilation with internal fans	System C Mechnical ventilation (ducted)	System D Full conventional HVAC	System E Proposed hybrid system
B	**ITQ** *Ability to continuously provide favorable PMV:*						
a	Ability to control operative temperature	25%	**1**	**1**	**2**	**5**	**5**
b	Ability to use air speed for temperature adjustment	20%	**1**	**5**	**2**	**1**	**4**
c	Ability to promote favorable clothing insulation	10%	**4**	**4**	**3**	**2**	**3**
d	Ability to avoid local discomfort through stratification and cold floors	10%	**2**	**2**	**3**	**3**	**4**
e	Ability to avoid overcooling	20%	**5**	**5**	**4**	**1**	**5**
f	Ability to use adaptive comfort experience	15%	**4**	**4**	**3**	**2**	**3**
	sum of ranking for criterion category >>	100%	**41%**	**61%**	**44%**	**36%**	**80%**
C	**Humidity control**						
a	Ability to keep optimum internal humidity in good range	100%	**1**	**1**	**1**	**3**	**5**
	sum of ranking for criterion category >>	100%	**0%**	**0%**	**0%**	**50%**	**100%**
D	**ILQ**						
a	Ease to implement natural light - daylighting	65%	**4**	**4**	**3**	**2**	**4**
b	Ability to reduce glare through solar gain	35%	**3**	**3**	**2**	**2**	**4**
	sum of ranking for criterion category >>	100%	**66%**	**66%**	**41%**	**25%**	**75%**
E	**ISQ**						
a	Ability to keep external noise out	35%	**1**	**1**	**4**	**4**	**4**
b	Ability to reduce internal noise from equipment	35%	**4**	**3**	**2**	**2**	**3**
c	Ease to install internal sound barriers	30%	**2**	**2**	**3**	**4**	**4**
	sum of ranking for criterion category >>	100%	**34%**	**25%**	**50%**	**58%**	**66%**
F	**IOQ**						
a	Ability to avoid intrusion of external odor	45%	**1**	**1**	**3**	**2**	**4**
b	Ability to limit distribution of odor through barriers	55%	**2**	**2**	**3**	**3**	**4**
	sum	100%	**14%**	**14%**	**50%**	**39%**	**75%**

Table 4.2.1: Ranking criteria definition and ranking of Systems A through F

No.	Ranking statement of ranking criterion	ranking weight for criterion category	System A Pure natural ventilation	System B Nat. Ventilation with internal fans	System C Mechnical ventilation (ducted)	System D Full conventional HVAC	System E Proposed hybrid system
G	**Biophilia & Aesthetics**						
a	Ability to provide affinity to natural environment	70%	**4**	**4**	**3**	**2**	**4**
b	Ability to creating zones that have a spatial identity through outside view and internal layout	30%	**4**	**4**	**2**	**2**	**3**
	sum of ranking for criterion category >>	100%	**75%**	**75%**	**43%**	**25%**	**68%**
H	**Energy saving potential** (relative to conventional HVAC)						
a	Ability to save electrical energy for ventilation	30%	**5**	**5**	**3**	**1**	**3**
b	Ability to save electrical energy for cooling	35%	**5**	**5**	**5**	**1**	**3**
c	Ability to save electrical energy for Dehumidification	35%	**5**	**5**	**5**	**1**	**5**
	sum of ranking for criterion category >>	100%	**100%**	**100%**	**85%**	**0%**	**68%**
I	**Energy saving support functions**						
a	Ability to use of renewable or recyclable thermal energy	40%	**1**	**1**	**1**	**2**	**5**
b	Energy savings from adaptive thermal comfort	10%	**4**	**4**	**4**	**2**	**4**
c	Ease of using thermal energy storage	25%	**1**	**1**	**1**	**1**	**5**
d	Ability to save artificial light	25%	**4**	**4**	**3**	**3**	**3**
	sum of ranking for criterion category >>	100%	**26%**	**26%**	**20%**	**25%**	**85%**

Table 4.2.2 shows the summary of the ranking scores for the criteria. These results will be used in determining the overall results in the following sections.

Table 4.2.2: Summary of the ranking scores for the criteria

Criteria groups		**System A** *Only natural ventilation*	**System B** *Nat. Ventilation with internal fans*	**System C** *Mechnical ventilation (ducted)*	**System D** *Full conventional HVAC*	**System E** *Proposed hybrid system*
IAQ	*Indoor Air Quality*	48%	48%	51%	64%	83%
ITQ	*Indoor Thermal Quality*	41%	61%	44%	36%	80%
Humidity control		0%	0%	0%	50%	100%
ILQ	*Indoor Lighting Quality*	66%	66%	41%	25%	75%
ISQ	*Indoor SoundQuality*	34%	25%	50%	58%	66%
IOQ	*Indoor Odor Quality*	14%	14%	50%	39%	75%
Biophilia & Aesthetics		75%	75%	43%	25%	68%
Energy saving potential (relative to conv. HVAC)		100%	100%	85%	0%	68%
Energy saving support functions		26%	26%	20%	25%	85%

4.3 Assessing Ranking Scores for Criterion Categories

The overall ranking score was determined by creating ranking categories and assigning relative weights. Figure 4.3.1 Illustrates how four criterion categories are composed. These four categories and weights were used for determining the final score. Table 4.3.1 and Figures 4.3.1 through 4.3.10 show the results of the ranking across the four criterion categories.

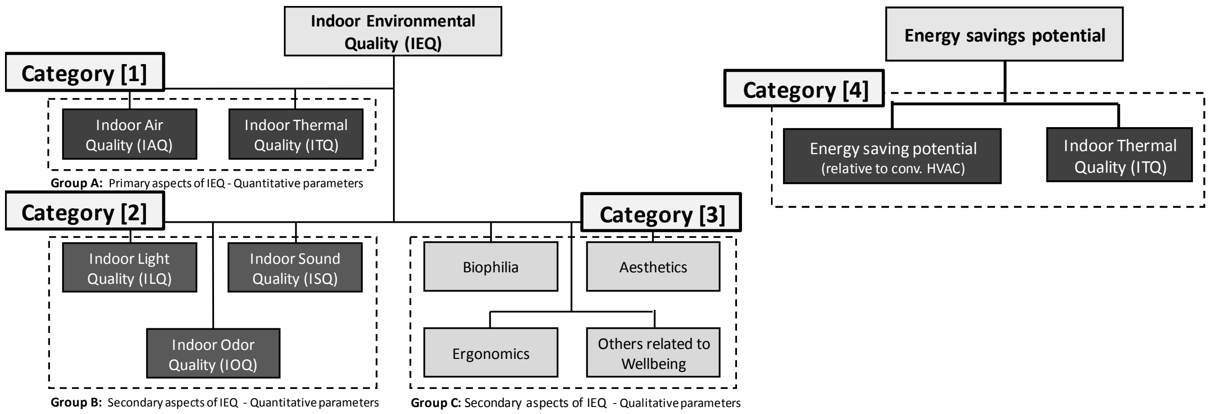


Figure 4.3.1: Four criterion categories

Table 4.3.1: Results of ranking of four criterion categories

	overall weights	System A	System B	System C	System D	System E
		Only natural ventilation	*Nat. Ventilation with internal fans*	*Mechnical ventilation (ducted)*	*Full conventional HVAC*	*Proposed hybrid system*
[1] Group A: Primary aspects of IEQ - Quantitative parameters						
IAQ Indoor Air Quality	*30%*	14%	14%	15%	19%	25%
ITQ Indoor Thermal Quality	*30%*	12%	18%	13%	11%	24%
Humidity control	*40%*	0%	0%	0%	20%	40%
Sum	*100%*	**27%**	**33%**	**29%**	**50%**	**89%**
[2] Group B: Secondary aspects of IEQ - Quantitative parameters						
ILQ Indoor Lighting Quality	*35%*	23%	23%	14%	9%	26%
ISQ Indoor SoundQuality	*35%*	12%	9%	18%	20%	23%
IOQ Indoor Odor Quality	*30%*	4%	4%	15%	12%	23%
Sum	*100%*	**39%**	**36%**	**47%**	**41%**	**72%**
[3] Group C: Secondary aspects of IEQ - Qualitative parameters						
Biophilia & Aesthetics	*100%*	**75%**	**75%**	**43%**	**25%**	**68%**
[4] Energy savings potential:						
Energy saving potential (relative)	*70%*	70%	70%	60%	0%	47%
Energy saving support functions	*30%*	8%	8%	6%	8%	26%
Sum	*100%*	**78%**	**78%**	**66%**	**8%**	**73%**

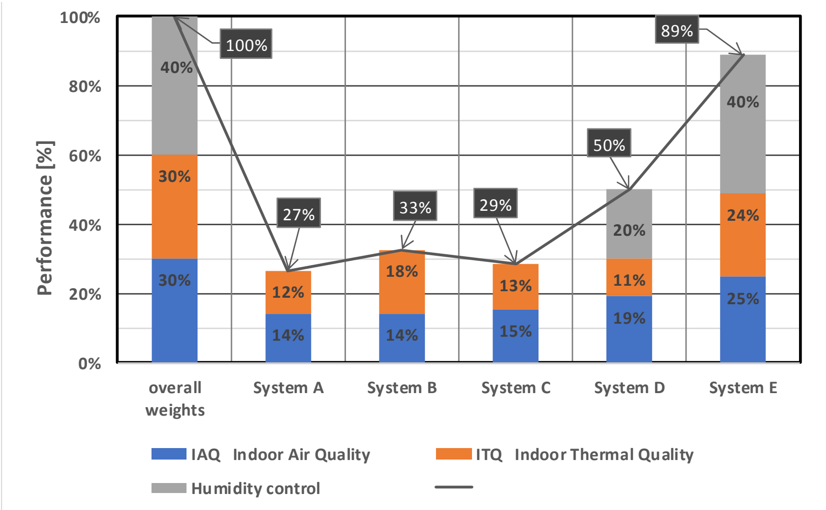


Figure 4.3.1:
Ranking scores for Group A:
Primary aspects of IEQ - Quantitative parameters

Refer to group [1]

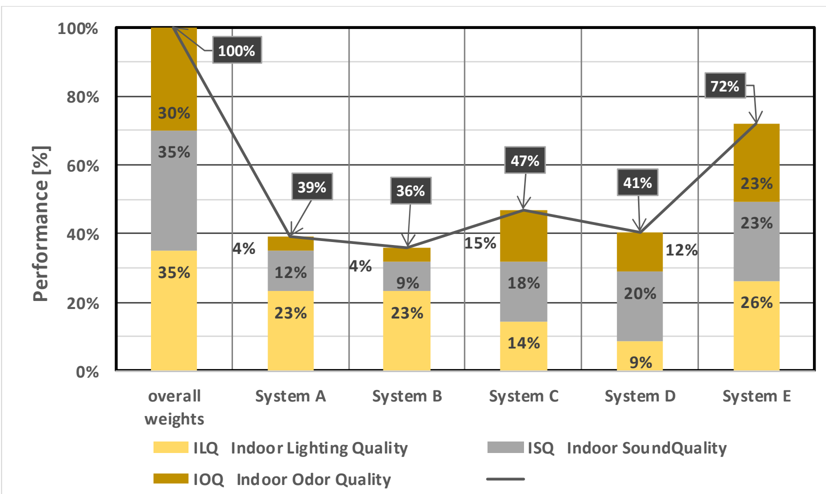


Figure 4.3.2:
Ranking scores for Group B:
Secondary aspects of IEQ - Quantitative parameters

Refer to group [2]

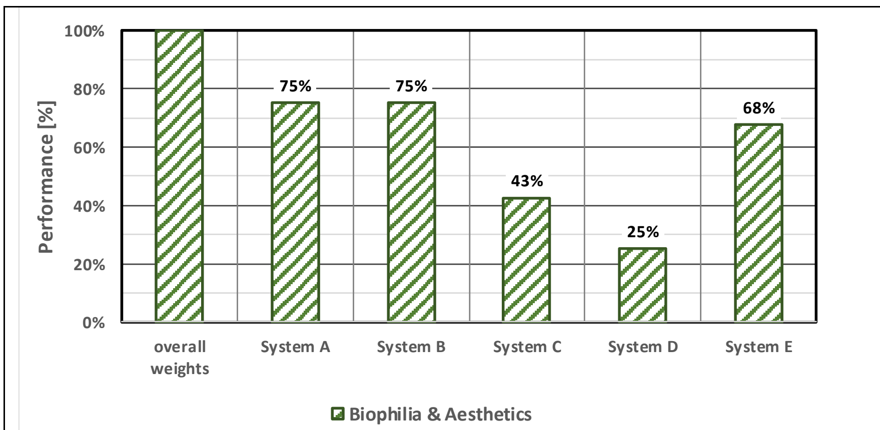


Figure 4.3.3:
Ranking scores for Group C:
Secondary aspects of IEQ - Qualitative parameters

Refer to group [3]

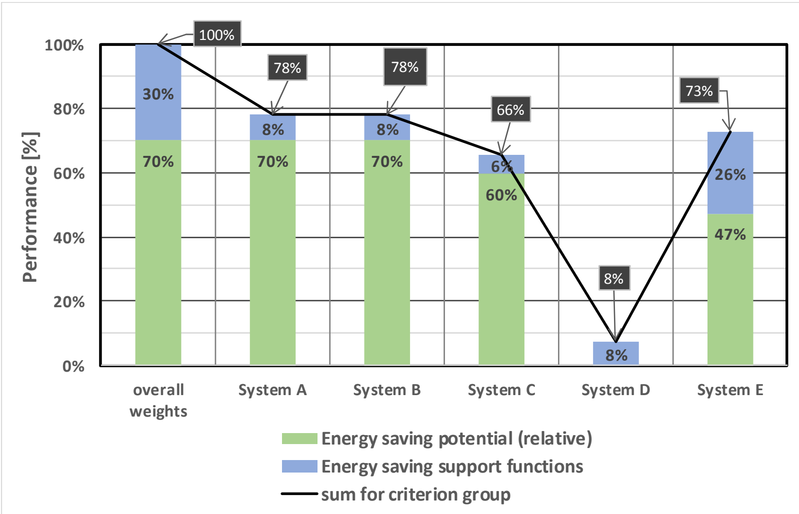


Figure 4.3.4:
Ranking scores for Energy savings potential

Refer to group [4]

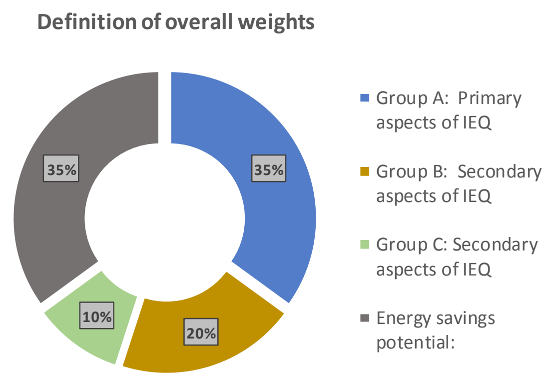


Figure 4.3.5: Basis for ranking weight

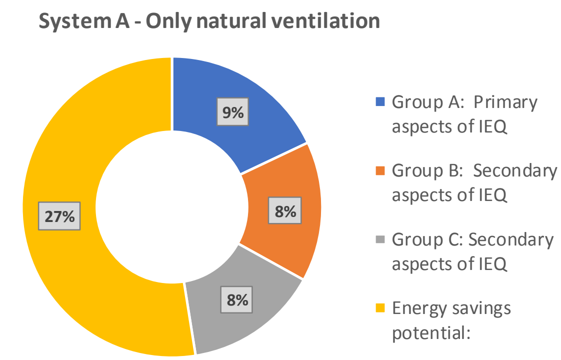


Figure 4.3.6: Ranking for System A

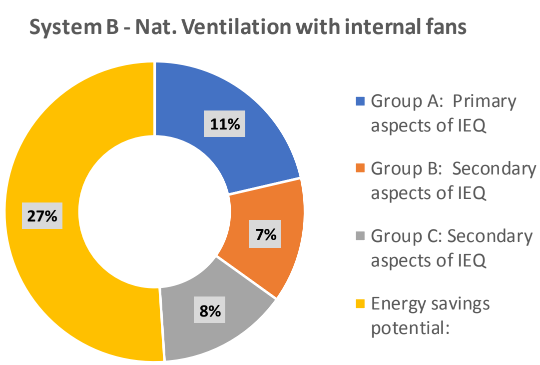


Figure 4.3.7: Ranking for System B

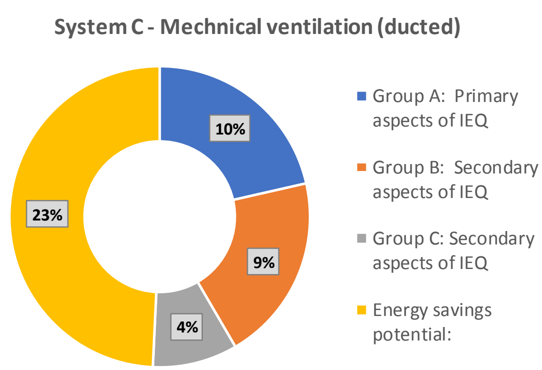


Figure 4.3.8: Ranking for System C

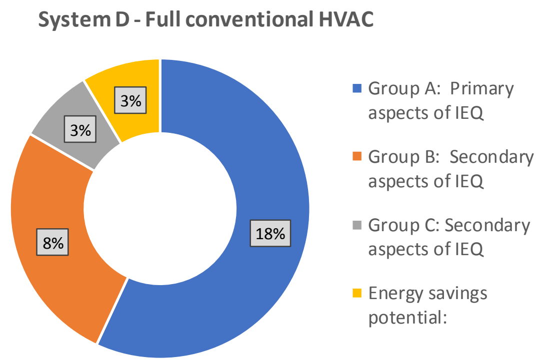


Figure 4.3.9: Ranking for System D

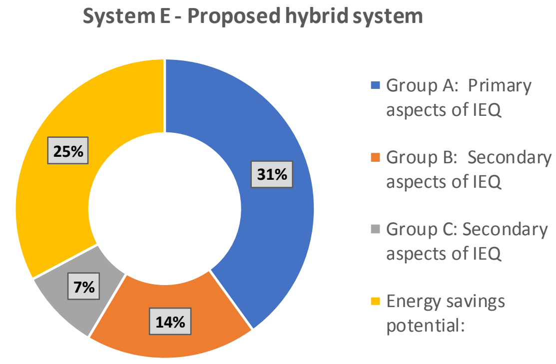


Figure 4.3.10: Ranking for System E

4.4 Assessing Overall Ranking Scores for Systems A Through E

The ranking score for the criterion categories are weighted and used to determine the overall ranking score for Systems A through E. Table 4.4.1 and Figures 4.4.1 and 4.4.2 show the overall ranking scores.

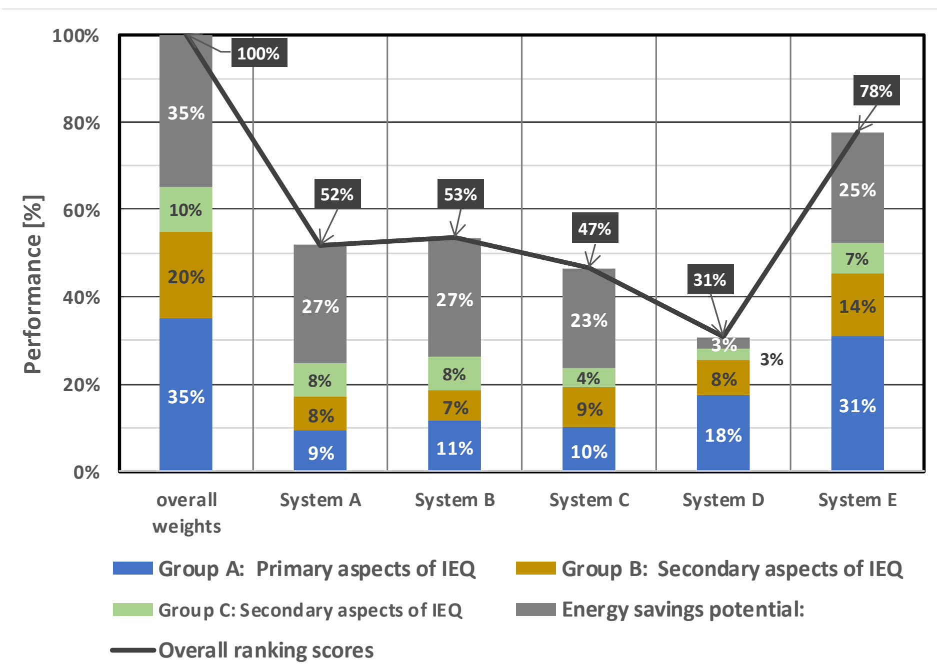


Figure 4.4.1: Overall ranking scores of System A through E

Table 4.4.1: Overall ranking scores of System A through E

	overall weights	System A *Only natural ventilation*	System B *Nat. Ventilation with internal fans*	System C *Mechnical ventilation (ducted)*	System D *Full conventional HVAC*	System E *Proposed hybrid system*
Overall results per category [1] through [4]						
[1] Group A: Primary aspects of IEQ	*35%*	9%	11%	10%	18%	31%
[2] Group B: Secondary aspects of IEQ	*20%*	8%	7%	9%	8%	14%
[3] Group C: Secondary aspects of IEQ	*10%*	8%	8%	4%	3%	7%
[4] Energy savings potential:	*35%*	27%	27%	23%	3%	25%
Sum	*100%*	**52%**	**53%**	**47%**	**31%**	**78%**
Rank of Alternatives >>>		**3**	**2**	**4**	**5**	**1**

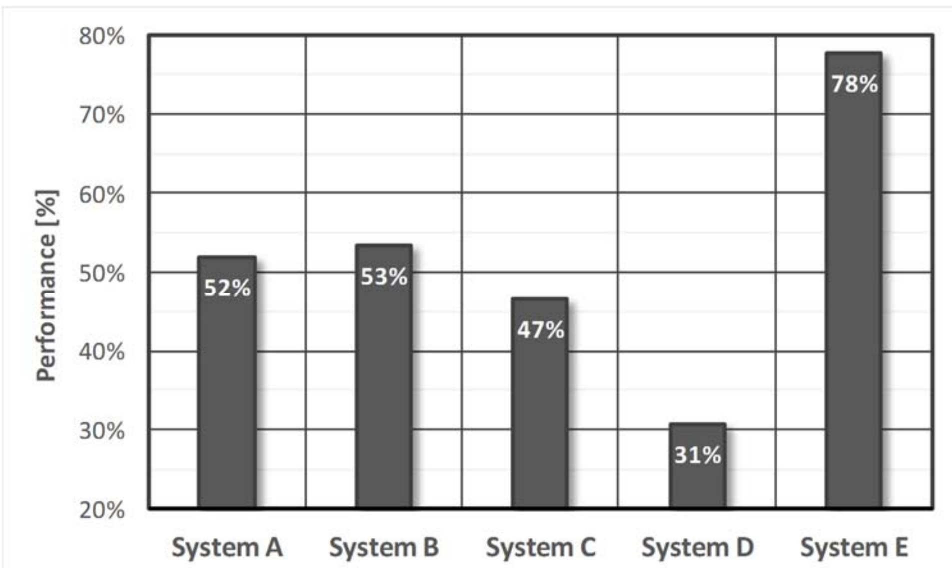


Figure 4.4.2: Overall ranking scores of System A through E

4.5 Sensitivity Analysis of Overall Ranking for Energy

The overall scores of Systems A through E is dependent on the ranking weights of numerous parameters. In this sensitivity analysis only the quantity expressing the importance of the energy savings potential to the overall scores is varied, to determine the overall score as a function of what importance energy savings are attributed. The sum of categories [1] through [4] remains always 100%. When the contribution of the energy savings potential (Category [4]) is varied between 0% and 100%, the other categories [1] through [3] are also varied to keep the sum equal to 100%. While categories [1] through [3] retain their relative percentages, as defined in Table 4.4.1, their sum attains the value 100% minus x % of category [4]. Figure 4.5.1 and Table 4.5.1 show the correlation of the resulting overall scores for System A through F to the applied contribution of the energy savings.

Table 4.5.1: Relationship between the importance of energy savings potential to ranking weights to overall ranking score

	Overall ranking scores				
Percentage of energy for overall ranking	System A	System B	System C	System D	System E
0%	38%	40%	36%	43%	80%
10%	42%	44%	39%	40%	80%
20%	46%	48%	42%	36%	79%
30%	50%	52%	45%	33%	78%
40%	54%	55%	48%	29%	77%
50%	58%	59%	51%	25%	77%
60%	62%	63%	54%	22%	76%
70%	66%	67%	57%	18%	75%
80%	70%	70%	60%	15%	74%
90%	74%	74%	63%	11%	74%
100%	78%	78%	66%	8%	73%

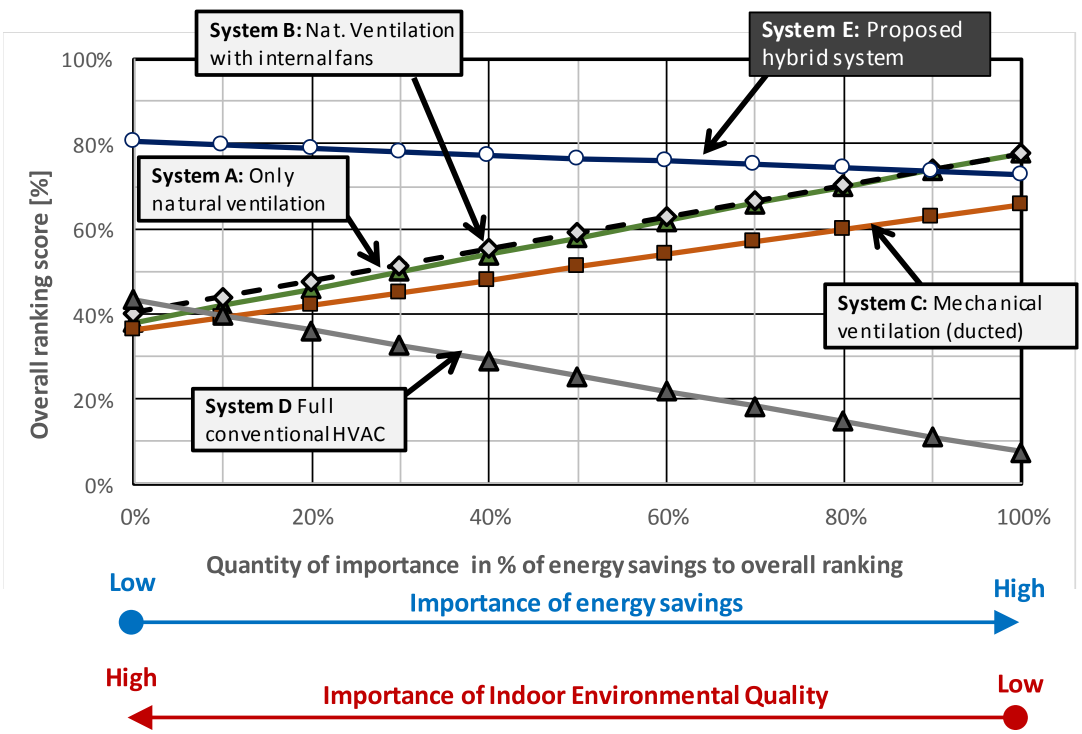


Figure 4.5.1: Relationship between the contribution of energy savings potential to ranking weights to overall ranking score

From the overall score the absolute ranks for Systems A through E are determined. The results are presented in Figure 4.5.2.

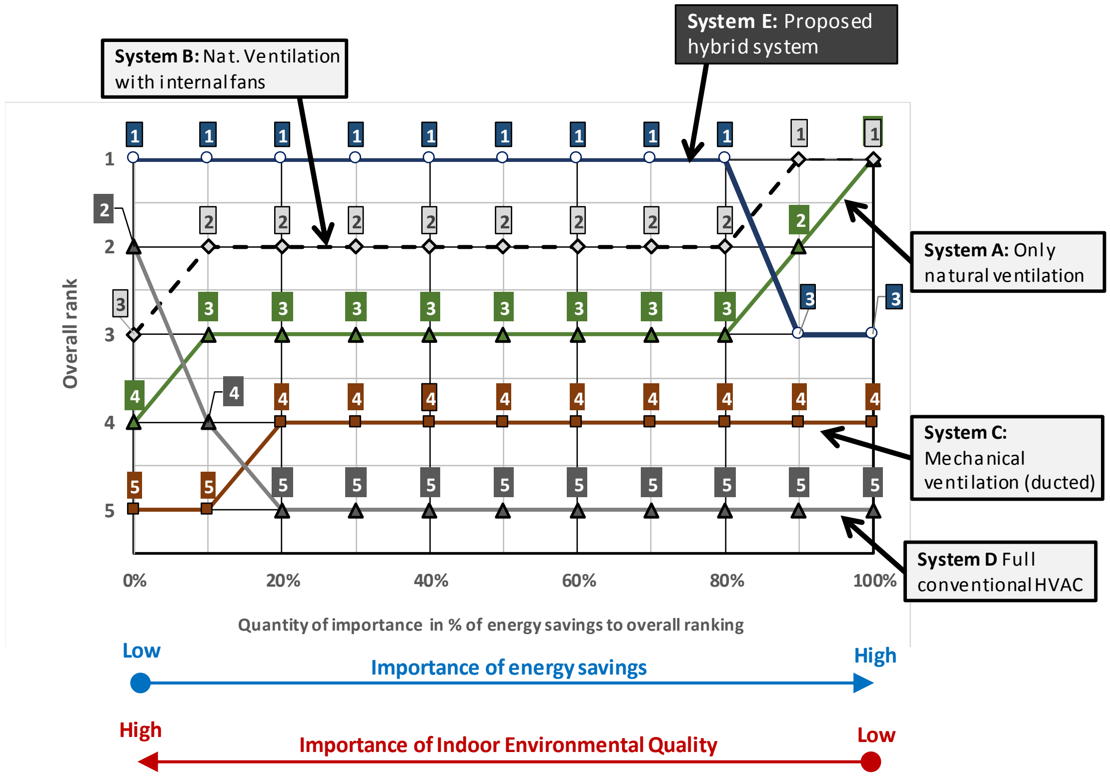


Figure 4.5.1: Relationship between the contribution of energy savings potential to ranking weights to overall ranks of Systems A through E

Discussion: The overall scores and ranks of Systems A and B differ little, because both represent naturally ventilated spaces, except that System B has uses internal fans which consume electric energy. The increased air speed from the fans provide additional cooling capacity for the occupants, which increases the IEQ for System B. The overall score of System C follows the trends of Systems A and B, but the overall score deviates at higher values because of the electric demand for the ventilation fans.

The Final score of System D, which represents full conventional HVAC, decreases as the importance of energy savings increases.

The Final score of System E, the proposed hybrid system, shows a high overall score over the entire range of contribution of energy, only to take third behind Systems A and B, at the highest values of importance of energy savings, e.g. at ()5 and 100%. **This relationship highlights the good performance of the proposed system over the entire range of values.**

SECTION 5 – INDOOR ENVIRONMENTAL REQUIREMENTS FOR SCHOOLS

One of the main application of the proposed hybrid space conditioning with a liquid desiccant dehumidification unit is for schools. Schools have a high requirement for high indoor environmental quality since children and young adults have a higher susceptibility to problems arising from unhealthy indoor conditions.

This section provides a summary of basic requirements for a high-quality learning environment. This section is based on a large part on the findings and recommendations of the Committee to Review and Assess the Health and Productivity Benefits of Green Schools, National Research Council ("NRC Committee"). The NRC committee released its report "Green Schools" in 2006. It should be noted that reference to "schools" in the following discussion conveys the Committee's emphasis on "green schools", those schools with environmentally responsible goals, and increased attention to environmental conditions that support healthy and positive learning experience. In fact, all schools should have attributes such as described for "green schools".

The NRC Committee identified good indoor environments which support the health and development (physical, social, intellectual) of students, teachers, and staff) provide healthy, safe, comfortable indoor conditions and fostering a positive environment and community. The goal of schools should be minimizing adverse environmental effects and supporting human health and development. Figure 5.1 illustrates the preferred working model to achieve the goals for environments that support the health and development in schools.

The NRC Committee identified a conducive indoor environment with appropriate levels of moisture, ventilation, air quality, noise, lighting, and other qualities. It also assumes that the indoor environment should be modified by season (e.g., presence of external pollutions such as airborne pollen), over time (e.g., mold growth from chronic water leakage), and by operational, maintenance, repair, and cleaning practices. The committee concluded that the indoor environment can significantly affect student learning and health and teacher health and productivity.

The NRC Committee's (NRC, 2006) general findings were as follows:

- Dryness: Excessive moisture, which has been associated with adverse health effects, particularly asthma and respiratory diseases, must be avoided.
- Good indoor air quality and thermal comfort: Ventilation rates, air pollutants, humidity levels, and temperature ranges, which have been linked to human health, learning, and productivity, should be effectively controlled.
- Quietness: The acoustical quality, which has been shown to affect student learning and the development of language skills, should meet the newly released Standard 12.60, "Acoustical Performance Criteria, Design Requirements, and Guidelines for Schools," of the American National Standards Institute.

- Well-maintained systems: Building systems should be commissioned to ensure that they perform as intended, and their performance is monitored over time. Routine preventive maintenance should be implemented throughout a school's service life.
- Cleanliness: Surfaces should be disinfected to interrupt the transmission of infectious diseases, and measures are implemented to help control indoor pollutants that have

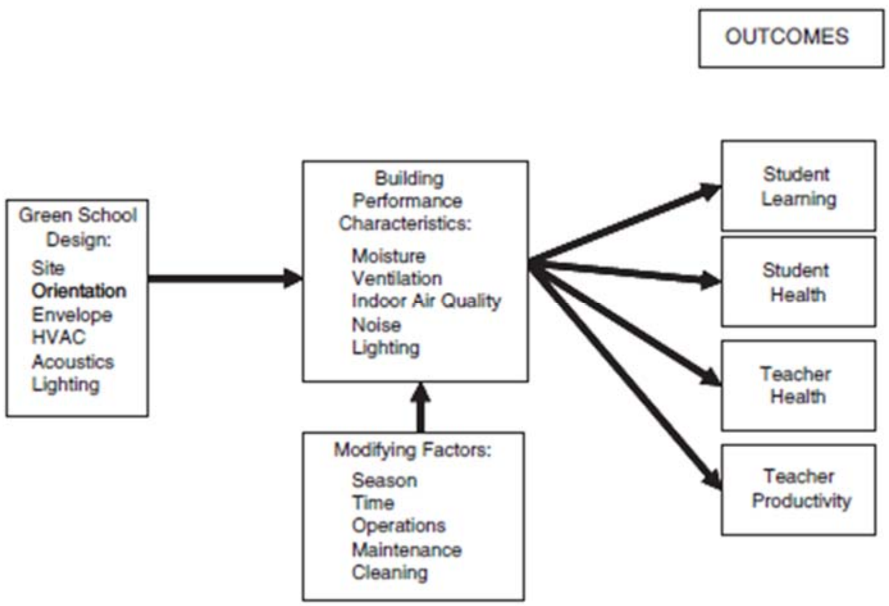


Figure 5.1: Working model to achieve the goals for environments that support the health and development in schools

(NRC, 2006)

The discussion in this report is concerned about performance issues of space conditioning systems. The following findings and recommendations of the NRC Committee about space condition, which can affect the performance of schools have been selected as providing good guidance:

Building Envelope, Moisture Management, and Health

- The Committee quotes ample evidence indicating that there is a strong relationship between excess moisture, dampness, and mold in buildings and adverse health outcomes, particularly asthma and respiratory symptoms, among children and adults.
- Excess moisture in buildings can cause structural damage, degraded performance of building systems and components. This can result in increased maintenance and repair costs.
- School guidelines should emphasize the control of excess moisture, dampness, and mold to protect the health of children and adults in schools and to protect a building's structural integrity. Such guidelines should specifically address moisture control as it relates to the design, construction, operation, and maintenance of a school building's envelope (foundations, walls, windows, and roofs) and related items such as siting and landscaping.

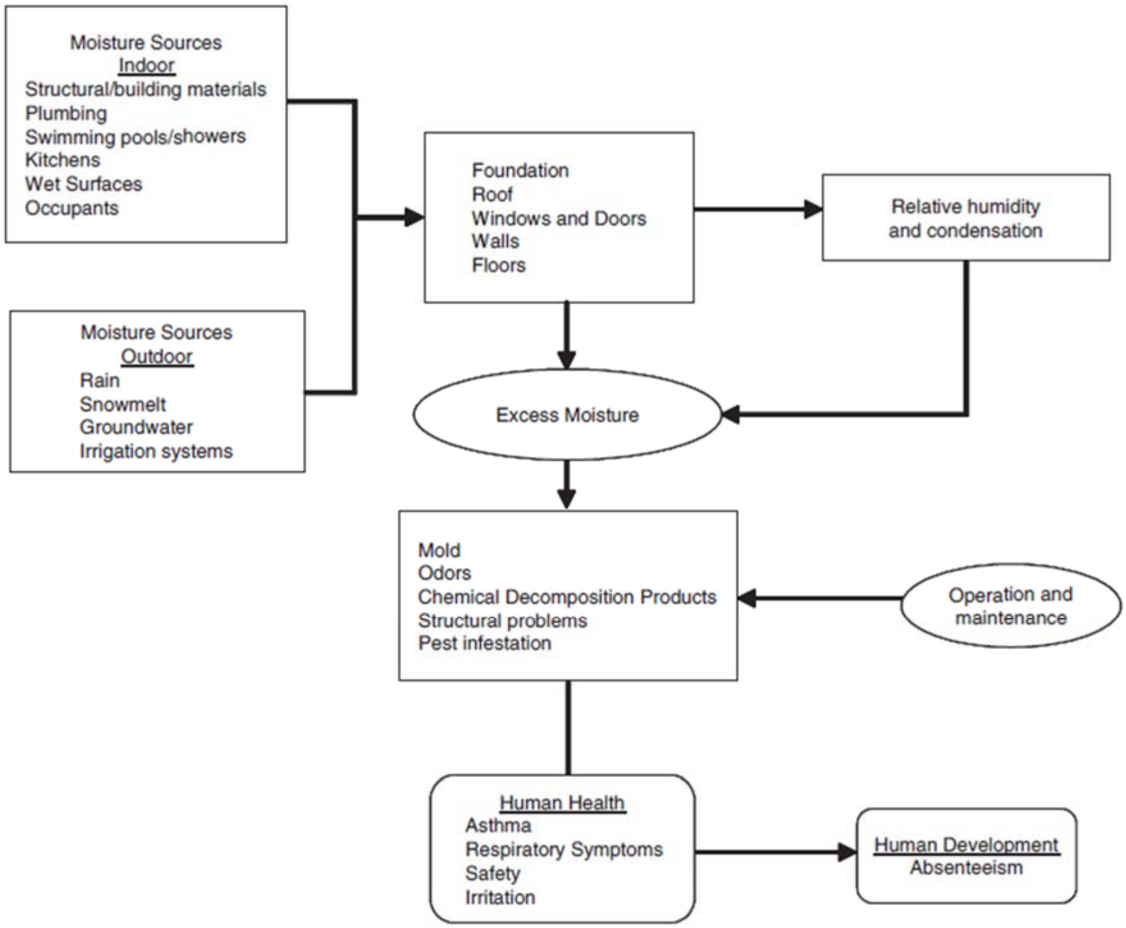


Figure 5.2: Conceptual model of excess moisture and its potential impacts on students, teachers, and support staff. (NRC, 2006)

Indoor Air Quality

- The Committee quotes evidence indicates that the health of children and adults can be affected by indoor air quality and that teacher productivity and student learning may also be affected by indoor air quality.
- Good indoor air quality requires sufficient ventilation rates and effectiveness, filter efficiency, the control of temperature, humidity, and excess moisture; and operations, maintenance, and cleaning practices. Future school guidelines should select ventilation systems that can be easily adapted to meet evolving standards for ventilation rates, temperature, and humidity control. In selecting space conditioning systems ventilation rates that exceed the current ASHRAE standard should be considered.

- Indoor air pollutants and allergens from mold can contribute to increased respiratory and asthma symptoms among children and adults.
- A reduction of pollutant loads through increased ventilation and effective filtration has been shown to reduce the occurrence of building-associated symptoms (eye, nose, and throat irritations; headaches; fatigue; difficulty breathing; itching; and dry, irritated skin) and to improve the health and comfort of building occupants.
- The is no conclusive evidence that natural ventilation has a better effect on human health than mechanical ventilation is. Improper design, maintenance, and operation of mechanical ventilation systems can, however, contribute to adverse health effects, including building related symptoms among occupants.
- School guidelines should emphasize the importance of appropriate operation and preventive maintenance practices for ventilation systems, including replacing filters, cleaning coils and drip pans to prevent them from becoming a source of air pollution, microbial contamination, and mold growth.

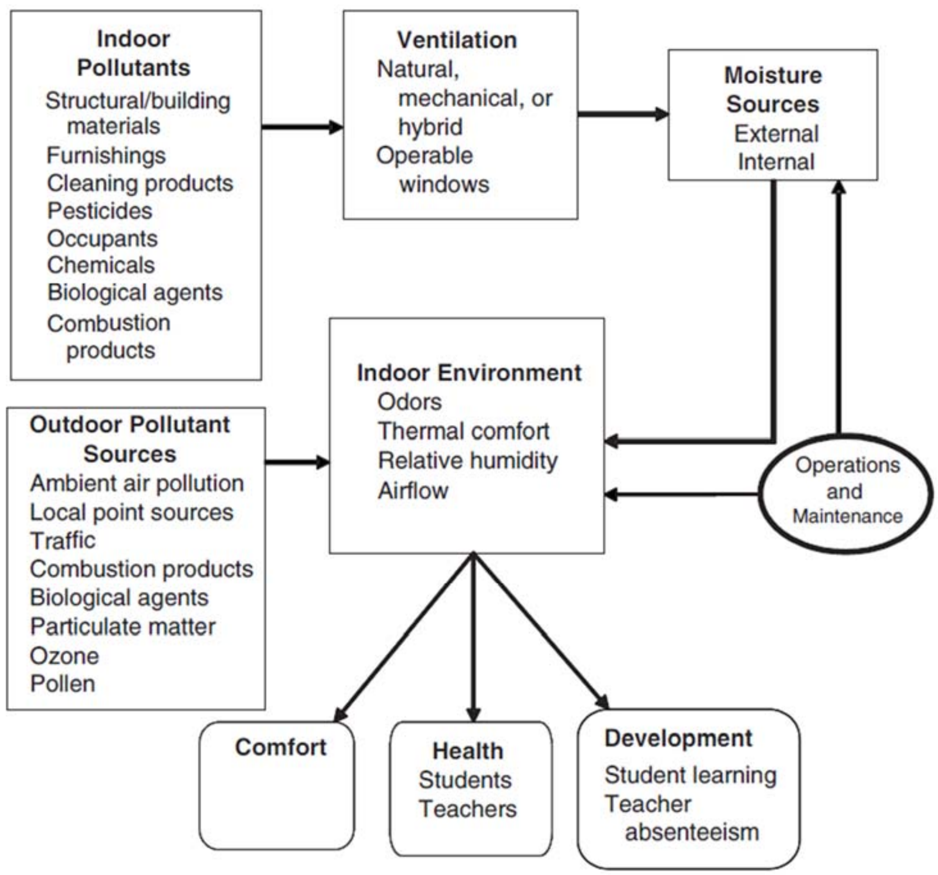


Figure 5.3: Relationships between pollutants, moisture, and ventilation and human comfort, health, and development (NRC, 2006)

Lighting

- The Committee suggested that schools focus on energy efficient lighting technologies and components and the use of daylight to further conserve energy when addressing lighting requirements. But guidance for lighting design that supports the visual performance of children and adults, based on task, school room configurations, layout, and surface finishes, is not provided.
- Daylighting should supplement electric light sources, providing high light levels, and good color rendering. Light from these sources is ever-changing and can cause glare unless appropriately managed. Currently, there is insufficient scientific evidence to determine whether or not an association exists between daylight and student achievement.
- School selection of electric lighting systems should conform to the latest published engineering practices (e.g. Illuminating Engineering Society of North America).
- School, when choosing to extensively use of daylight, should address electric control systems and specify easily operated manual blinds or other types of window treatments to control excessive sunlight or glare.

Acoustical Quality

- The Committee suggested that learning activities in school classrooms involve speaking and listening as the primary communication modes. The ability to hear speech in classrooms is related to the levels of speech sounds relative to the levels of ambient noise and to the amount of reverberation in a room. Excessive noise levels in schools can diminish student learning and is a more significant problem than too much reverberation in a classroom.
- Excessive noise has a more harmful on younger students than for adults, because the ability to focus on speech sound is a developmental skill that does not mature until about the ages of 13 to 15 years. Thus, younger children require quieter and less reverberant conditions than do adults to hear equally well. As adults, teachers may not appreciate the additional problems that excessive noise creates for younger students.
- School should require the appropriate design of HVAC systems, the design of walls and doors separating classrooms and corridors, and the acoustic quality of windows and walls adjoining the outdoors.

Thermal comfort

- The Committee suggested that thermal comfort standards such as ASHRAE 55 are based on investigations on the effects of temperature and humidity on occupant comfort and productivity for office buildings and not for schools. Furthermore, these standards are based on experimental studies of adults, not children. Therefore, established guidelines need to be adjusted for schools

- New "adaptive" models of thermal comfort have not been incorporated into current standards used for the design of mechanical ventilation systems for schools. The metabolic rates of students vary across a school day as they engage in recess or lunch and move between rooms.
- HVAC system design focuses almost exclusively on the thermal and humidity specifications as directed by building codes. Distribution of air diffusers is assumed to satisfy other requirements for air movement and prevention of thermal stratifications. Radiant heat gains and losses at a scale relevant to actual classroom utilization are not considered. Internal mixing, air velocities, and vertical temperature gradients are rarely explicit design considerations and are rarely assessed.
- Schools often have a higher occupancy density than office buildings. For these reasons and others, there is no assurance that school thermal conditions that meet current industry standards are optimal for student comfort or performance.

SECTION 6 – PREPARING VISITS TO REPRESENTATIVE SITES

This section presents efforts which were taken by the project team to engage stakeholders of educational facilities that were considered candidate locations for the installation of a pilot liquid desiccant dehumidification unit for space conditioning.

6.1 Engaging Stakeholders in the Educational Field

A main initial objective of the project was to inform decision makers at the Hawaii Department of Education about advantages of a new HVAC approach that separates latent and sensible loads. The proposed HVAC technology to achieve separation of latent and sensible loads will use liquid desiccant technology to provide precise humidity control and increase indoor environmental quality. Since the liquid desiccant system can utilize solar heat, instead of relying solely on electrical energy as conventional HVAC, the proposed innovative HVAC technology fully supports Hawaii's goals of increased use of renewable energy. Three informational pamphlets, Pamphlets A through C, were developed by the project team to introduce the proposed technology to DoE stakeholders.

6.2 Informational Pamphlet A

Header: Introducing a State-of-the-art AC technology for Hawaii's Schools which provides high-quality indoor comfort conditions while saving significant energy

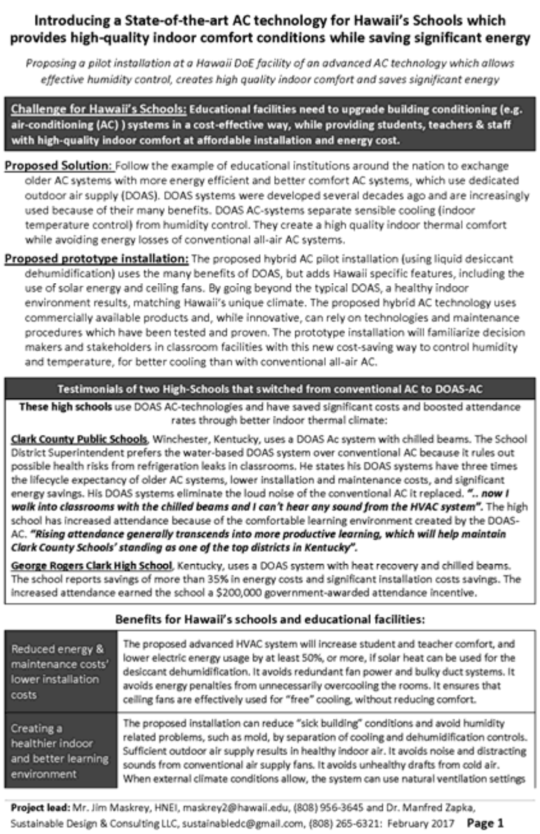
Sub header: Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control, creates high quality indoor comfort and saves significant energy

Figure 6.2.1 through 6.2.5 shows the five pages of Pamphlet A. The figures show reduced sizes of the pages while the full-size pages of Pamphlet A are presented in Appendix A. The Figures are accompanied with short summaries of the topics presented on the pages.

Synopsis of page 1 of Pamphlet A:

- Challenge for Hawaii's Schools: Educational facilities need to upgrade building conditioning (e.g. air-conditioning (AC) systems in a cost-effective way, while providing students, teachers & staff with high-quality indoor comfort at affordable installation and energy cost.
- Proposed Solution: It is proposed to install a pilot system of a liquid desiccant unit in a suitable space at a DoE facility. The proposed hybrid AC pilot installation (using liquid desiccant dehumidification) will provide a high quality indoor thermal comfort while avoiding energy losses of conventional all-air AC systems. The basic process of the hybrid AC pilot system has already been installed at schools on the US-mainland. The proposed pilot installation will adapt successful advanced HVAC system to Hawaii specific climate conditions.
- Benefits for Hawaii's schools and educational facilities:
    - Reduced energy & maintenance costs lower installation costs: The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification. The proposed system

avoids redundant power and bulky duct systems. It avoids energy penalties from unnecessarily overcooling the rooms. It ensures that ceiling fans are effectively used for “free” cooling, without reducing comfort.
  - Creating a healthier indoor and better learning environment: The proposed installation can reduce “sick building” conditions and avoid humidity related problems, such as mold, by separation of cooling and dehumidification controls. Sufficient outdoor air supply results in healthy indoor air. It avoids noise and distracting sounds from conventional air supply fans. It avoids unhealthy drafts from cold air. When external climate conditions allow, the system can use natural ventilation settings
- Testimonials of two mainland High-Schools that switched from conventional AC to DOAS-AC: (1) The high school has increased attendance because of the comfortable learning environment created by the DOAS-AC. (2) The school reports savings of more than 35% in energy costs and significant installation costs savings. The increased attendance earned the school a $200,000 government-awarded attendance incentive.



Introducing a State-of-the-art AC technology for Hawaii’s Schools which provides high-quality indoor comfort conditions while saving significant energy

Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control, creates high quality indoor comfort and saves significant energy

Challenge for Hawaii’s Schools: Educational facilities need to upgrade building conditioning (e.g. air-conditioning (AC)) systems in a cost-effective way, while providing students, teachers & staff with high-quality indoor comfort at affordable installation and energy cost.

Proposed Solution: Follow the example of educational institutions around the nation to exchange older AC systems with more energy efficient and better comfort AC systems, which use dedicated outdoor air supply (DOAS). DOAS systems were developed several decades ago and are increasingly used because of their many benefits. DOAS AC-systems separate sensible cooling (indoor temperature control) from humidity control. They create a high quality indoor thermal comfort while avoiding energy losses of conventional all-air AC systems.

Proposed prototype installation: The proposed hybrid AC pilot installation (using liquid desiccant dehumidification) uses the many benefits of DOAS, but adds Hawaii specific features, including the use of solar energy and ceiling fans. By going beyond the typical DOAS, a healthy indoor environment results, matching Hawaii’s unique climate. The proposed hybrid AC technology uses commercially available products and, while innovative, can rely on technologies and maintenance procedures which have been tested and proven. The prototype installation will familiarize decision makers and stakeholders in classroom facilities with this new cost-saving way to control humidity and temperature, for better cooling than with conventional all-air AC.

Testimonials of two High-Schools that switched from conventional AC to DOAS-AC

These high schools use DOAS AC-technologies and have saved significant costs and boosted attendance rates through better indoor thermal climate:

Clark County Public Schools, Winchester, Kentucky, uses a DOAS Ac system with chilled beams. The School District Superintendent prefers the water-based DOAS system over conventional AC because it rules out possible health risks from refrigeration leaks in classrooms. He states his DOAS systems have three times the lifecycle expectancy of older AC systems, lower installation and maintenance costs, and significant energy savings. His DOAS systems eliminate the loud noise of the conventional AC it replaced. ***“.. now I walk into classrooms with the chilled beams and I can’t hear any sound from the HVAC system”.*** The high school has increased attendance because of the comfortable learning environment created by the DOAS-AC. ***“Rising attendance generally transcends into more productive learning, which will help maintain Clark County Schools’ standing as one of the top districts in Kentucky”.***

George Rogers Clark High School, Kentucky, uses a DOAS system with heat recovery and chilled beams. The school reports savings of more than 35% in energy costs and significant installation costs savings. The increased attendance earned the school a $200,000 government-awarded attendance incentive.

Benefits for Hawaii’s schools and educational facilities:

Reduced energy & maintenance costs’ lower installation costs	The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification. It avoids redundant fan power and bulky duct systems. It avoids energy penalties from unnecessarily overcooling the rooms. It ensures that ceiling fans are effectively used for “free” cooling, without reducing comfort.
Creating a healthier indoor and better learning environment	The proposed installation can reduce “sick building” conditions and avoid humidity related problems, such as mold, by separation of cooling and dehumidification controls. Sufficient outdoor air supply results in healthy indoor air. It avoids noise and distracting sounds from conventional air supply fans. It avoids unhealthy drafts from cold air. When external climate conditions allow, the system can use natural ventilation settings

Project lead: Mr. Jim Maskrey, HNEI, maskrey2@hawaii.edu, (808) 956-3645 and Dr. Manfred Zapka, Sustainable Design & Consulting LLC, sustainabledc@gmail.com, (808) 265-6321: February 2017 **Page 1**

Figure 6.1.1: Pamphlet A – Page 1 of 5

The full-size pages of the Pamphlet A are presented in Appendix A.

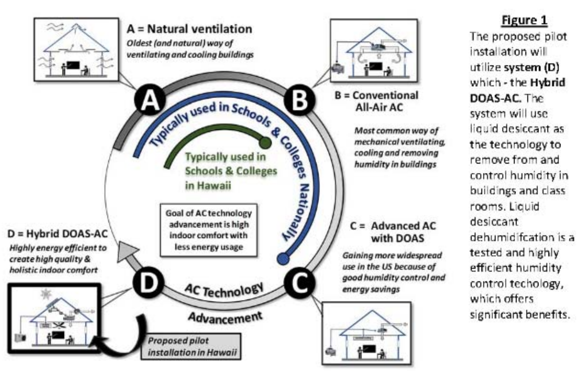
Topics covered on this page:
- Challenge for Hawaii’s Schools
- Proposed Solution
- Benefits for Hawaii’s schools and educational facilities
- Reduced energy & maintenance costs’ lower installation costs
- Creating a healthier indoor and better learning environment
- Testimonials of two High-Schools that switched from conventional AC to advanced HVAC

Synopsis of page 2 of Pamphlet A:

- A description of what space conditioning technologies are presently in use in schools and education facilities in Hawaii and on the US mainland. Four technologies were identified:
  - A - Natural ventilation
  - B - Conventional All-air AC
  - C - Advanced AC with DOAS
  - D - Hybrid DOAS-AC (system) PROPOSED for pilot installation

- For these four space conditioning technologies A through D a performance levels matrix was prepared with five important functions of building conditions systems:
  1. Electricity savings relative to conventional AC
  2. Capacity of using renewable and waste energy for AC
  3. Continuous control of indoor thermal conditions
  4. Continuous control of indoor humidity & mitigation of humidity related problems
  5. Providing continuous healthy indoor environment & comfort

The matrix used the performance levels “High”, “Medium”, “Low to medium”, “Low”, “Very limited”, and “Not applicable”.



The proposed hybrid DOAS-AC pilot installation will use a liquid desiccant dehumidifier, a small electrical water chiller and ceiling fans to provide effective and healthy indoor temperature and humidity conditions. The heat for the regeneration of the liquid desiccant material will be provided by solar heat, if space requirements for the solar panels can be met. In Figure 1 above, the **proposed pilot installation is System D, Hybrid DOAS-AC.** Figure 1 shows how the proposed Hybrid DOAS-AC fits into current AC technology advances in the US and world-wide, and how it compares to three other technologies for indoor thermal control, referred to as Technologies A through C. Table 1 below illustrates the performance characteristics for the four building conditioning technologies A through D.

Table 1 - COMPARISON

	Relative Performance across Systems			
Important functions of building conditions systems	**A = Natural ventilation**	**B = Conventional All-air AC**	**C = Advanced AC with DOAS**	**D = Hybrid DOAS-AC**
1. Electricity savings relative to conventional AC	**High:** only natural processes used, no electricity	**Not applicable:** savings are relative to conv. AC	**Medium:** more efficient heat removal	**High:** more efficient heat removal & other energy savings
2. Capacity of using renewable and waste energy for AC	**Not applicable:** ventilation requires no electric energy	**Very limited:** some quantities of solar electricity	**Medium:** some solar & waste heat dehumidification	**High:** more solar & waste heat for dehumidification
3. Continuous control of indoor thermal conditions	**Low:** wind induced ventilation is intermittent	**High:** always provides sufficient & continuous cooling	**High:** always provides sufficient & continuous cooling	**High:** always provides sufficient & continuous cooling
4. Continuous control of indoor humidity & mitigation of humidity related problems	**Low: Cannot control -** intermittent outdoor conditions	**Low to Medium:** no separate humidity controls	**High:** separate humidity control	**High:** separate humidity control
5. Providing continuous healthy indoor environment & comfort	**High, but intermittent:** dependent on outdoor conditions	**Low to Medium:** frequent over-cooling, noisy, others comfort impairments	**Medium to High:** fitting temps. & humidity, low noise, others comfort gains	**High:** fitting temps. & humidity, low noise, individual ceiling fan controls
				Pilot Installation

Figure 6.1.2: Pamphlet A – Page 2 of 5

The full-size pages of the Pamphlet A are presented in Appendix A.

Topics covered on this page:

- Four types of space conditioning technologies (A though D) presently used in schools and education facilities in Hawaii and on the US mainland.
- Basic performance evaluation of A through D using five important aspects:
  1. Electricity savings
  2. Using renewable & alternative energy for AC
  3. Thermal comfort
  4. Indoor humidity related problems
  5. Healthy indoor environment & comfort

Synopsis of page 3 of Pamphlet A:

- Performance characteristics of building conditioning technologies A through D as a relationship of Energy Efficiency and Quality indoor comfort and humidity control
- Matrix which correlates abilities to provide high energy efficiency and high indoor environmental quality.
- Defining four performance characteristics (metrics):
  - o Base performer: Low energy efficiency and limited ability to continuously and effectively control indoor comfort and humidity
  - o Energy performer: High energy efficiency but limited ability to continuously and effectively control indoor comfort and humidity
  - o Comfort performer: Low energy efficiency but high ability to continuously and effectively control indoor comfort and humidity
  - o Star performer: Low energy efficiency AND high ability to continuously and effectively control indoor comfort and humidity
- Space Requirements for New Pilot Installation, for (A) retrofit a classroom with or (B) new installation of the proposed Hybrid AC system in a classroom or other space at a DoE facility. The spaces have or do not have existing HVAC systems (Part 1 of 2)

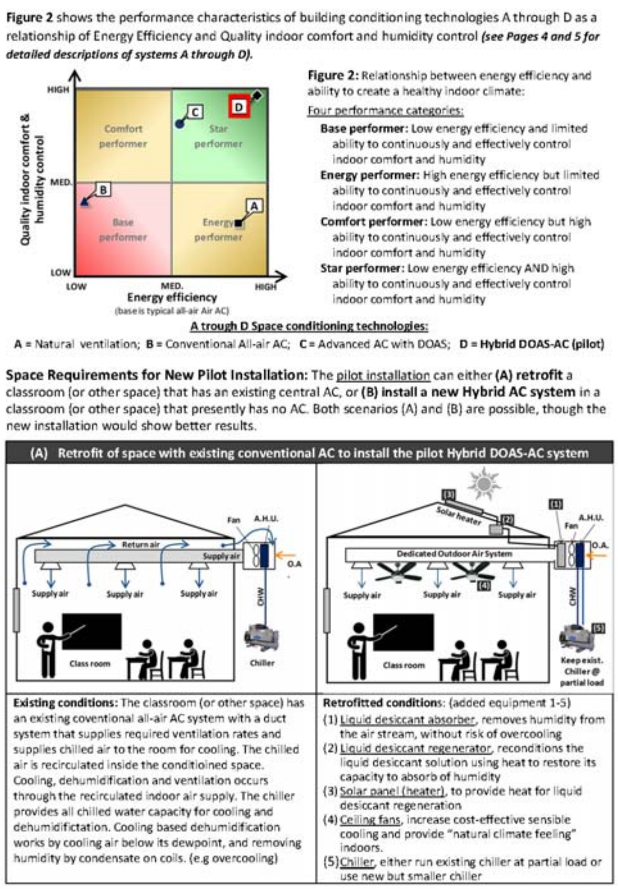


Figure 2 shows the performance characteristics of building conditioning technologies A through D as a relationship of Energy Efficiency and Quality indoor comfort and humidity control ***(see Pages 4 and 5 for detailed descriptions of systems A through D).***

Figure 2: Relationship between energy efficiency and ability to create a healthy indoor climate:

Four performance categories:

Base performer: Low energy efficiency and limited ability to continuously and effectively control indoor comfort and humidity
Energy performer: High energy efficiency but limited ability to continuously and effectively control indoor comfort and humidity
Comfort performer: Low energy efficiency but high ability to continuously and effectively control indoor comfort and humidity
Star performer: Low energy efficiency AND high ability to continuously and effectively control indoor comfort and humidity

A trough D Space conditioning technologies:

A = Natural ventilation; **B** = Conventional All-air AC; **C** = Advanced AC with DOAS; **D = Hybrid DOAS-AC (pilot)**

Space Requirements for New Pilot Installation: The pilot installation can either **(A) retrofit** a classroom (or other space) that has an existing central AC, or **(B) install a new Hybrid AC system** in a classroom (or other space) that presently has no AC. Both scenarios (A) and (B) are possible, though the new installation would show better results.

(A) Retrofit of space with existing conventional AC to install the pilot Hybrid DOAS-AC system

Existing conditions: The classroom (or other space) has an existing coventional all-air AC system with a duct system that supplies required ventilation rates and supplies chilled air to the room for cooling. The chilled air is recirculated inside the conditioined space. Cooling, dehumidification and ventilation occurs through the recirculated indoor air supply. The chiller provides all chilled water capacity for cooling and dehumidifictation. Cooling based dehumidification works by cooling air below its dewpoint, and removing humidity by condensate on coils. (e.g overcooling)

Retrofitted conditions: (added equipment 1-5)
(1) Liquid desiccant absorber, removes humidity from the air stream, without risk of overcooling
(2) Liquid desiccant regenerator, reconditions the liquid desiccant solution using heat to restore its capacity to absorb of humidity
(3) Solar panel (heater), to provide heat for liquid desiccant regeneration
(4) Ceiling fans, increase cost-effective sensible cooling and provide "natural climate feeling" indoors.
(5) Chiller, either run existing chiller at partial load or use new but smaller chiller

Figure 6.1.2: Pamphlet A – Page 2 of 5

The full-size pages of the Pamphlet A are presented in Appendix A.

Topics covered on this page:

- Performance characteristics of building conditioning technologies A through D
- Matrix which correlates energy efficiency & indoor environmental quality performance
- Four performance characteristics (metrics) in matrix:
  - Base performer
  - Energy performer
  - Comfort performer
  - Star performer
- Space Requirements for New Pilot Installation, (A) retrofit or (B) new installation in spaces that either have or have not existing HVAC systems

Synopsis of page 4 of Pamphlet A:

- Space Requirements for New Pilot Installation, for (A) retrofit a classroom with or (B) new installation of the proposed Hybrid AC system in a classroom or other space at a DoE facility. The spaces have or do not have existing HVAC systems (Part 2 of 2)

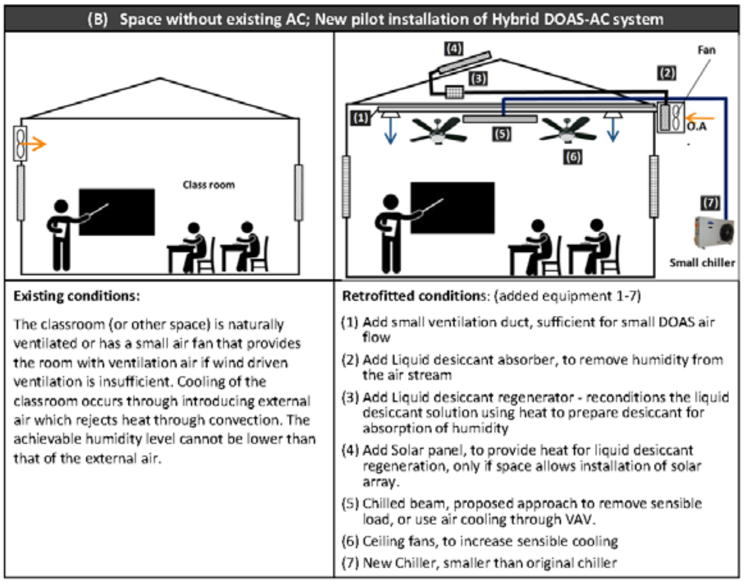


Figure 6.1.2: Pamphlet A – Page 4 of 5

The full-size pages of the Pamphlet A are presented in Appendix A.

Topics covered on this page:

- Continuation of Space Requirements for New Pilot Installation, (A) retrofit or (B) new installation in spaces that either have or have not existing HVAC systems

Synopsis of page 5 of Pamphlet A:

- Space Requirements for New Pilot Installation

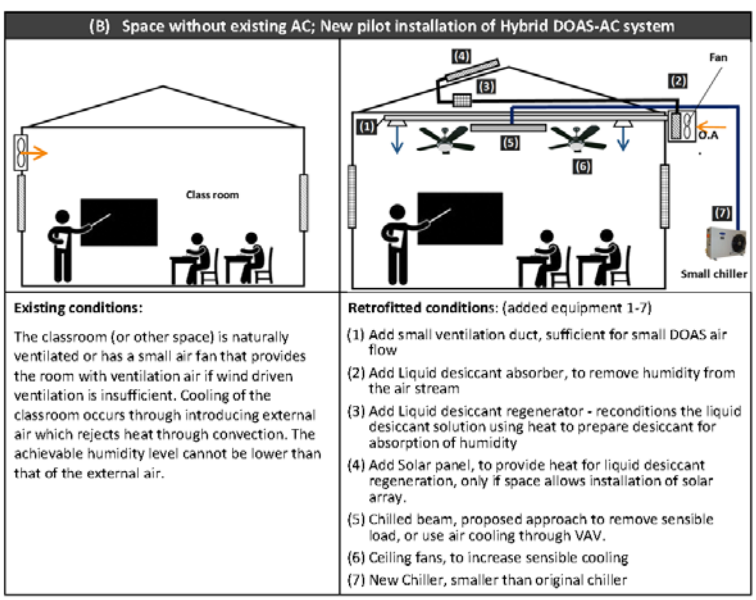


Figure 6.1.2: Pamphlet A – Page 5 of 5

The full-size pages of the Pamphlet A are presented in Appendix A.

Topics covered on this page:

- Continuation of Space Requirements for New Pilot Installation, (A) retrofit or (B) new installation in spaces that either have or have not existing HVAC systems

6.3 Informational Pamphlet B

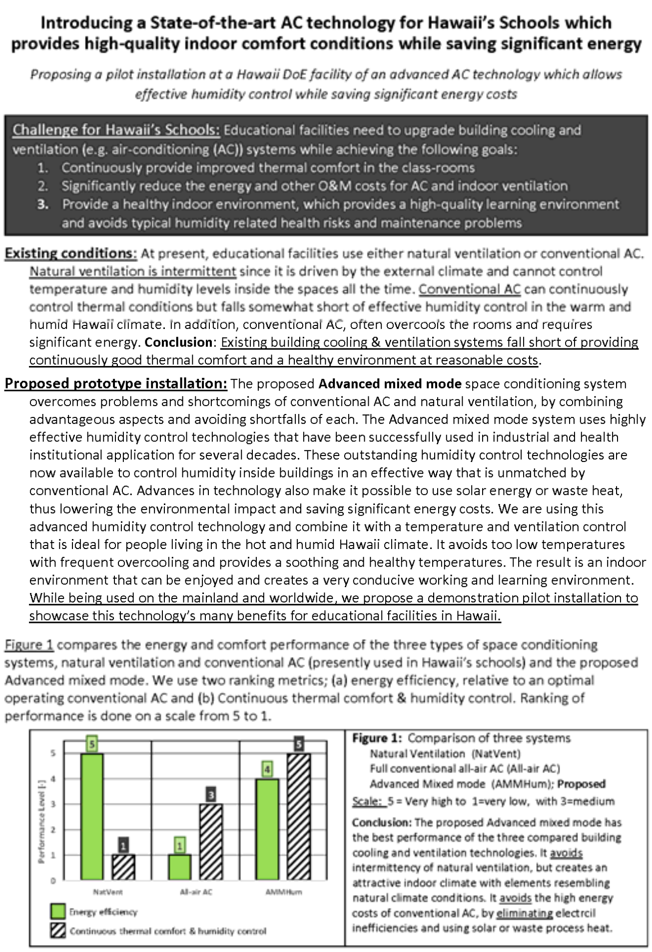
Header: Introducing a State-of-the-art AC technology for Hawaii's Schools which provides high-quality indoor comfort conditions while saving significant energy

Sub header: Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control, creates high quality indoor comfort and saves significant energy

Figure 6.3.1 through 6.3.2 shows the two pages of Pamphlet B. The figures show reduced sizes of the pages while the full-size pages of Pamphlet A are presented in Appendix A. The Figures are accompanied with short summaries of the topics presented on the pages.

Synopsis of page 1 of Pamphlet B:

- Challenge for Hawaii's Schools: Educational facilities need to upgrade building conditioning (e.g. air-conditioning (AC) systems in a cost-effective way, while providing students, teachers & staff with high-quality indoor comfort at affordable installation and energy cost.



Introducing a State-of-the-art AC technology for Hawaii's Schools which provides high-quality indoor comfort conditions while saving significant energy

Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control while saving significant energy costs

Challenge for Hawaii's Schools: Educational facilities need to upgrade building cooling and ventilation (e.g. air-conditioning (AC)) systems while achieving the following goals:
1. Continuously provide improved thermal comfort in the class-rooms
2. Significantly reduce the energy and other O&M costs for AC and indoor ventilation
3. Provide a healthy indoor environment, which provides a high-quality learning environment and avoids typical humidity related health risks and maintenance problems

Existing conditions: At present, educational facilities use either natural ventilation or conventional AC. Natural ventilation is intermittent since it is driven by the external climate and cannot control temperature and humidity levels inside the spaces all the time. Conventional AC can continuously control thermal conditions but falls somewhat short of effective humidity control in the warm and humid Hawaii climate. In addition, conventional AC, often overcools the rooms and requires significant energy. **Conclusion**: Existing building cooling & ventilation systems fall short of providing continuously good thermal comfort and a healthy environment at reasonable costs.

Proposed prototype installation: The proposed **Advanced mixed mode** space conditioning system overcomes problems and shortcomings of conventional AC and natural ventilation, by combining advantageous aspects and avoiding shortfalls of each. The Advanced mixed mode system uses highly effective humidity control technologies that have been successfully used in industrial and health institutional application for several decades. These outstanding humidity control technologies are now available to control humidity inside buildings in an effective way that is unmatched by conventional AC. Advances in technology also make it possible to use solar energy or waste heat, thus lowering the environmental impact and saving significant energy costs. We are using this advanced humidity control technology and combine it with a temperature and ventilation control that is ideal for people living in the hot and humid Hawaii climate. It avoids too low temperatures with frequent overcooling and provides a soothing and healthy temperatures. The result is an indoor environment that can be enjoyed and creates a very conducive working and learning environment. While being used on the mainland and worldwide, we propose a demonstration pilot installation to showcase this technology's many benefits for educational facilities in Hawaii.

Figure 1 compares the energy and comfort performance of the three types of space conditioning systems, natural ventilation and conventional AC (presently used in Hawaii's schools) and the proposed Advanced mixed mode. We use two ranking metrics; (a) energy efficiency, relative to an optimal operating conventional AC and (b) Continuous thermal comfort & humidity control. Ranking of performance is done on a scale from 5 to 1.

Figure 1: Comparison of three systems
Natural Ventilation (NatVent)
Full conventional all-air AC (All-air AC)
Advanced Mixed mode (AMMHum); **Proposed**
Scale: 5 = Very high to 1=very low, with 3=medium

Conclusion: The proposed Advanced mixed mode has the best performance of the three compared building cooling and ventilation technologies. It avoids intermittency of natural ventilation, but creates an attractive indoor climate with elements resembling natural climate conditions. It avoids the high energy costs of conventional AC, by eliminating electrcil inefficiencies and using solar or waste process heat.

Figure 6.3.1: Pamphlet B – Page 1 of 2

The full-size pages of the Pamphlet B are presented in Appendix A.

Topics covered on this page:

- Challenge for Hawaii's Schools
- Proposed Solution
- Comparison of energy and indoor comfort performance of natural ventilation and conventional AC and the proposed Advanced mixed mode

Synopsis of page 2 of Pamphlet B continue

- Proposed Solution: It is proposed to install a pilot system of a liquid desiccant unit in a suitable space at a DoE facility. The proposed hybrid AC pilot installation (using liquid desiccant dehumidification) to provide a high quality indoor thermal comfort while avoiding energy losses of conventional all-air AC systems. The basic process of the hybrid AC pilot system has already been installed at schools on the US-mainland. The proposed pilot installation will adapt successful advanced HVAC system to Hawaii specific climate conditions.
- Comparison of energy and indoor comfort performance of the three types of space conditioning systems, natural ventilation and conventional AC and the proposed Advanced mixed mode.

Synopsis of page 2 of Pamphlet B:

- Benefits for Hawaii's schools and educational facilities:
  - Reduced energy & maintenance costs' lower installation costs: The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification.
  - Creating a healthier indoor and better learning environment: The proposed installation can reduce "sick building" conditions and avoid humidity related problems, such as mold, by separation of cooling and dehumidification controls. When external climate conditions allow, the system can use natural ventilation settings
- Illustration of how the proposed hybrid system mitigates shortcomings and uses advantages of natural ventilation and full HVAC, thereby offering an effective optimization. The proposed new system augments natural ventilation by adding mechanical means of space conditioning. It reduces the high energy demand of conventional Ac and provides a better indoor climate.
- Brief description of Advanced mixed mode: The proposed hybrid pilot installation will use a liquid desiccant dehumidifier, a small electrical or evaporative cooler and ceiling fans to provide effective and healthy indoor temperature and humidity conditions. The heat for the regeneration of the liquid desiccant material will be provided entirely or partly by solar heat.
- Two options of installation of the proposed system
  - As part of a RETROFIT, in spaces where a conventional AC systems will be upgraded
  - As a NEW INSTALLATION, in spaces that have no existing AC

6.4 Informational Pamphlet C

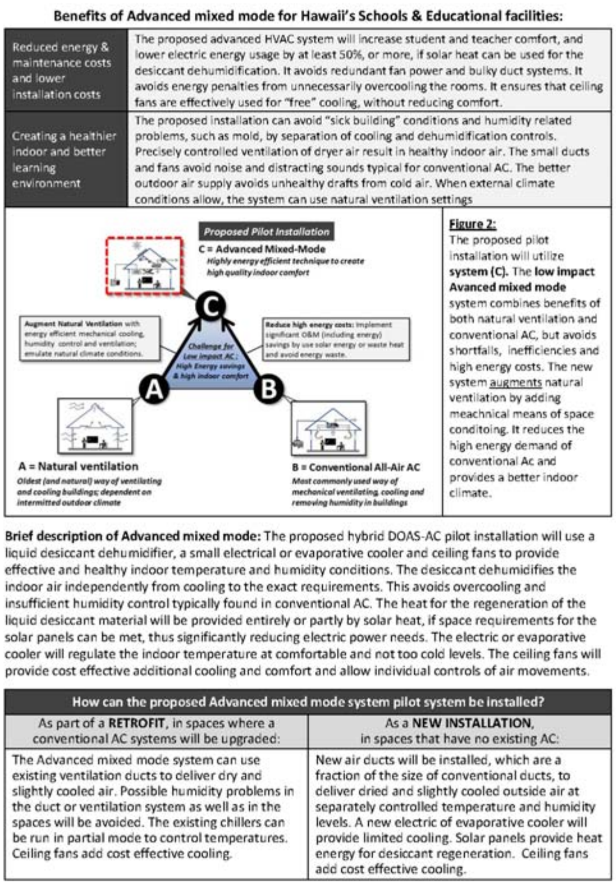
The informational pamphlet C has three large format (11 x 17 inches) pages. These three pages, Briefing Pages 1 through 3, will be reformatted to six smaller pages for easier presentation.

Synopsis of Briefing page 1/A of Pamphlet A

- Situation Assessment of HVAC in Hawaii's schools: Three main challenges and critical issues related to DoE buildings, which need improvements
  A - Thermal comfort

B - Energy & Power
C - Health and IAQ

- Improve thermal comfort for occupants: Challenge of present state and desired state:
- Discussion of how to improve thermal comfort



Benefits of Advanced mixed mode for Hawaii's Schools & Educational facilities:

Reduced energy & maintenance costs and lower installation costs	The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification. It avoids redundant fan power and bulky duct systems. It avoids energy penalties from unnecessarily overcooling the rooms. It ensures that ceiling fans are effectively used for "free" cooling, without reducing comfort.
Creating a healthier indoor and better learning environment	The proposed installation can avoid "sick building" conditions and humidity related problems, such as mold, by separation of cooling and dehumidification controls. Precisely controlled ventilation of dryer air result in healthy indoor air. The small ducts and fans avoid noise and distracting sounds typical for conventional AC. The better outdoor air supply avoids unhealthy drafts from cold air. When external climate conditions allow, the system can use natural ventilation settings

Figure 2: The proposed pilot installation will utilize **system (C).** The **low impact Avanced mixed mode** system combines benefits of both natural ventilation and conventional AC, but avoids shortfalls, inefficiencies and high energy costs. The new system augments natural ventilation by adding meachnical means of space conditoing. It reduces the high energy demand of conventional Ac and provides a better indoor climate.

Brief description of Advanced mixed mode: The proposed hybrid DOAS-AC pilot installation will use a liquid desiccant dehumidifier, a small electrical or evaporative cooler and ceiling fans to provide effective and healthy indoor temperature and humidity conditions. The desiccant dehumidifies the indoor air independently from cooling to the exact requirements. This avoids overcooling and insufficient humidity control typically found in conventional AC. The heat for the regeneration of the liquid desiccant material will be provided entirely or partly by solar heat, if space requirements for the solar panels can be met, thus significantly reducing electric power needs. The electric or evaporative cooler will regulate the indoor temperature at comfortable and not too cold levels. The ceiling fans will provide cost effective additional cooling and comfort and allow individual controls of air movements.

How can the proposed Advanced mixed mode system pilot system be installed?	
As part of a **RETROFIT**, in spaces where a conventional AC systems will be upgraded:	As a **NEW INSTALLATION**, in spaces that have no existing AC:
The Advanced mixed mode system can use existing ventilation ducts to deliver dry and slightly cooled air. Possible humidity problems in the duct or ventilation system as well as in the spaces will be avoided. The existing chillers can be run in partial mode to control temperatures. Ceiling fans add cost effective cooling.	New air ducts will be installed, which are a fraction of the size of conventional ducts, to deliver dried and slightly cooled outside air at separately controlled temperature and humidity levels. A new electric of evaporative cooler will provide limited cooling. Solar panels provide heat energy for desiccant regeneration. Ceiling fans add cost effective cooling.

Figure 6.3.2: Pamphlet B – Page 2 of 2

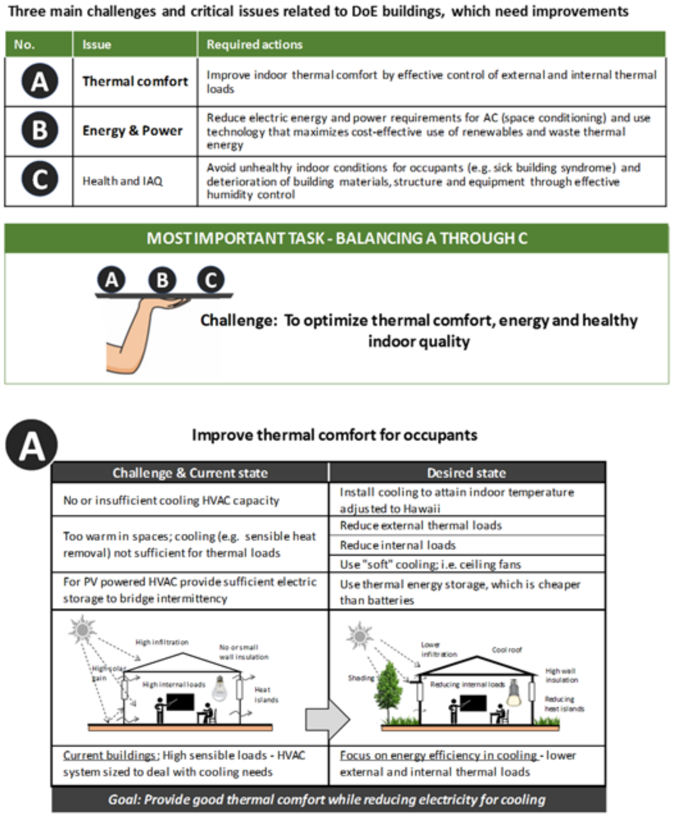
The full-size pages of the Pamphlet B are presented in Appendix A.

Topics covered on this page:

- Benefits for Hawaii's schools and educational facilities
- Illustration of how the proposed hybrid system mitigates shortcomings and uses advantages of natural ventilation and full HVAC
- Brief description of Advanced mixed mode:
- Two options of installation of the proposed system
  - o As part of a RETROFIT, in spaces where a conventional AC systems will be upgraded
  - o As a NEW INSTALLATION, in spaces that have no existing AC

Synopsis of Briefing page 1/B of Pamphlet C

- Situation Assessment of HVAC in Hawaii's schools: Three main challenges and critical issues related to DoE buildings, which need improvements (continued)
  A - Thermal comfort
  B - Energy & Power
  C - Health and IAQ
- Reduce electric energy & power demands for space conditioning: Challenge of present state and desired state - Discussion of measures to use renewable energy sources and to reduce energy use.
- Provide healthy indoor air & environmental quality: Challenge of present state and desired state: Improve humidity control, ventilation and create a quiet, clean and productive learning space.



Three main challenges and critical issues related to DoE buildings, which need improvements

No.	Issue	Required actions
A	Thermal comfort	Improve indoor thermal comfort by effective control of external and internal thermal loads
B	Energy & Power	Reduce electric energy and power requirements for AC (space conditioning) and use technology that maximizes cost-effective use of renewables and waste thermal energy
C	Health and IAQ	Avoid unhealthy indoor conditions for occupants (e.g. sick building syndrome) and deterioration of building materials, structure and equipment through effective humidity control

MOST IMPORTANT TASK - BALANCING A THROUGH C

A B C

Challenge: To optimize thermal comfort, energy and healthy indoor quality

A **Improve thermal comfort for occupants**

Challenge & Current state	Desired state
No or insufficient cooling HVAC capacity	Install cooling to attain indoor temperature adjusted to Hawaii
Too warm in spaces; cooling (e.g. sensible heat removal) not sufficient for thermal loads	Reduce external thermal loads Reduce internal loads Use "soft" cooling; i.e. ceiling fans
For PV powered HVAC provide sufficient electric storage to bridge intermittency	Use thermal energy storage, which is cheaper than batteries
Current buildings: High sensible loads - HVAC system sized to deal with cooling needs	Focus on energy efficiency in cooling - lower external and internal thermal loads

Goal: Provide good thermal comfort while reducing electricity for cooling

Figure 6.4.1: Pamphlet C – Page 1 of 6

Briefing Page 1/A; The full-size pages of the Pamphlet C are presented in Appendix A.

Topics covered on this page:

- Situation Assessment of HVAC in Hawaii's schools
- Three main challenges and critical issues, A through C, related to DoE buildings, which need improvements
  - Discussion of A: Improve thermal comfort for occupant

Synopsis of Briefing page 2/A of Pamphlet C

Comparison between conventional versus Proposed Mixed mode AC system

- Conventional DX-AC with cooling coil dehumidification: Cooling (sensible load removal) and humidity control (dehumidification) cannot be separated and therefore cannot be optimized individually. Conventional AC controlled by high and low temperature set points
- Mixed mode AC with Desiccant dehumidification and on demand cooling: Cooling (sensible load removal) and humidity control (dehumidification) are separated and can therefore be optimized individually. Advanced Mixed Mode AC controlled by independent temperature and humidity set points

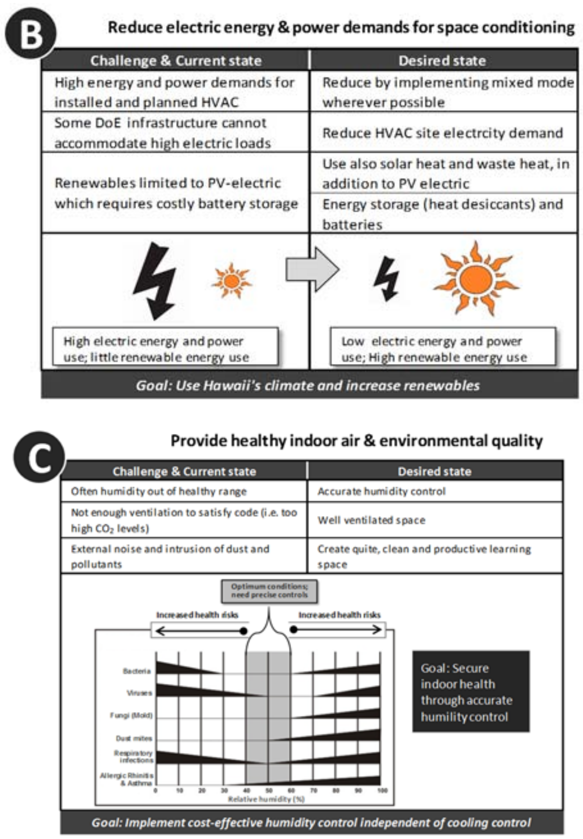


Figure 6.4.2: Pamphlet C – Page 1 of 6

Briefing Page 1/A; The full-size pages of the Pamphlet C are presented in Appendix A.

Topics covered on this page:

- Situation Assessment of HVAC in Hawaii's schools (continued)
- Three main challenges and critical issues, A through C, related to DoE buildings, which need improvements
  - o Discussion of B: Reduce electric energy & power demands for space conditioning:
  - o Discussion of C: Provide healthy indoor air & environmental quality

Synopsis of Briefing page 2/B of Pamphlet C

- Advantages / Disadvantages of conventional cooling based AC and Ac with desiccant dehumidification
  - o O&M costs
  - o Control over humidity
  - o Indoor air quality
  - o Indoor thermal comfort
  - o Installation / type and costs
- Proposed advanced mixed mode: Proposed advanced Mixed Mode combines advantages of natural ventilation and forced HVAC
- Illustration of how the proposed hybrid system mitigates shortcomings and uses advantages of natural ventilation and full HVAC, thereby offering an effective optimization. The proposed new system augments natural ventilation by adding mechanical means of space conditioning. It reduces the high energy demand of conventional Ac and provides a better indoor climate.

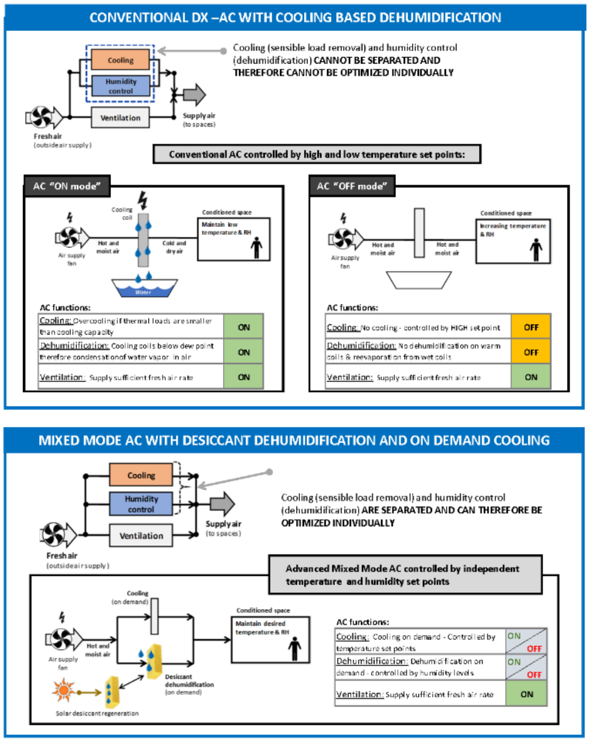
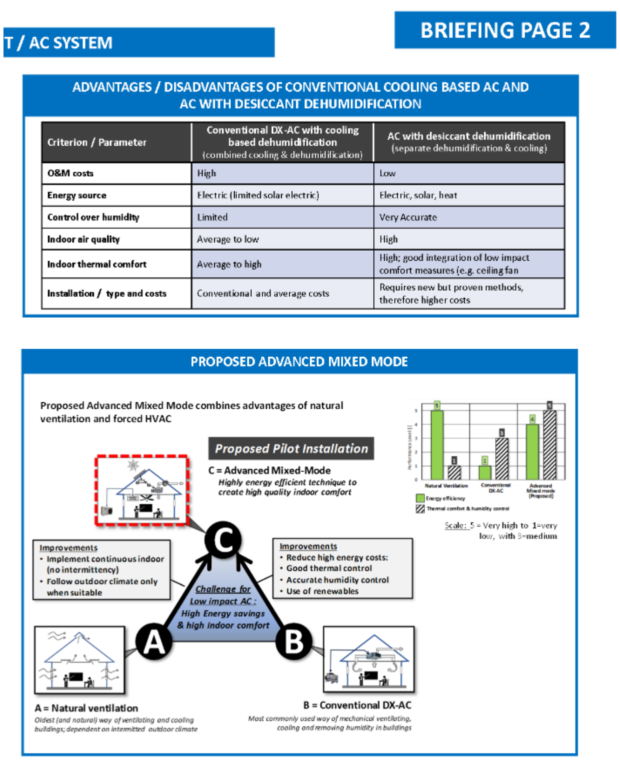


Figure 6.4.3: Pamphlet C – Page 3 of 6

Briefing Page 2/A; The full-size pages of the Pamphlet C are presented in Appendix A.

<u>Topics covered on this page:</u>

- Difference between conventional versus mixed mode desiccant / AC system
- Comparison between conventional versus Proposed Mixed mode AC system
- Description of conventional DX-AC with cooling coil dehumidification
- Description of mixed mode AC with desiccant dehumidification



Criterion / Parameter	Conventional DX-AC with cooling based dehumidification (combined cooling & dehumidification)	AC with desiccant dehumidification (separate dehumidification & cooling)
O&M costs	High	Low
Energy source	Electric (limited solar electric)	Electric, solar, heat
Control over humidity	Limited	Very Accurate
Indoor air quality	Average to low	High
Indoor thermal comfort	Average to high	High; good integration of low impact comfort measures (e.g. ceiling fan
Installation / type and costs	Conventional and average costs	Requires new but proven methods, therefore higher costs

Figure 6.4.4: Pamphlet C – Page 4 of 6

Briefing Page 2/B; The full-size pages of the Pamphlet C are presented in Appendix A.

<u>Topics covered on this page:</u>

- Advantages / Disadvantages of conventional cooling based AC and AC with desiccant dehumidification
- Proposed advanced mixed mode
- Illustration of how the proposed hybrid system

Synopsis of Briefing page 3/A of Pamphlet C

- Pilot installation implementation options
  - Liquid desiccant dehumidification is a proven industrial technology: . Conventional Liquid desiccant (LD) dehumidification technology has been used for over 70 years for precise humidity control in industrial and institutional applications, such as pharmaceutical industry, storage, archives, museums, hospitals. - Industrial & institutional liquid desiccant applications were precise but costly and maintenance is intensive
  - HVAC applications: Since 2000 intensive technology development for liquid desiccant HVAC applications. Improvements over industrial desiccant systems with Low-flow Liquid desiccant (LD) conditioner and LD regenerator for HVAC application:
- Proposed pilot liquid desiccant (LD) installation for DoE:
  - Description of the basic process diagram of pilot liquid desiccant installation; including main system parts
  - Projected: Possible energy savings up to 70-80% if all solar options are used (NREL)

Synopsis of Briefing page 3/A of Pamphlet C

- Implementation options of Liquid desiccant (LD) system
- Option: LLD conditioner inside space installed in existing duct: The liquid desiccant(LD) conditioner (dehumidifier) and the LD regenerator (desorption unit) can be installed apart from each other. This provides extra flexibility & requires less space for integration of the LD conditioner into the existing HVAC ducts.
- Option: Packaged LD unit outside of space: For this type installation of a liquid desiccant air condition (LDAC) unit it is assumed that the space has either no existing AC system or an old AC system that needs total replacement. The new installation will include a packaged LDAC with a LD conditioner and a LD regenerator housed inside one unit. The heat sink and source for the LD conditioner and LD regenerator are located externally.

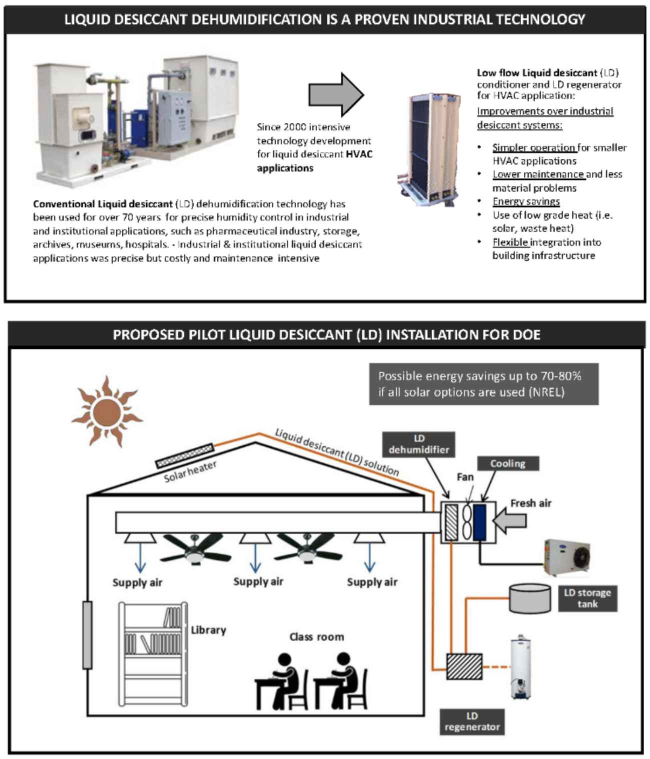


Figure 6.4.5: Pamphlet C – Page 5 of 6

Briefing Page 3/A; The full-size pages of the Pamphlet C are presented in Appendix A.

Topics covered on this page:

- Liquid desiccant dehumidification is a proven industrial technology
- Since 2000 intensive technology development for liquid desiccant HVAC applications
- Process diagram of proposed pilot liquid desiccant (LD) installation for DoE:

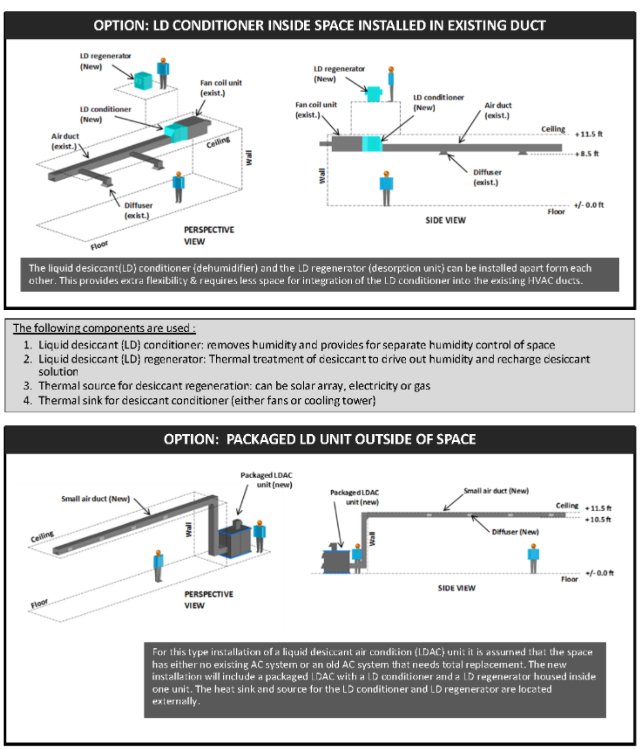


Figure 6.4.6: Pamphlet C – Page 6 of 6

Briefing Page 3/B; The full-size pages of the Pamphlet C are presented in Appendix A.

Topics covered on this page:

- Implementation options of Liquid desiccant (LD) system
- Option: LLD conditioner inside space installed in existing duct:
- Option: Packaged LD unit outside of space:

SECTION 7 – CONDUCTING VISITS TO REPRESENTATIVE SITES

Several site visits were conducted to obtain information about different building aspects and space conditioning technologies. which are of importance to the proposed innovative hybrid space systems with liquid desiccant dehumidification.

7.1 Objectives of the Site Visits and Observations

The proposed innovative space conditioning system is an assembly of different system components, where each of which have an established track record in the HVAC and building industry. The innovation of the proposed system is not to reestablish the feasibility of different component, but to integrate these component into a system that offers unique benefits in the Hawaii climate in which it will be operating. Inspecting different locations, each with their own specific technical and operational characteristics provided important design information to the project team. The lessons learned by the operators and designers furthermore provided guidance of what level of innovation will be acceptable.

In the following six sections, locations with a variety of space conditioning technologies are presented and discussed. Five of these locations are on Oahu and one is in California. All locations featured a specific technology and component of the proposed innovative space conditioning systems.

Table 7.1.1 describes the locations visited and the type of technology or aspects of operation which relate directly to the proposed hybrid space conditioning system.

No. / section	Type of space conditioning or operation	Location	Lessons learned by the operator & Component of proposed innovative system
1 / 7.2	The test site was a naturally ventilated space on the UH Manoa campus. This location was used as a test site for a previous project. These investigations related to thermal comfort of a naturally ventilated space.	Honolulu, UHM Manoa Campus	Lessons learned: The test site quantified the relief of heat induced discomfort through ceiling fans and mechanical ventilation. The test showed that requirements of an open building envelope, e.g. open windows and doors can cause excessive and unabated external noise and fugitive dust. These were major discomfort aspects in addition to the heat related discomfort. The internal wall mounted fans were considered too noisy and ineffective. Components for proposed system: Ceiling fans and mechanical ventilation.

No. / section	Type of space conditioning or operation	Location	Lessons learned by the operator & Component of proposed innovative system
2/ 7.3	The Whole Food Market (WFM) in Kailua used a liquid desiccant system to supplement the dehumidification capacity of the existing conventional vapor compression HVAC system. The thermal energy for liquid desiccant regeneration was supplied by a solar system with a hot water storage.	Kailua, Oahu	Lessons learned: The test site is the only site on Oahu that uses liquid desiccants for dehumidification. Liquid desiccant system uses solar process heat through a large array of solar panels. The system has been out of operation because the liquid desiccant conditioner and regenerator heat exchangers exhibited water leakage. In response to these operational difficulties the liquid desiccant technology developer has changed the design of the heat exchangers. Components for proposed system: Liquid desiccant dehumidification, cooling tower to provide process heat sink and solar energy to provide heat source for desiccant regeneration
3/ 7.4	The Whole Food Market (WFM) in Tustin uses a liquid desiccant system that is like that in Kailua, but with an improved liquid desiccant conditioner and regenerator design and the use of natural gas as the heat source for desiccant regeneration.	Tustin, CA	Lessons learned: The liquid desiccant system for the WFM in Tustin is operating successfully. This system configuration uses a liquid desiccant conditioner and regenerators design which is a significant improvement of the design used by WFM in Kailua. The footprint and complexity of the system is significantly less for the WFM in Tustin, due to the use of natural gas in lieu of solar array for process heat for desiccant regeneration. Components for proposed system: Liquid desiccant dehumidification, cooling tower to provide process heat sink and the use of gas to provide heat source for desiccant regeneration. A new design of liquid desiccant conditioner and regenerator which would be used in the proposed pilot installation.

No. / section	Type of space conditioning or operation	Location	Lessons learned by the operator & Component of proposed innovative system
4/ 7.5	The Kahuku High School has mainly naturally ventilated classrooms, where some of which displaying significant mold problems.	Kahuku, Oahu	Lessons learned: The Kahuku High School has a large student and teacher body. The school has several "portable" classrooms which are naturally ventilated and which have very high internal temperatures and humidity levels. Some of the class rooms have mold problems. The school has installed portable dehumidifiers to mitigate mold problems in the classrooms with the most significant mold related problems. The portable dehumidification units are conventional cooling coils units. The outcome of using the dehumidifiers are mixed, as the classrooms cannot be sealed effectively to avoid humidity intrusion. Components for proposed system: Ceiling fans and portable dehumidification.
5/ 7.6	The Cancer Center of the University of Hawaii uses chilled beams for added sensible load removal. The chilled beams are integrated into the existing HVAC chilled are supply. The cooling of the chilled beam uses secondary chilled water loop. A larger portion of the building has a DOAS system. The low RH discharge air from the spaces is used for indirect evaporative cooling.	Honolulu, Oahu	Lessons learned: The operator of the building stated good experiences with the chilled beams. There have been no instances of condensation and humidity related problems that were caused by the chilled beams. The indirect evaporative cooling using the dry exhaust air has been working well until there have been some problems with the wetted media. The operator suggested that the evaporative cooling unit should use a dedicated air duct to avoid a required building wide HVAC system shutdown to repair the evaporative cooling loop. Components for proposed system: Chilled beam and evaporative cooling using dry building exhaust air.

No. / section	Type of space conditioning or operation	Location	Lessons learned by the operator & Component of proposed innovative system
6/ 7.7	The NOAA center on Ford Island, Pearl harbor, Oahu was designed as one of the state's most efficient building in the state. The building includes passive cooling, active cooling with displacement air technology, chilled beams, and use of cold deep seawater derived from a 1,500-feet well for sensible cooling. A portion of the building has a DOAS system to supply 100% supply air.	Pearl Harbor, Oahu	Lessons learned: Some aspects of the passive cooing using roof top ventilation shafts do not work as efficiently as the design intent. The lab space uses 100% outdoor air supply with a DOAS system. Chilled beams are used in the lab space to provide sensible cooling capacity. There have been issues with condensation on the chilled beams piping as the indoor air RH surpassed design levels. The use of cold deep seawater, derived from a 1,500-feet deep well provides significant savings as it is use for precooling.

7.2 Experience with Existing Site – Previous Research Work at Sinclair Library

Background: The authors had conducted an extensive investigation of the indoor thermal conditions of Room 301 in Sinclair Library of the University of Hawaii Manoa Campus. The team leader of the work group occupying Room 301 had asked for a thermal comfort review and proposal of excessive heat mitigation and other related unsatisfactory indoor conditions.

Room specifics: The Room 301 has 5,000 sqft floor area and a 10 feet ceiling height. The space is on the upper floor of the Sinclair Building.

Type of space conditioning: The space is a naturally ventilated. There are 20 wall mounted oscillating 30-inch fans, which are too noisy to operate all the time.

Conditions experienced by the occupants: The negative indoor environmental conditions experienced by the occupants included:

- Complaints about excessive temperatures and humidity levels,
- Excessive exterior noise from the adjacent road and DXAC system located on nearby roof, when windows were open
- Excessive interior noise from the wall mounted and oscillating 30-inch fans.
- Dust entering the room when windows were open
- Odor from adjacent roadway

Recommendations impact mitigation to the owner / occupant: Installing close to 20 55-inch ceiling fans and a new lighting system in Room 301. The room would remain naturally ventilated and the existing interior room layout would remain unchanged. Elevated air speeds from ceiling fans have been identified as a very cost-effective measure to increase thermal comfort and reduce heat index values. This recommended solution was considered the most cost-effective solution and suggested effective impact mitigation with limited indoor work required.

Presentation of selected content of the investigations:

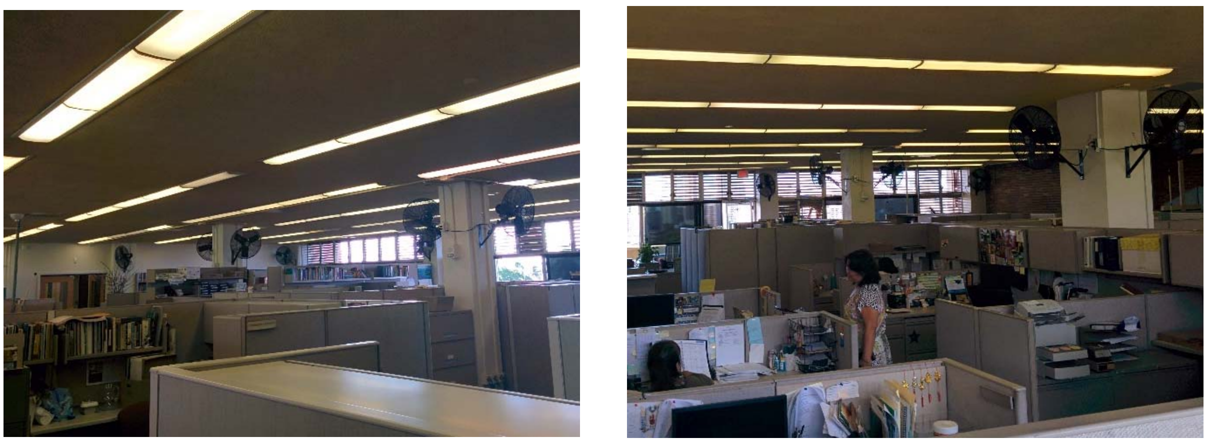


Figure 7.2.1: Room 301 in Sinclair Library, site of a previous investigation (2014) of thermal comfort in a naturally ventilated space at the University of Hawaii

Figure 7.2.2 shows the test result of a thermal comfort analysis using the adaptive comfort model of the ASHRAE 55 standard. As indicated with the red bars, thermal conditions were outside the compliance range. Figure 7.2.3 shows the same thermal conditions but with ceiling fans operating in the room, which would provide a 120 fmp air speed. The predicted thermal conditions with the ceiling fans providing an air speed of 120 fpm indicated that thermal conditions would be within the ASHRAE 55 compliance range.

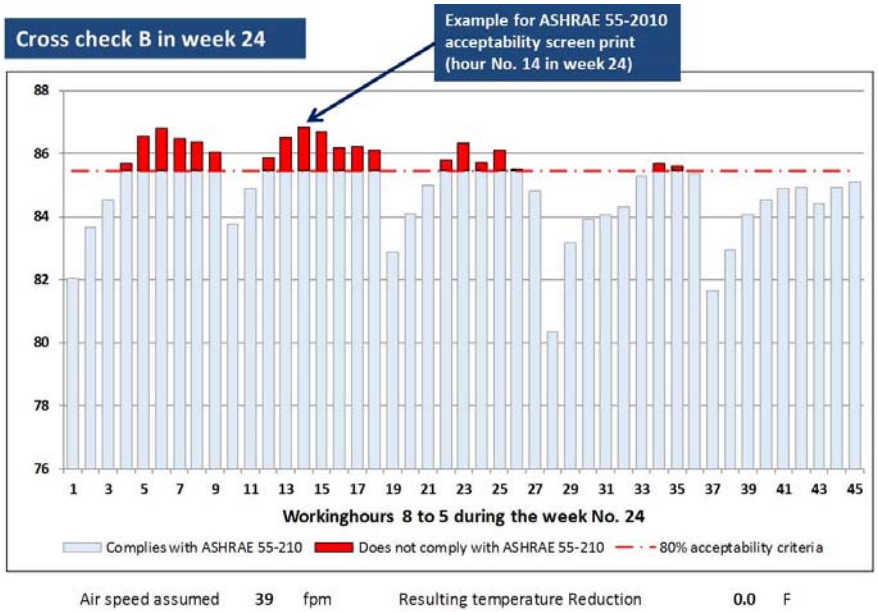


Figure 7.2.2: Measured comfort levels based on adaptive comfort mode in ASHRAE 55

The red bars indicate that during several working hours in the reference week, thermal conditions exceeded ASHRAE 55 standards

(Zapka, et al, 2014)

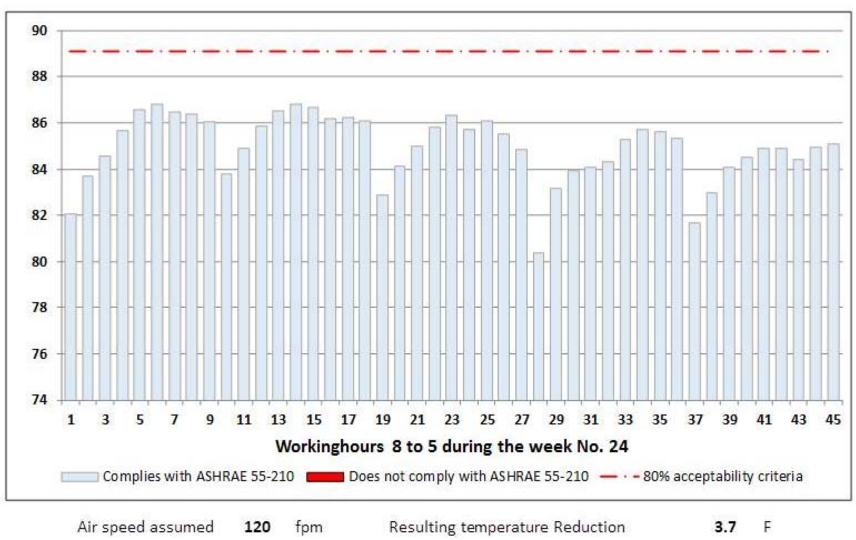


Figure 7.2.3: predicted comfort levels based on adaptive comfort mode in ASHRAE 55 with increased air speed at 120 fpm

The same thermal conditions, e.g. operative temperatures and humidity, applied as in conditions depicted in in Figure 7.2.2. The predicted comfort level suggest that comfort levels would be satisfied.

(Zapka, et al, 2014)

Besides the ASHRAE 55 thermal comfort standard, the NOAA/OSHA heat index was used to assess the thermal conditions in Room 301. The Heat Index as a thermal comfort indicator that combines air temperature and relative humidity into a single value, the so-called “apparent temperature”. The heat index suggests how occupant experience the effects of humidity at higher temperatures.

Figure 7.2.4 shows the results of the heat index calculated from the operative temperatures and relative humidity levels of the same date set that was used in Figure 7.2.5.

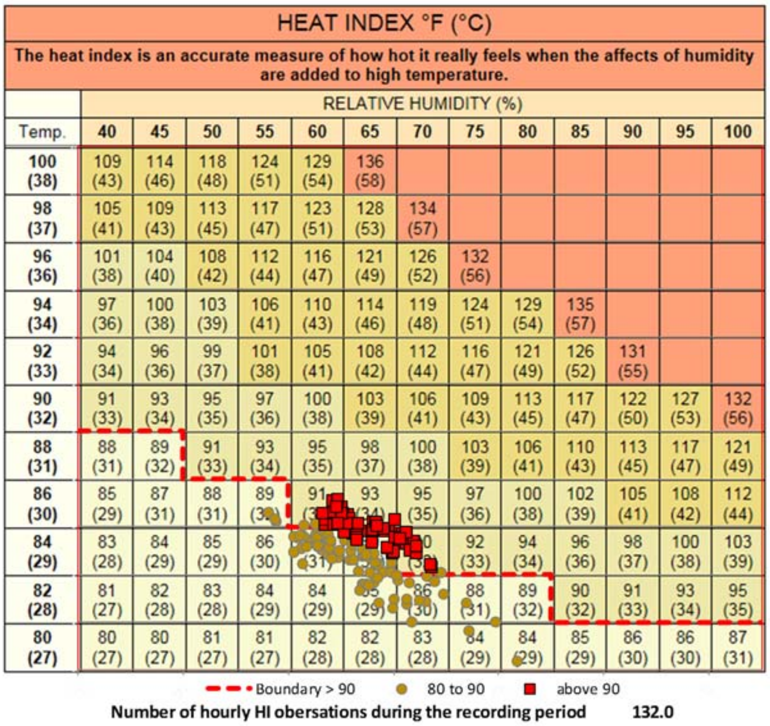


Figure 7.2.4: Hourly mean values of heat index measured in Room 301 during regular working hours in reference week.
(Zapka, et. al, 2014)

Boundary between HI 80 F and 91F
HI between 80F and 90F
HI above 90F

Heat index (HI) range: 80 – 90F; "Uncomfortable range"; OSHA HI risk level: "Lower"

Heat index (HI) range: 90 – 105 F; "Increased risk of heat related illness"; OSHA HI risk level: "Moderate"

Category	Heat Index	Possible heat disorders for people in high risk groups
Extreme Danger	130°F or higher (54°C or higher)	Heat stroke or sunstroke likely.
Danger	105 - 129°F (41 - 54°C)	Sunstroke, muscle cramps, and/or heat exhaustion likely. Heatstroke possible with prolonged exposure and/or physical activity.
Extreme Caution	90 - 105°F (32 - 41°C)	Sunstroke, muscle cramps, and/or heat exhaustion possible with prolonged exposure and/or physical activity.
Caution	80 - 90°F (27 - 32°C)	Fatigue possible with prolonged exposure and/or physical activity.

The legend to the left indicate the four different zones defined for the heat index. The conditions that were measured in Room were inside the “Caution” and “Extreme Caution” zone

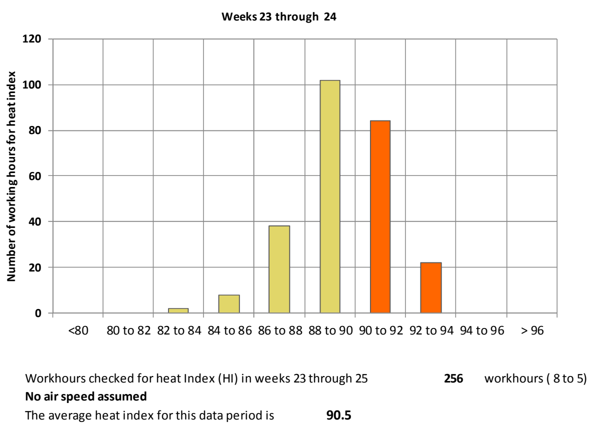
The assessment of providing increased wind speed to the occupants of Room 301 suggested that heat index would significantly be reduced. Figure 7.2.5 (a) indicates the exceedance of heat index of the data shown in Figure 7.2.4. Figure 7.2.5 (b) and (c) suggest that the heat index with increased air speed can be reduced. For this analysis, the operative temperature was reduced as a function of air speed, in accordance with ASHRAE 55.

The main conclusions of the investigation were as follows:

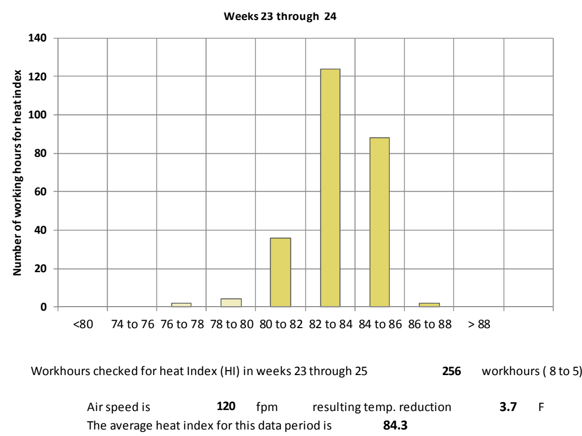
- Without air movement, there were periods during working hours when the thermal conditions in Room 301 did not comply with the 80% acceptability criteria of the ASHRAE 55 Adaptive Comfort method.

- Increasing air speed up to a moderate level of 120 fpm could reduce high levels of operative temperature and therefore satisfy the 80% acceptability threshold of ASHRAE 55.
- Measured temperatures and relative humidity within the reference week indicated elevated heat indexes.
- At elevated air speeds calculated heat indexes are reduced to a significantly lower level, with the resulting heat indexes below or slightly above the threshold of “uncomfortable”, e.g. the 80F threshold.

The proposed mitigation measure of installing ceiling fans along with new LED lighting would only lower the heat related complaints but would not address the space ventilation related and humidity related problems.

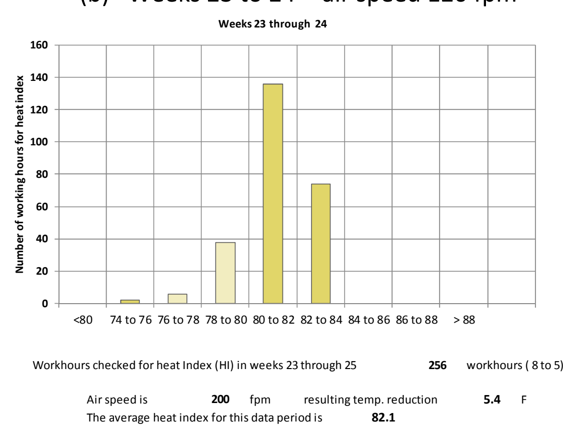


(a) Weeks 23 to 24 - no detectable air speed



(b) Weeks 23 to 24 - air speed 120 fpm

Heat Index during normal working hours for weeks 5 to 24	
Air speed [fpm]	Average Heat Index for period
Not detectable	90.5 F
120 fpm	84.3 F
200 fpm	82.1 F



(c) Weeks 23 to 24 - air speed 200 fpm

Figure 7.2.5: Heat index calculated with different air speeds for regular working hours during reference week (Zapka, et. al. (2014)

7.3 Site Visit to Whole FOOD Market in Kailua, Oahu

Background: In March of 2017 the authors visited the Whole Foods Market (WFM) in Kailua, Oahu. WFM had the first liquid desiccant system installed in Hawaii. As with supermarkets in general, there is a high latent load within the WFM, which cannot be readily removed from the space. The source of humidity related problems is the intrusion of warm and humid outdoor air through the frequently open entrance doors and the numerous refrigerated cases, and the associated significant amount of condensation. WFM had opted to install a liquid desiccant system with a large array of solar panels to provide hot water for desiccant regeneration. The liquid desiccant systems operated in parallel with a conventional roof mounted AC unit. The dehumidified air was mixed with the return air that was supplied to the store. The system stopped operating due to problems with the liquid desiccant absorber (conditioner) and the regenerator. The liquid desiccant technology owner shared with the authors that the problems of the conditioner and regenerator was based on material problems. A new type of conditioner and regenerator, based on a different design has fixed the problems.

Room specifics: The has 25,000 sqft floor area and a 25 feet ceiling height. The space has many refrigerated cases.

Type of space conditioning: The space is cooled by a conventional Roof top AC unit (capacity not known). The dehumidification is supported by the parallel air supply of dehumidified air by the liquid desiccant system.

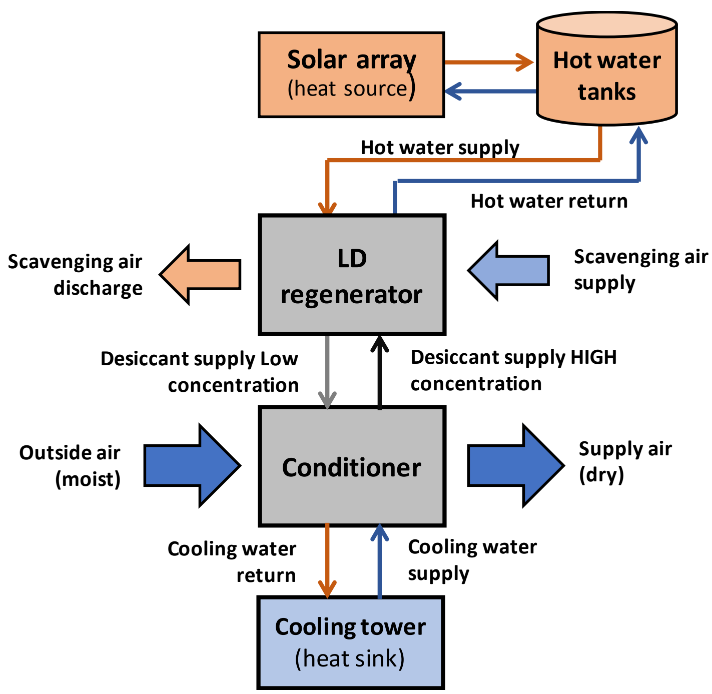


Figure 7.3.1: Basic process diagram of liquid desiccant system for WFM Kailua

The basic process diagram indicates the main system components:

Conditioner: Outside air passes through liquid desiccant solution and is dried (Heat sink of latent heat of fusion for desiccants = cooling tower)

Regenerator: Liquide desiccant solution concentration is increased by applying heat (Heat source for regeneration of desiccant solution = Solar panels)

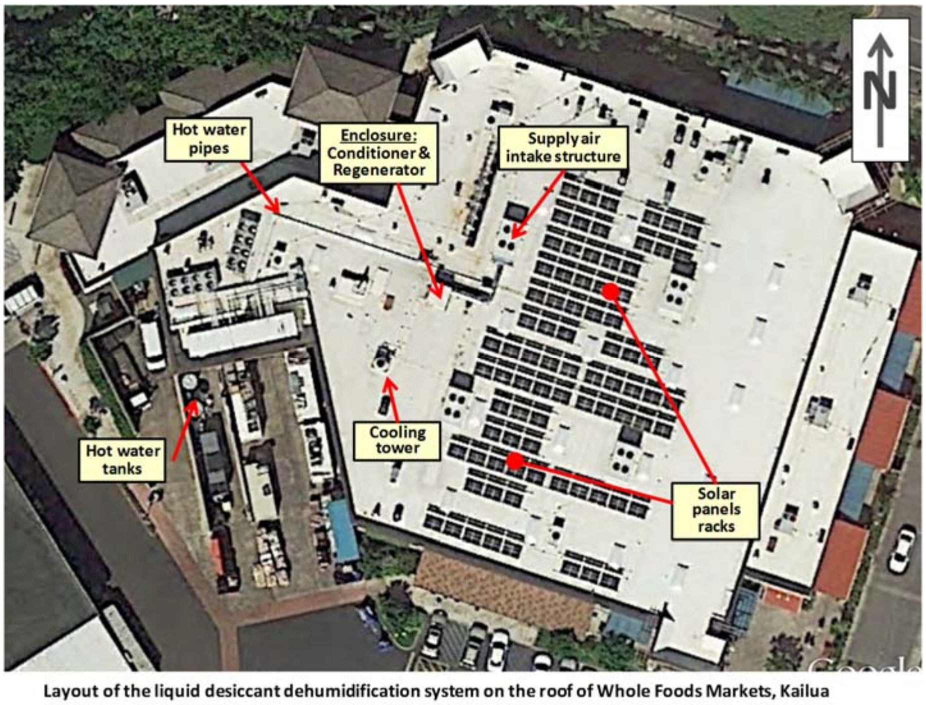
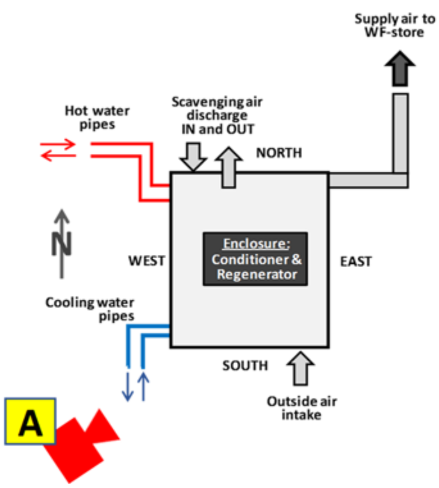


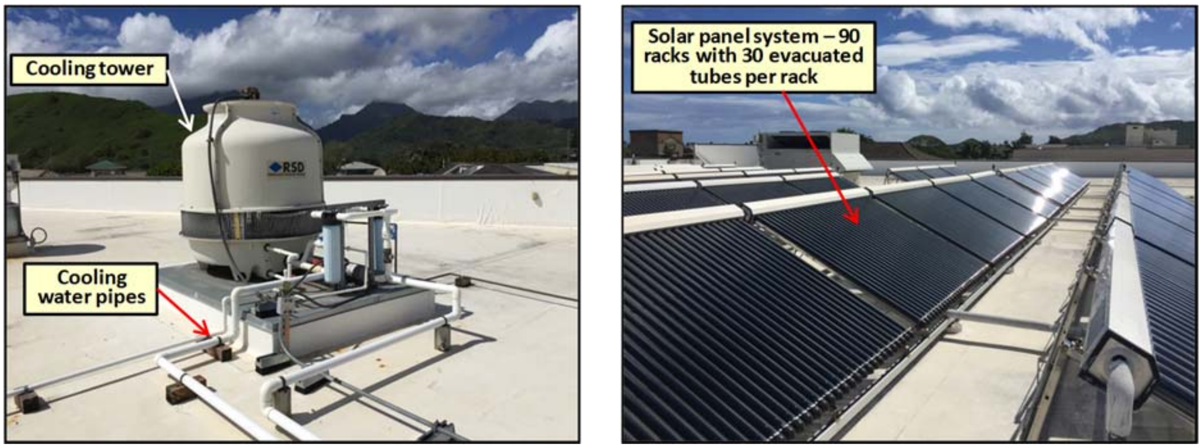
Figure 7.3.2: The liquid desiccant system located in the roof of WFM

The image shows the large solar thermal installation with 90 tube racks with 30 evaporated tubes each.



View A: Enclosure of the Conditioner and regenerator

Figure 7.3.3: Enclosure of the liquid desiccant conditioner and regenerator; fans, filters, pumps and controls are all inside the enclosure



Cooling tower | Solar panel system

Figure 7.3.4: Cooling tower and solar panel system

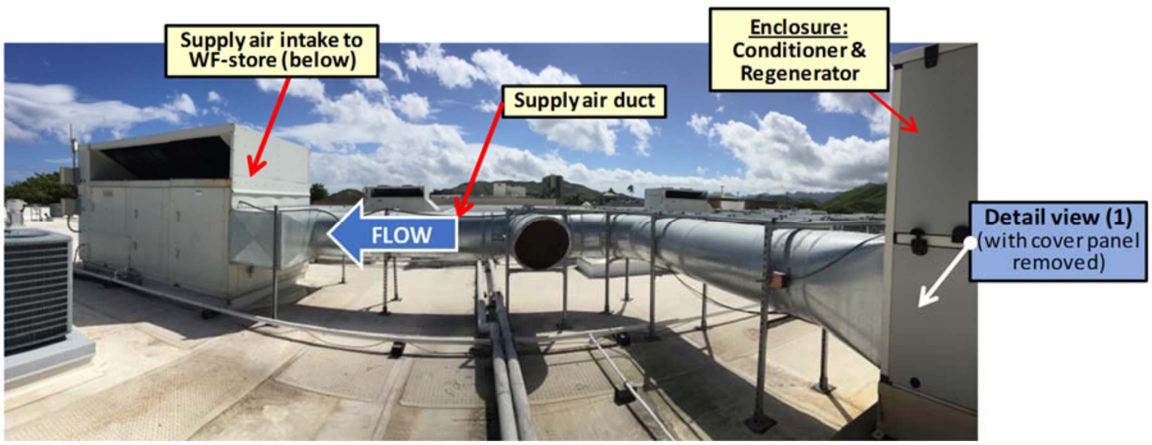
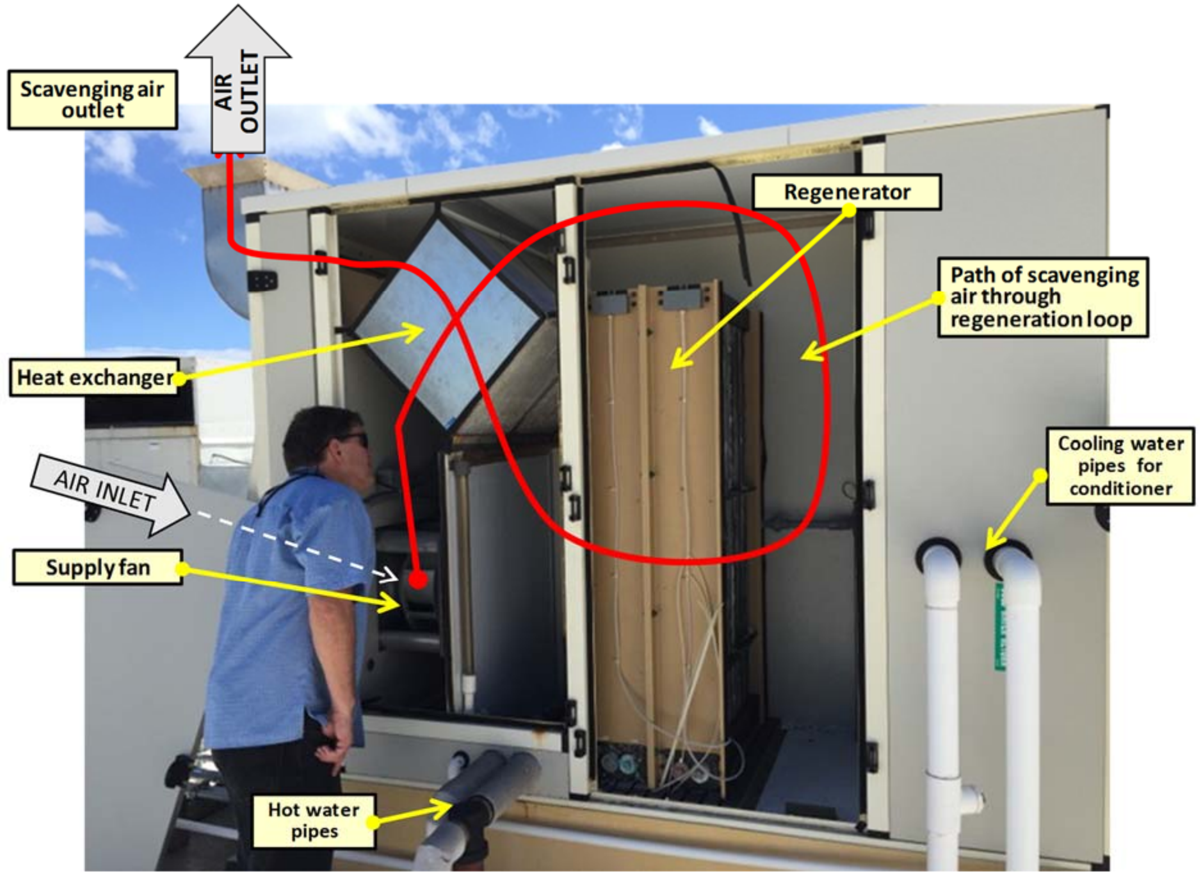
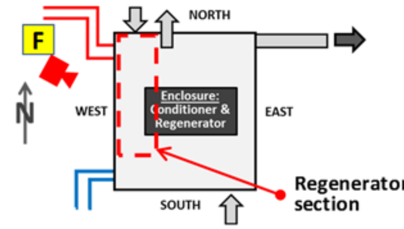


Figure 7.3.5: Supply air duct downstream of the conditioner

Figure 7.3.4 shows the cooling tower, which rejects the latent heat of fusion of the desiccant solution generated inside the conditioner, and the solar panel system, which provides heat for the regeneration of the liquid desiccant. Figure 7.3.5 shows the air supply duct downstream of the conditioner. The dried supply air coming from the conditioner is mixed with the supply air from the conventional rooftop AC-unit.

Figures 7.3.6 through 7.3.8 depicts the enclosure with the covers removed, thus showing the details of conditioner and regenerators.





The figure shows the scavenger air flow through the conditioner. Incoing outside air is flowing through a heat exchnager which preheats the air going to the regenerators.

Figure 7.3.6: View E of the liquid desiccant regenerator (see hot water pipes, which supply the solar heat for regeneration)

The figure shows deterioration of the regenerator unit. The cause of the deterioration and ultimately decommissioning of the regenerator unit was the design and construction of the internally heated regenerator heat exchanger. In this older design, plastic heat exchanger plates were glued to a plastic manifold. Hot water circulated inside the heat exchanger plates and heated the liquid desiccant which flowed downwards, outside the plates. The glued connections showed signs of leakage which resulted in a range chemical reactions rendering the system operating below the design intent. In newer installations of similar liquid desiccant system, a different design of the heat exchanger is use. The new design has been operating well.

Figure 7.3.7: Details of the liquid desiccant regenerator

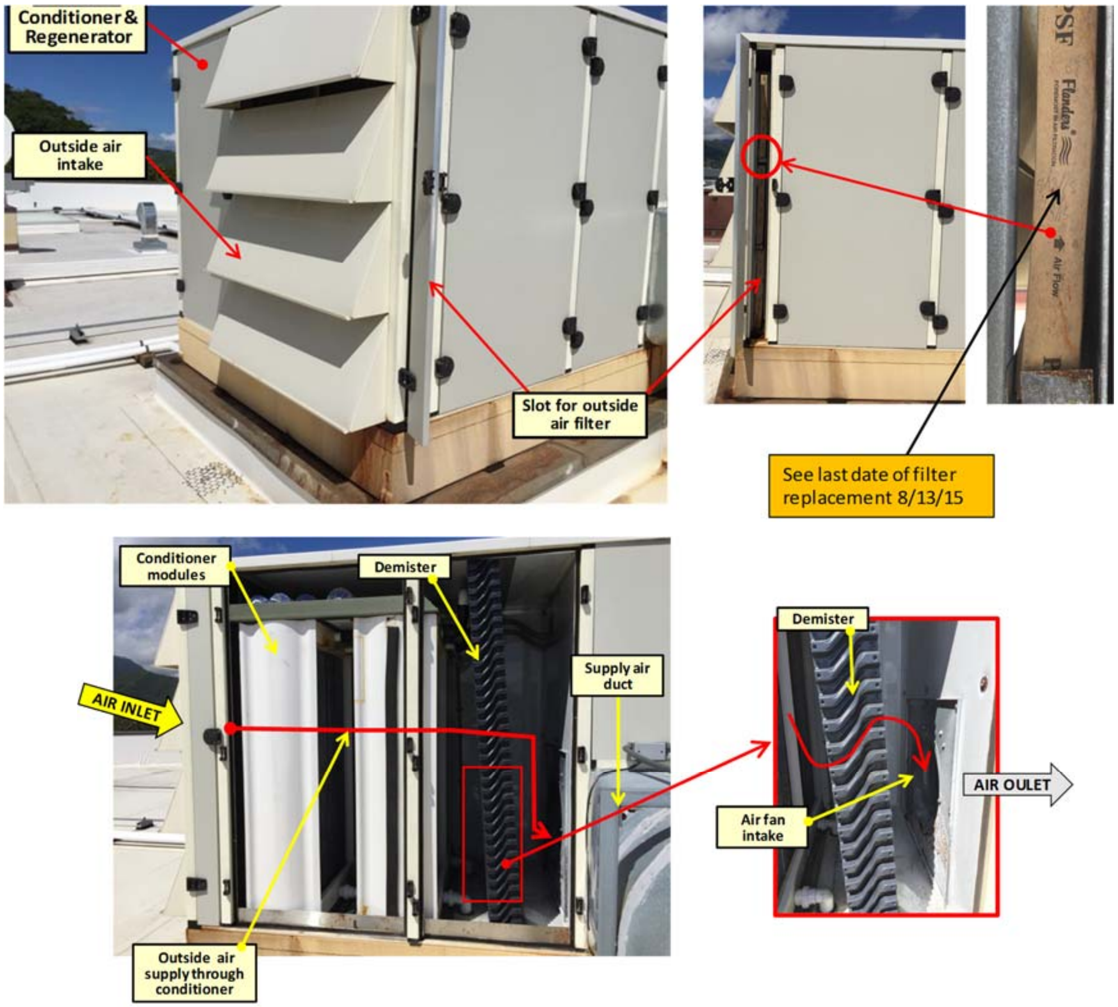
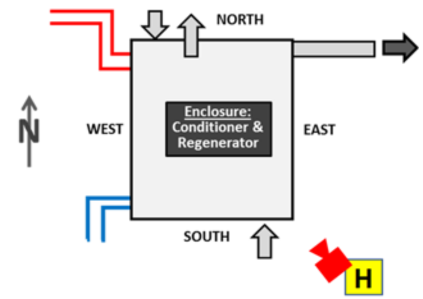
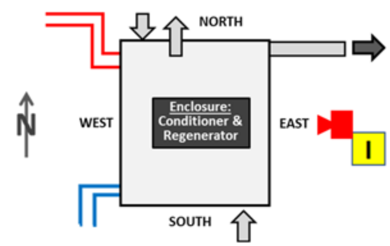


Figure 7.3.8: Details of the liquid desiccant conditioner



View H: The figure shows the intake of the outside air. The outside air first passes through a filter. The cover for the conditioner unit is still in place



View I: The figure shows the flow of outside air through the conditioner (two separate units). Downstream of the conditioner the dried air flows through a demister before it enters the supply air duct that conveys the supply air to the air intake of the store area below.

Conclusions of the site visit: The design intent of the liquid desiccant installation at the Whole Foods market in Kailua, Oahu, was to lower the indoor humidity level to mitigate condensation on the chilled cases inside the store. The Liquide desiccant system was configured to use renewable energies for the process heat rejection and supply, through a conventional cooling tower and a large array of solar panels, respectively. Therefore, electric energy consumption was significantly lowered. The hot water tanks that were included in the hot water loop of the solar panel provided energy storage capacity in form of concentrated desiccant solution for hours of the day when solar thermal energy supply was not sufficient or absent. While the configuration of the system with its use of solar and environmental energy conversion is very capable for Hawaii, the design systematic of the conditioner and regenerator plastic heat exchangers caused unsatisfactory performance. In subsequent system installations the design of the conditioners and regenerator units was changed and their performance has been good.

7.4 Site Visit to Whole FOOD Market in Tustin, California

Background: In May of 2017 one of the authors visited the Whole Foods Market (WFM) in Tustin, California. WFM successfully a first liquid desiccant system that is a follow-up design of the system used in Kailua (see Section 6.6). As with supermarkets in general, there is a high latent load within the WFM, which cannot be readily removed from the space. The source of the humidity related problems is the intrusion of warm and humid outdoor air through the frequently open entrance doors and the numerous refrigerated cases, which experience significant amounts of condensation.

The climatic conditions in Tustin require additional dehumidification in the WFM during several months of the year. WFM decided to install a liquid desiccant system to provide additional dehumidification capacity without the need to install additional conventional rooftop AC-units which use conventional cooling coil dehumidification. The installation liquid desiccant systems uses natural gas to provide heat for desiccant regeneration.

Room specifics: The store has 55,000 sqft of floor area and a 25 feet ceiling height. The space has many refrigerated cases. There are several tenants in the store, which prepare and sell food.

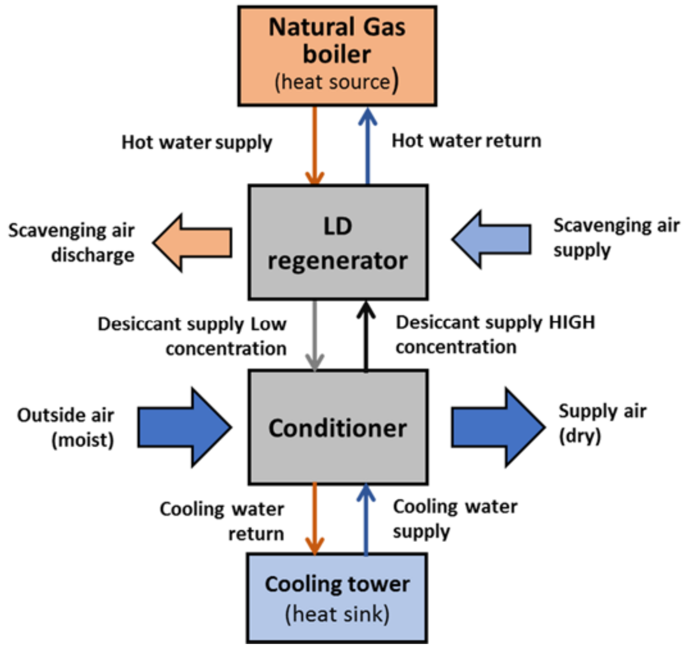
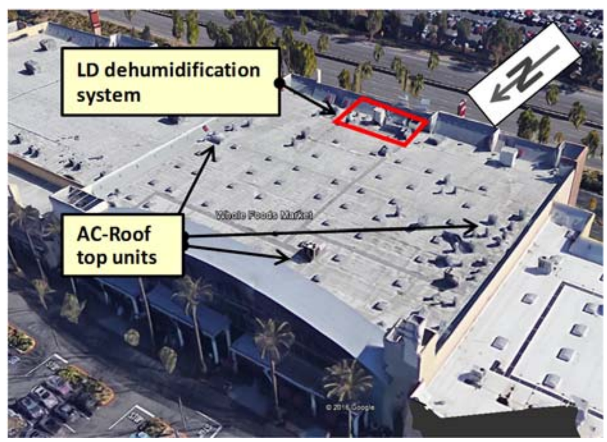


Figure 7.4.1: Basic process diagram of liquid desiccant system for WFM Tustin, CA

The basic process diagram indicates the main system components:

<u>Conditioner</u>**:** Here the outside air passes through liquid desiccant and is dried (Heat sink of latent heat of fusion for desiccants = cooling tower)
<u>Regenerator:</u> Liquide desiccant solution concentration is increased by applying heat ((Heat source for regeneration of desiccant solution = natural gas)

Overview of the WFM Tustin



Configuration of the roof top of the WFM in Tustin

Figure 7.4.2: location of the WFM Tustin

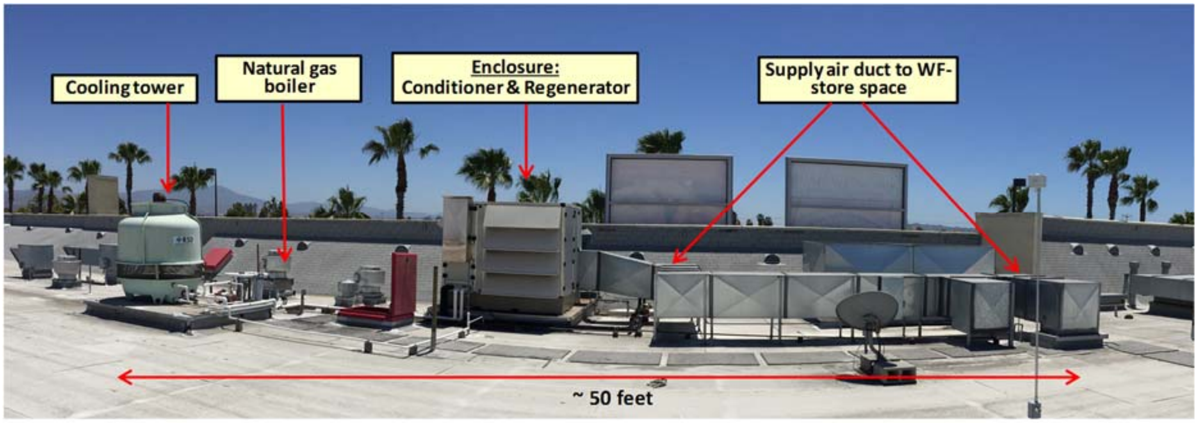


Figure 7.4.3: View of the liquid desiccant system installed on the roof of the WFM store

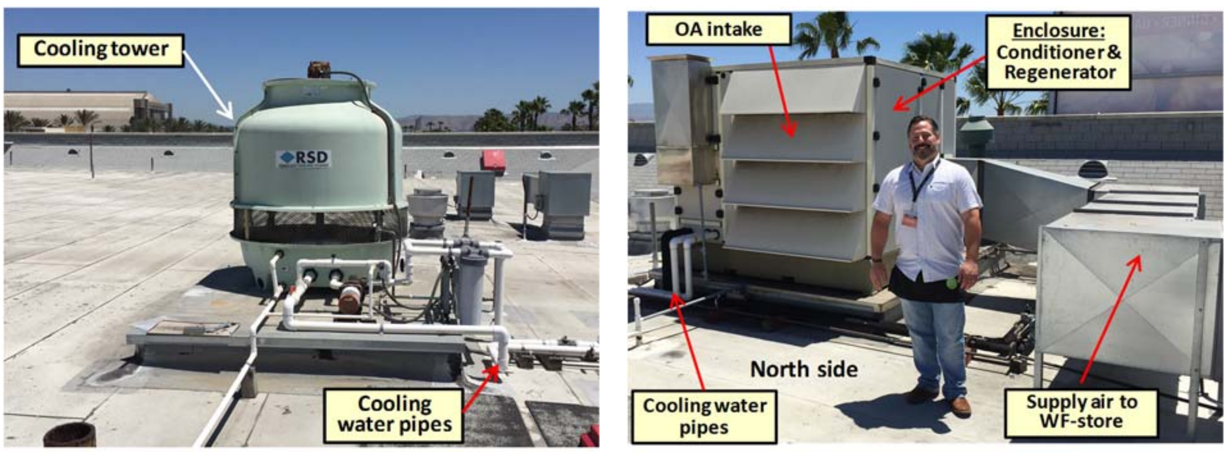


Figure 7.4.4: Cooling tower and system housing (Left images: Cooling tower; Right image: System housing (enclosure conditioners & regenerator); WFM operations manager depicted

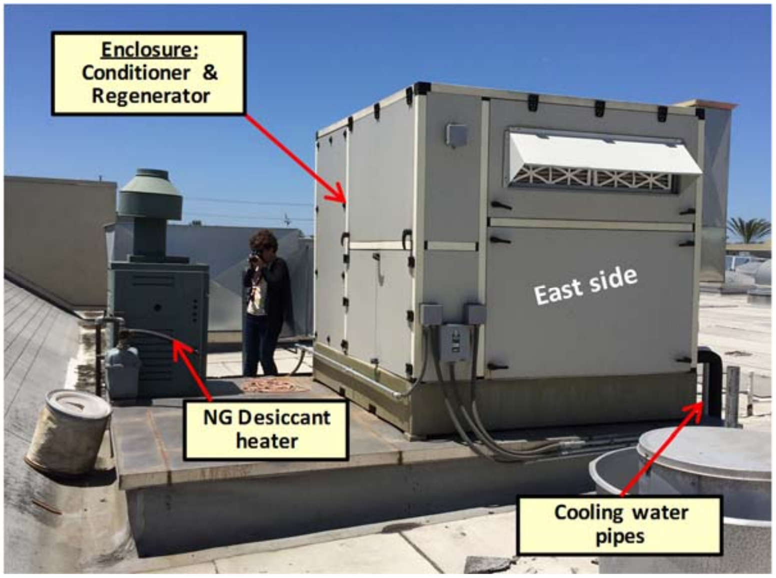


Figure 7.4.5: System housing (enclosure conditioners & regenerator)

The image shows the system housing from the East.

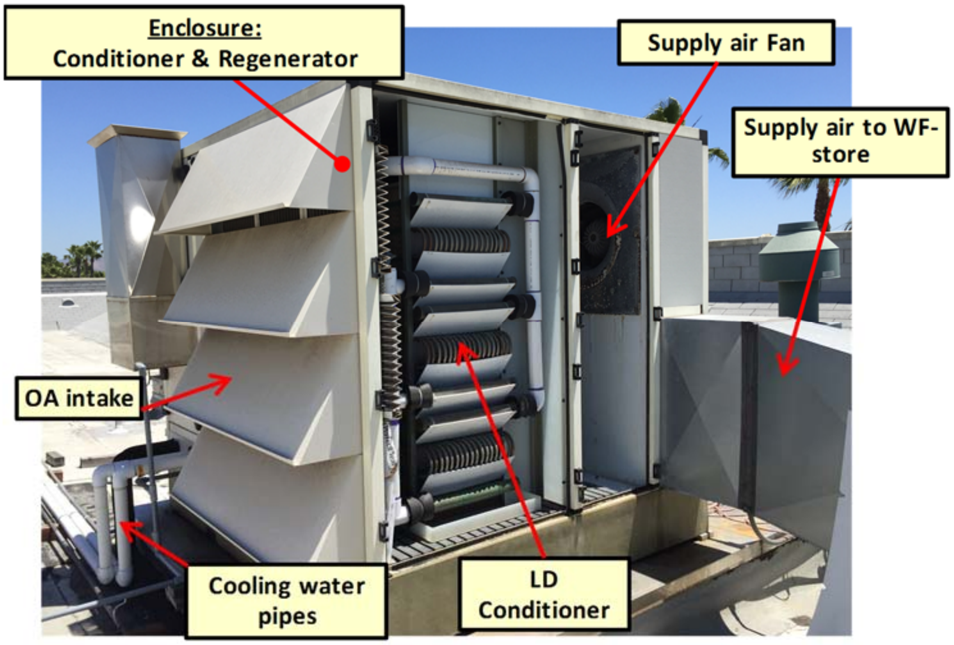


Figure 7.4.6: The liquid desiccant conditioner

With covers of the system enclosure removed.

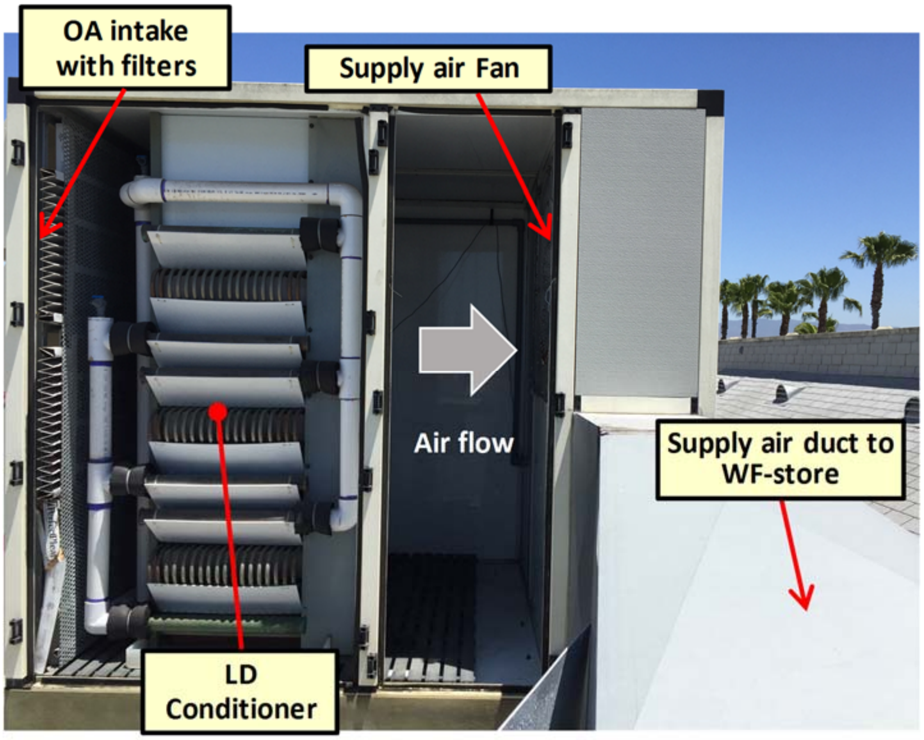


Figure 7.4.7: The liquid desiccant conditioner

With covers of the system enclosure removed.

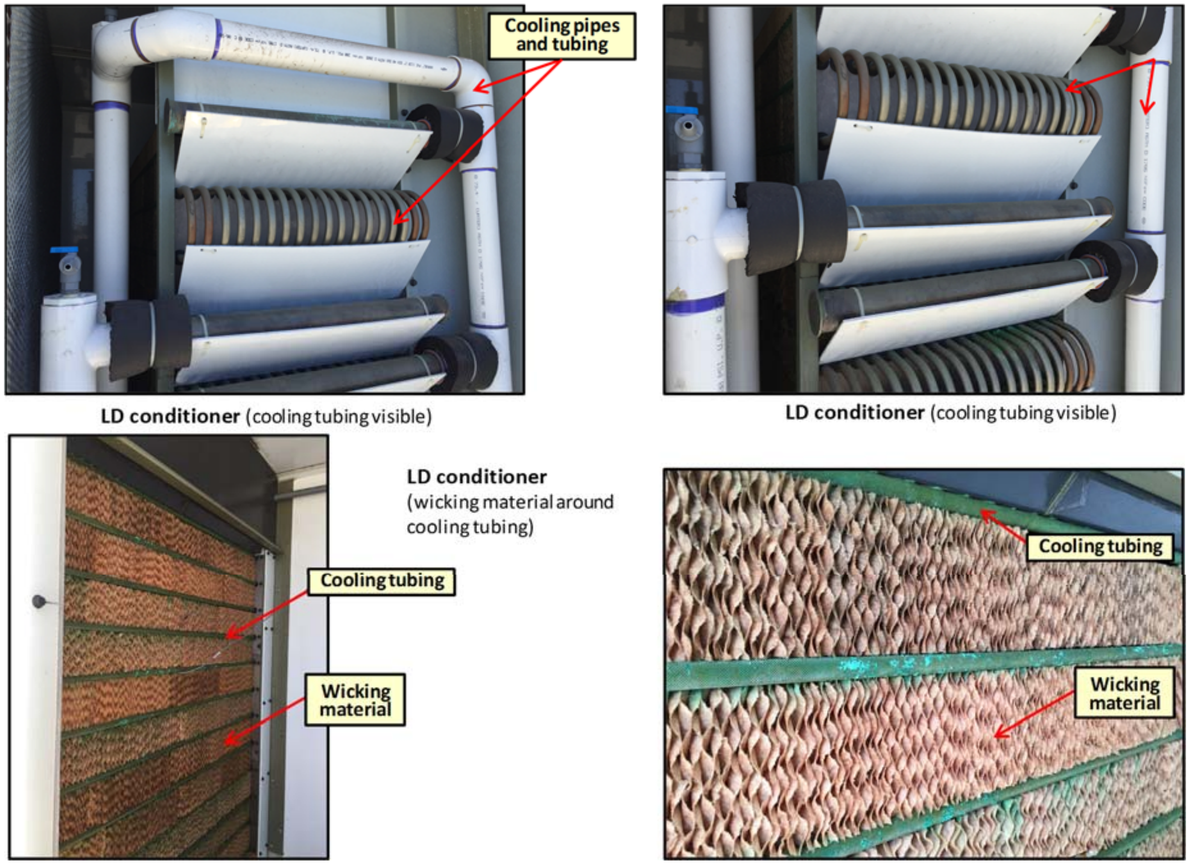


Figure 7.4.8: Liquide desiccant conditioner

The images show the new design of the liquid desiccant conditioner, which replaces the heat exchanger design used of the WFM in Kailua. In the new heat exchanger design plastic plate heat exchanges are replaced by cooper tubing heat exchanger design. The copper tubing is surrounded by wicking material, a lattice of corrosive resistant soft material. Liquid desiccant solution flows downward through the wicking material that is placed between the tubing. Air is flowing through the lattice of the wicking material. The cooling water supply piping is made of regular PVC pipes. The supply pipes connect to the header manifold of the copper tubing.
The regenerator units are built in the same way, but here the hot water pipes are insulated.

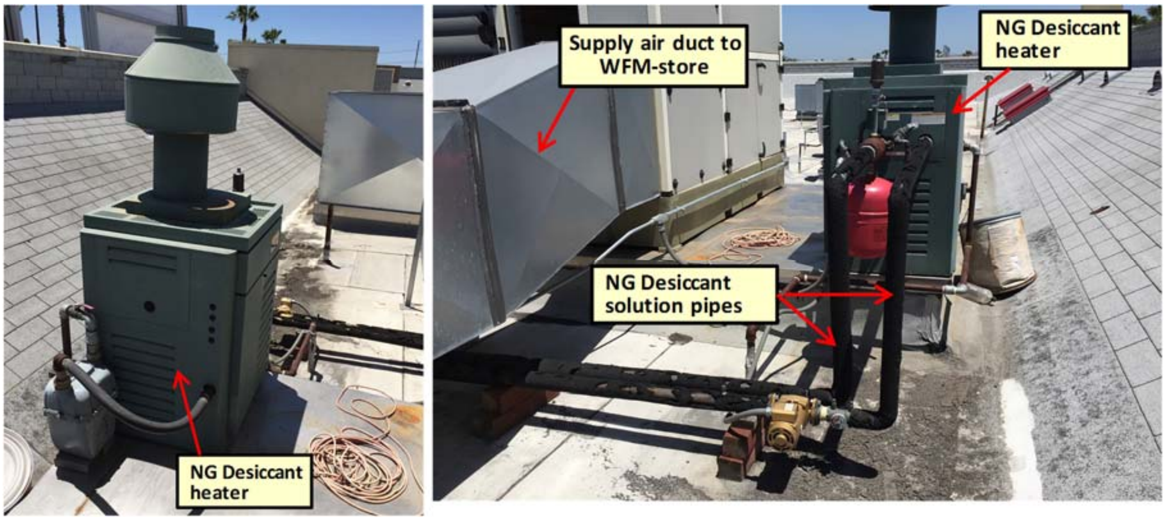


Figure 7.4.9: The Natural gas (NG) boiler; heat source for the liquid desiccant regeneration

Conclusion of the site visit: The liquid desiccant installation at the Whole Foods market in Tustin been has performing to the satisfaction of the WFM operator. The system has a significantly smaller footprint than the liquid desiccant system on the WFM Kailua store roof. This is due to the use of natural gas in lieu at the WFM Tustin in lieu of the solar heat that provide the thermal heat for desiccant regeneration at the WFM Kailua system. The new design of the liquid desiccant conditioners and regenerator with tube instead of a plate heat exchanger will be used for the proposed pilot installation in Hawaii.

7.5 Site Visit to Kahuku High School

Background: In April of 2017 the authors met with decision makers of the Hawaii Department of Education (DoE). At the meeting, issues of humidity related problems at educations facilities were discussed. The DoE indicated that mold problems have been encountered in several DoE facilities. Included in these location with humidity related problems are naturally ventilated classrooms, specifically in portable naturally ventilated classrooms. The project team and the DoE agreed to conduct a site visit to inspect conditions at the affected class rooms.

Room specifics: There are presently about 25 portable class rooms at the Kahuku High School, with a combined sqft floor area of about 30,000 sqft. All of the portable classrooms are naturally ventilated classrooms. Most of them have ceiling fans for added sensible cooling. The windows of the class rooms have louvered galls covers without insect screens. Apparently, bugs entering the class rooms with the naturally ventilated air flow is not a major problem. Some of the classrooms inspected by the author exhibited mold on ceiling and walls. Some of the classrooms, which were considered tackling with the worst mold problems had conventional cooling coil dehumidifiers to mitigate humidity problems.

Type of space conditioning: With the exception of very few space containing computer equipment no spaces on the Kahuku High School grounds are air conditioned. All other spaces are naturally ventilated.

Annotated pictures of the site visit are presented in Figures 7.5.1 through 7.5.7.

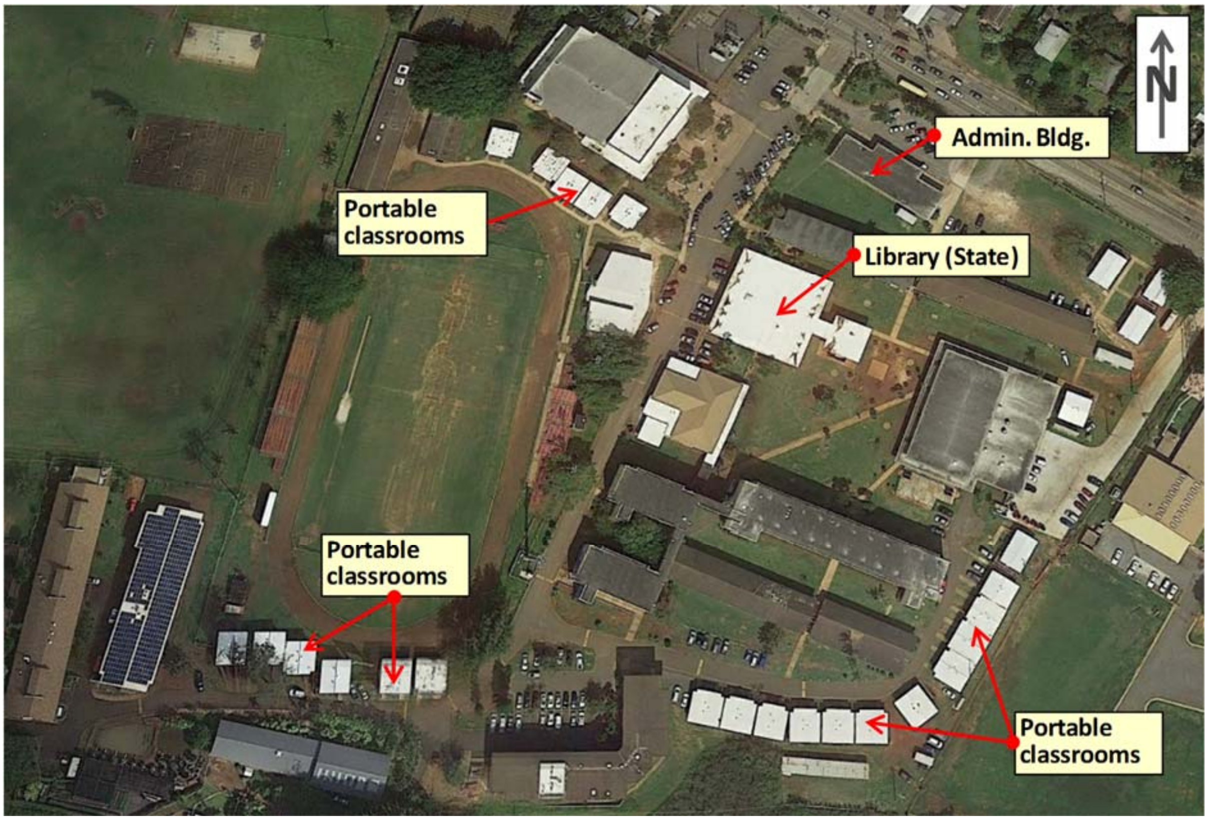


Figure 7.5.1: Overview of the grounds of Kahului High School, the portable class rooms are indicated

Figure 7.5.2: External views of one portable classrooms

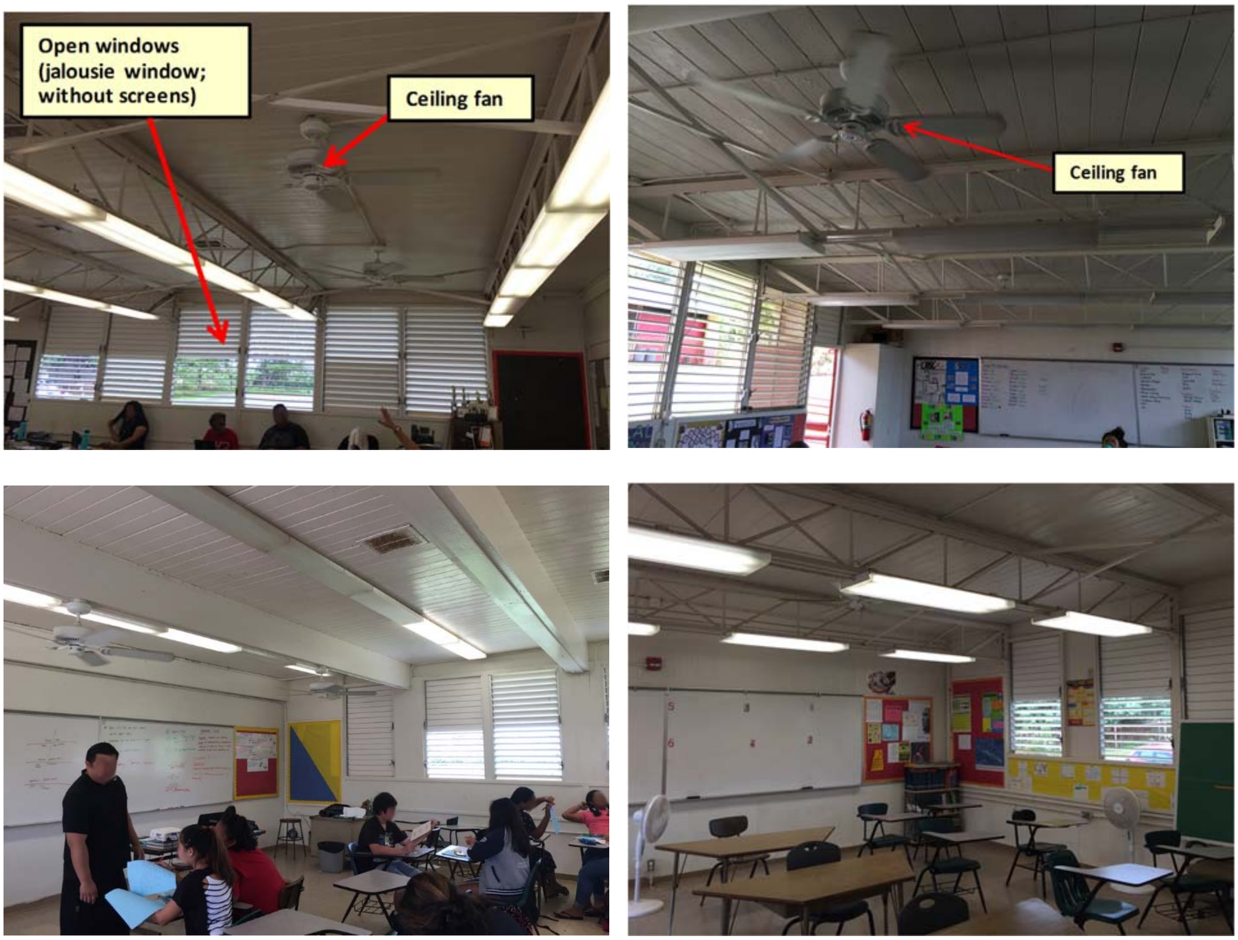


Figure 7.5.3: Inside configuration of portable classrooms

Figure 7.5.4: Some of the class rooms which were affected the most by mold growth and very high indoor temperatures. Typical indoor temperatures and R.H. for portables classrooms inspected: Air temperature range 85^{o}F - 87^{o}F, ceiling temperature range 84^{o}F - 85^{o}F, Wall temperature range 84^{o}F - 85^{o}F, R.H. 60% to 65%

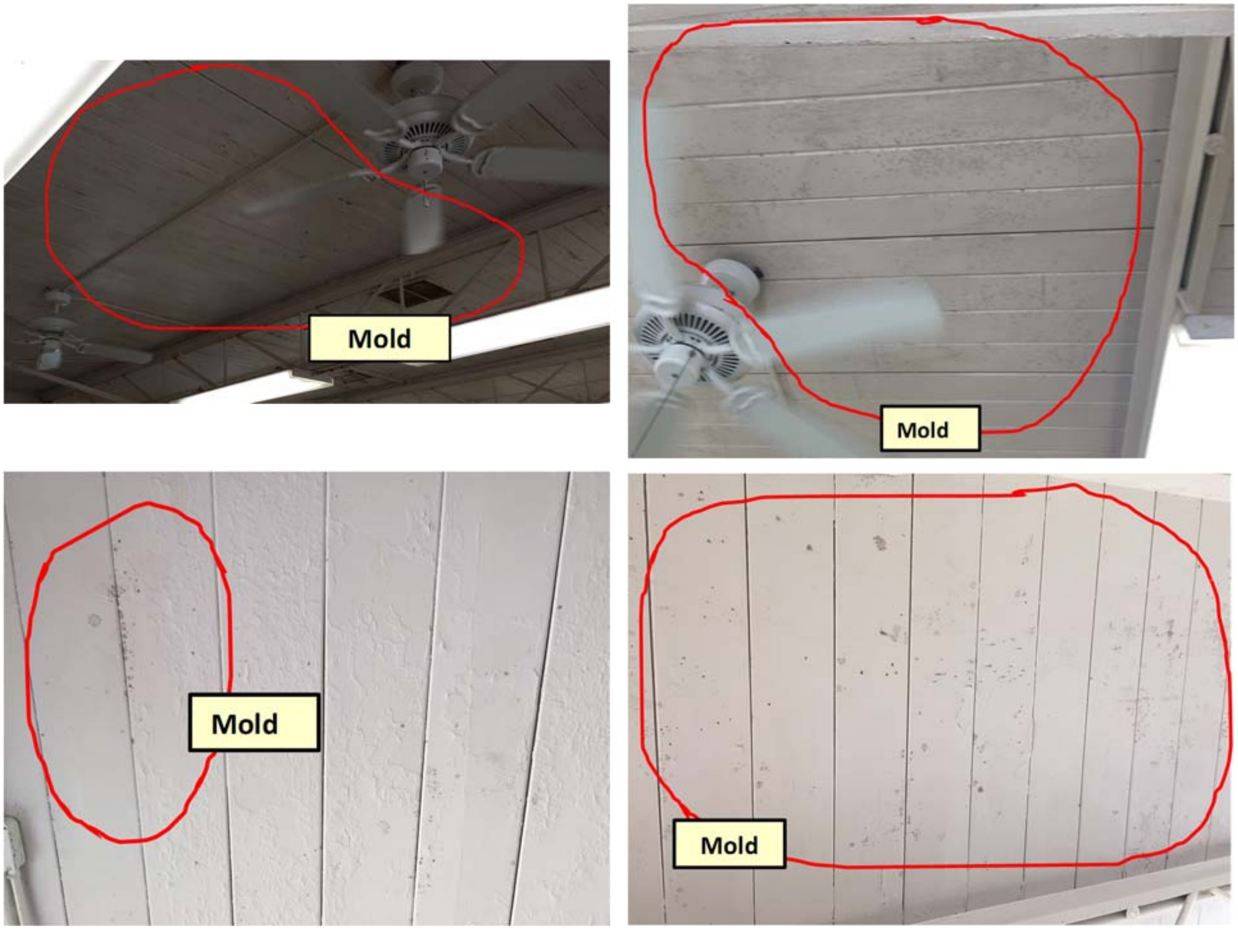


Figure 7.5.5: Typical mold growth on the room ceiling and walls

Figure 7.5.6: Mold growth in a space that was considered the most affected by mold, shown are the two portable dehumidifier that were used to lower the humidity level.

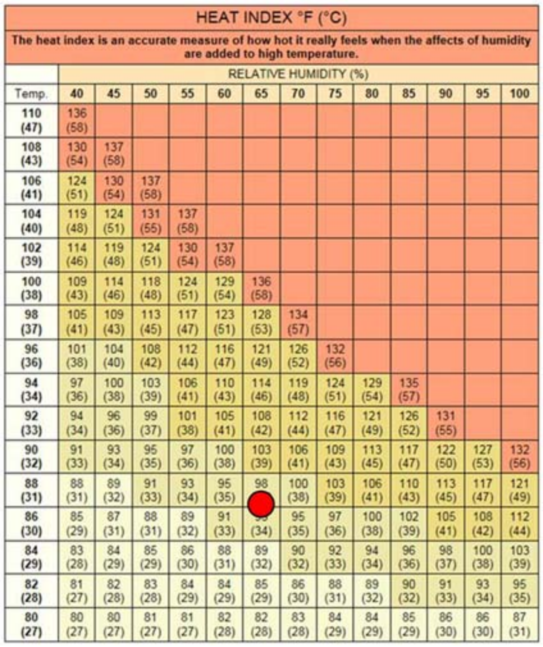
Typical indoor temperatures and R.H. for permanent (brick) buildings:

- Air temperature range 85^{o}F - 87^{o}F
- Ceiling temperature range 80^{o} - 81^{o}
- Wall temperature range 80^{o}F - 81^{o}F
- R.H. 60% to 65%

Figure 7.5.7: Classrooms inside permanent (brick) buildings

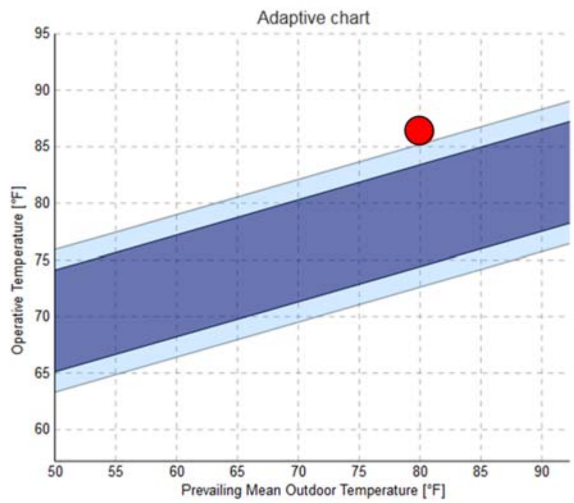
Conclusion of the site visit: The site visit demonstrated that poor indoor thermal comfort is provided in parts of the school. Measurements of the air and radiant temperatures as well as the relative humidity levels indicated higher than recommended indoor conditions. The portable classrooms had higher ceiling and wall temperatures than the permanent classroom with brick walls. The teachers interviewed suggested that the day the measurements were done was actually a “good” day compared with typical summer and early fall days, which have higher temperatures. Figure 7.5.8 shows average values of operative temperatures and RH measures in the class rooms. The data suggests temperature and humidity values to be outside the ASHRAE Adaptive comfort range and at a higher than satisfactory Heat index value.

Observations by the school staff indicated that mold growth was detected in selected portable classrooms after their roofs were upgraded with “cool roof” paint and some class rooms were equipped with wind driven turbine ventilators. A special site audit would be needed to evaluate the scope of the mold problem and appropriate mitigation measures.



HEAT INDEX °F (°C)													
The heat index is an accurate measure of how hot it really feels when the affects of humidity are added to high temperature.													
	RELATIVE HUMIDITY (%)												
Temp.	40	45	50	55	60	65	70	75	80	85	90	95	100
110 (47)	136 (58)												
108 (43)	130 (54)	137 (58)											
106 (41)	124 (51)	130 (54)	137 (58)										
104 (40)	119 (48)	124 (51)	131 (55)	137 (58)									
102 (39)	114 (46)	119 (48)	124 (51)	130 (54)	137 (58)								
100 (38)	109 (43)	114 (46)	118 (48)	124 (51)	129 (54)	136 (58)							
98 (37)	105 (41)	109 (43)	113 (45)	117 (47)	123 (51)	128 (53)	134 (57)						
96 (36)	101 (38)	104 (40)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	132 (56)					
94 (34)	97 (36)	100 (38)	103 (39)	106 (41)	110 (43)	114 (46)	119 (48)	124 (51)	129 (54)	135 (57)			
92 (33)	94 (34)	96 (36)	99 (37)	101 (38)	105 (41)	108 (42)	112 (44)	116 (47)	121 (49)	126 (52)	131 (55)		
90 (32)	91 (33)	93 (34)	95 (35)	97 (36)	100 (38)	103 (39)	106 (41)	109 (43)	113 (45)	117 (47)	122 (50)	127 (53)	132 (56)
88 (31)	88 (31)	89 (32)	91 (33)	93 (34)	95 (35)	98 [illegible]	100 (38)	103 (39)	106 (41)	110 (43)	113 (45)	117 (47)	121 (49)
86 (30)	85 (29)	87 (31)	88 (31)	89 (32)	91 (33)	[illegible] (34)	95 (35)	97 (36)	100 (38)	102 (39)	105 (41)	108 (42)	112 (44)
84 (29)	83 (28)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	92 (33)	94 (34)	96 (36)	98 (37)	100 (38)	103 (39)
82 (28)	81 (27)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	88 (31)	89 (32)	90 (32)	91 (33)	93 (34)	95 (35)
80 (27)	80 (27)	80 (27)	81 (27)	81 (27)	82 (28)	82 (28)	83 (28)	84 (29)	84 (29)	85 (29)	86 (30)	86 (30)	87 (31)

The NOAA heat index chart suggests that the combination of temperature and Relative humidity (RH) places the measured thermal conditions in the portable classrooms inside a “extreme caution” range



The ASHRAE 55 Adaptive comfort tool for naturally ventilated spaces indicates that the measured thermal conditions in the portable classroom are outside the compliance range

Figure 7.5.8: Assessment of thermal comfort conditions based on spot measurements in the classrooms

7.6 Site Visit to Cancer Center of the University of Hawaii

Background: In April of 2017 the authors visited the Cancer Center of the University of Hawaii located in Honolulu. The building was completed in 2013 and features several advanced HVAC. The goal of the site visit was to learn about the operators experience with chilled beams and the use of indirect evaporative cooling using the discharge air of the buildings. A large portion of the building, with lab facilities, receives 100% of outdoor air supply. The dried indoor air exhaust is used as the secondary air flow for the indirect evaporative cooling process, which provides additional sensitive cooling.

Type of space conditioning: The building is conditioned with a conventional chilled water system. The chilled water provides air handling units (AHU) with sensible and latent heat removal capacity. Downstream of the AHUs are chilled beams, which receive primary air supply to induce air movement over the water-to-air heat exchangers inside the chilled beams. Secondary chilled water supply is used to remove sensible load from the indoor air that is drawn into the chilled beams. The indirect evaporative cooling unit provides sensible cooling load by taking advantage of the low enthalpy of the indoor air discharge flow.

Figure 7.6.1: The Cancer Center, University of Hawaii (Source: Cancer Center website)

Figure 7.6.2 shows a typical chilled beam installation with primary air and cooling water supply and return piping in the Cancer Center. The chilled beam receives primary air from the air handing units. Warm indoor air is drawn into the chilled beam by the primary air discharge and the warm indoor air inside the chilled beam mixes with the cold primary air. Additional cooling is provided to the indoor air inside the chilled beam by the chilled water supply to the chilled beam. The chilled water supply to the chilled beams has a temperature range of 58° to 61°F. The indoor dew point is held below the chilled water supply to the chilled beams to avoid condensation.

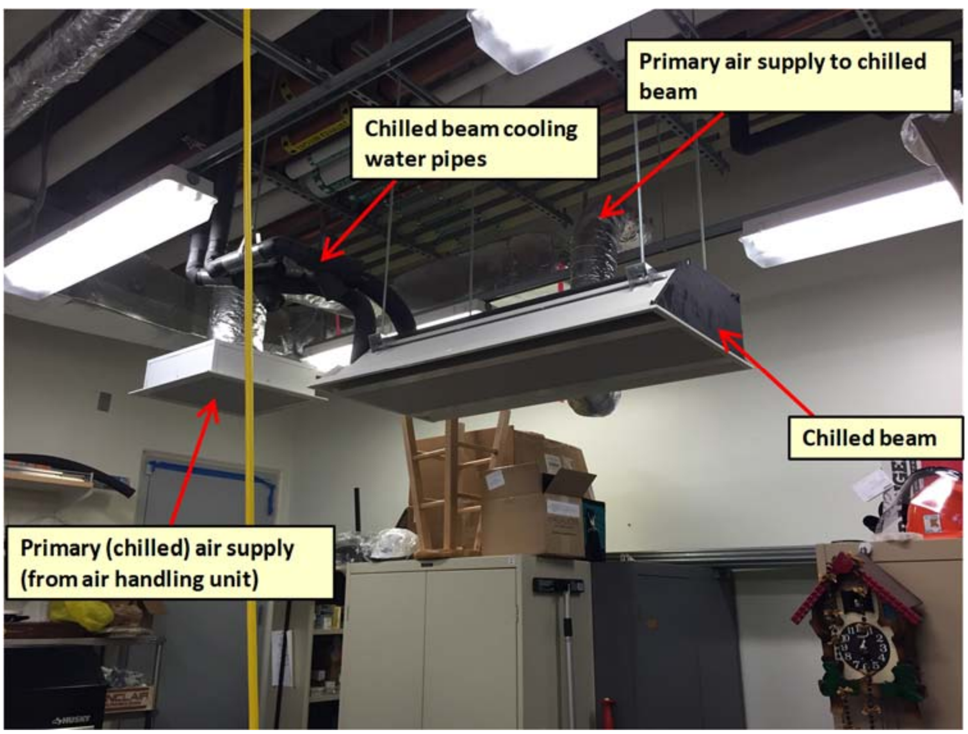


Figure 7.6.2: Chilled beam with primary air and cooling water supply

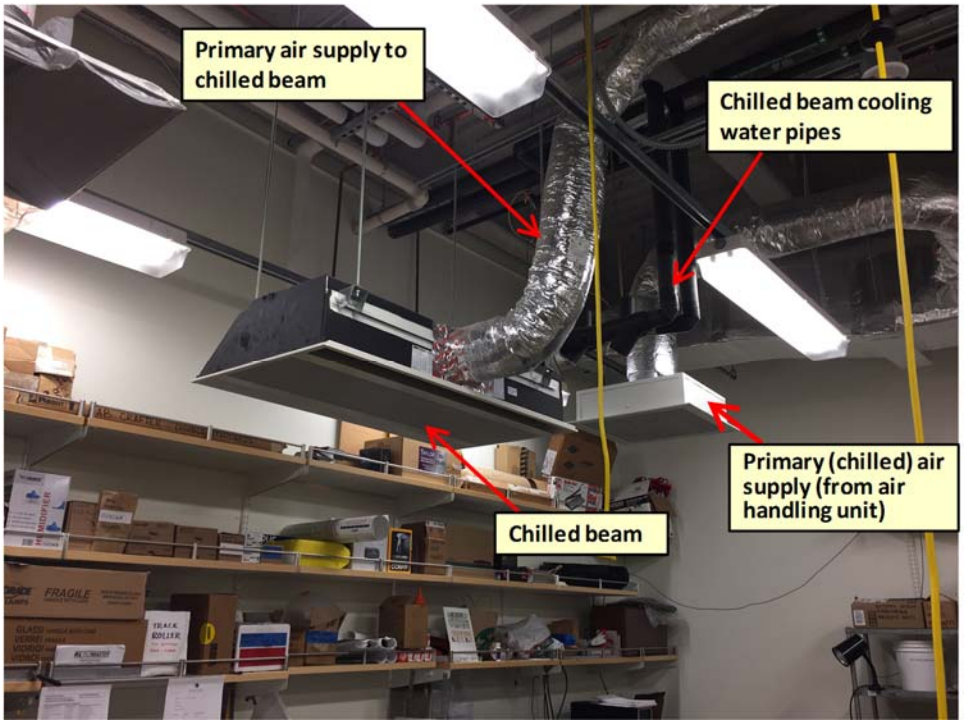
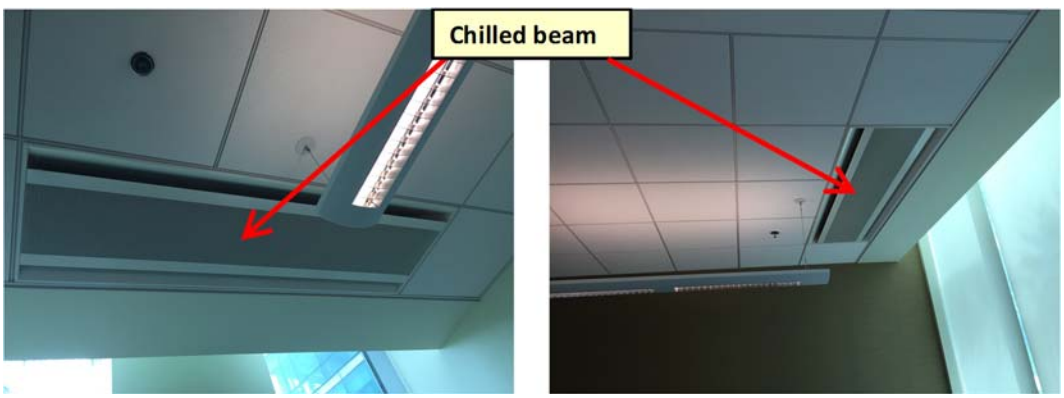


Figure 7.6.3: Chilled beam with primary air and cooling water supply



7.6.2: Chilled beams inside the cancer center

Conclusions of the site visit: The building operator indicated that there were no operational problems with the chilled beams. Condensation on the chilled beam, which have been encountered at times in other chilled beam installation in warm and humid climate has not occurred in the Cancer Center. Several occupants were interviewed by the authors and indicated that they enjoyed the thermal comfort provided by the chilled beams. The operator suggested that the indirect evaporative cooler unit did not function as intended. The likely cause was a deteriorated evaporative pad which needed replacement. The design approach of using the low relative humidity of the indoor air as the secondary air supply for an indirect evaporative cooler provides for an effective energy recovery.

7.7 Site Visit to the NOAA Building on Ford Island

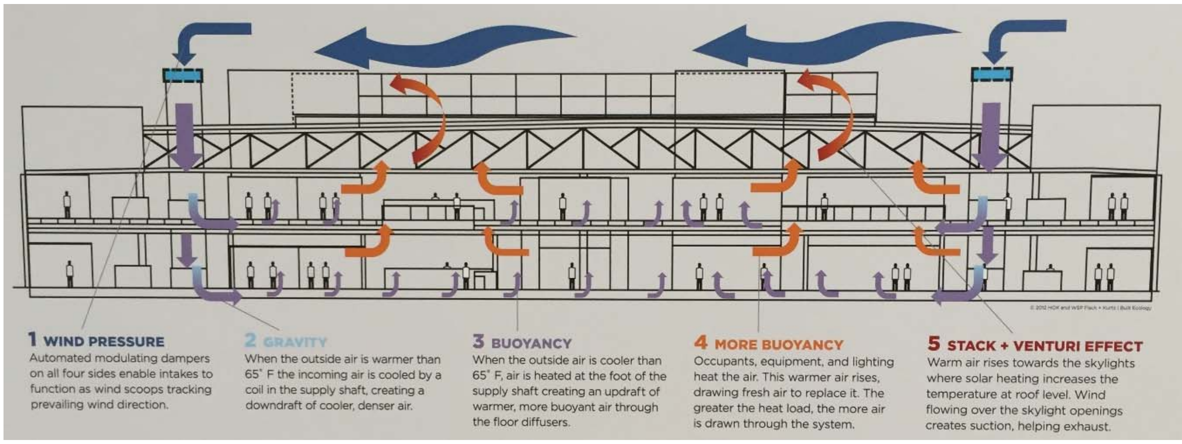
Background: In May 2017, the authors visited the NOAA Inouye Regional Center (IRC) on Ford Island in Pearl Harbor, Oahu. The facility is located on a 35-acre parcel and included four restored historic buildings in addition to outdoor facilities. The four connected buildings have received Leadership in Environmental and Energy Design (LEED) Gold Certification, in part for its innovative building cooling and conditioning system. The four buildings house offices, library, cafeteria, auditorium, classroom, dive center, training rooms, conference and meeting rooms, laboratories.

Type of space conditioning: The buildings are cooled and conditioned with a combination of conventional chilled water system, derived for several mechanical chillers, passive ventilation using stack effect and wind towers on the roof and cold seawater for pre-cooling derived from 1,500 feet depth. The chilled water system provides sensible and latent load removal capacity to air handling units. Displacement ventilation is used in most offices and hallways. Chilled beams are used in offices and lab spaces. Cold seawater at around 70^{o}F is used for pre-cooling of the chilled water generation. Sections of the indoor walls are actively cooled and thus provide radiant cooling.

U.S. Navy photo, NAVFAC Hawaii Public Affairs/Released.

Figure 7.7.1: NOAA Inouye Regional Center (IRC) on Ford Island in Pearl Harbor, Oahu

Figure 7.7.2 illustrates the passive ventilation approach of the NOAA building that augments the chilled water cooling systems. The intended building cooling approach includes rooftop wind “scoop” towers which have adjustable damper inlets at four directions to selectively capture air movement and convey the wind downwards into the building. The incoming air is cooled by cooling coils which remove sensible and latent thermal loads. Stack effect is used to discharge indoor air to rooftop ventilation.



`Figure 7.7.2: Passive ventilation and cooling approach (source NOAA)

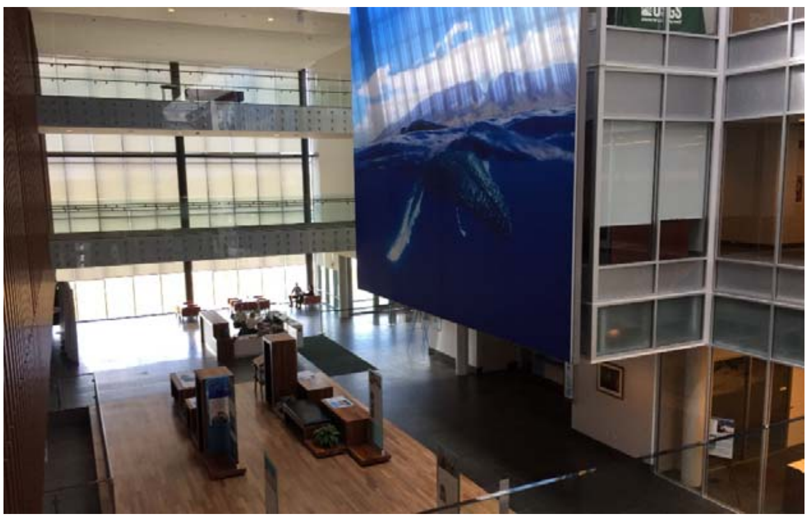


Figure 7.7.3: The high vaulted open spaces provide stack effect for passive ventilation

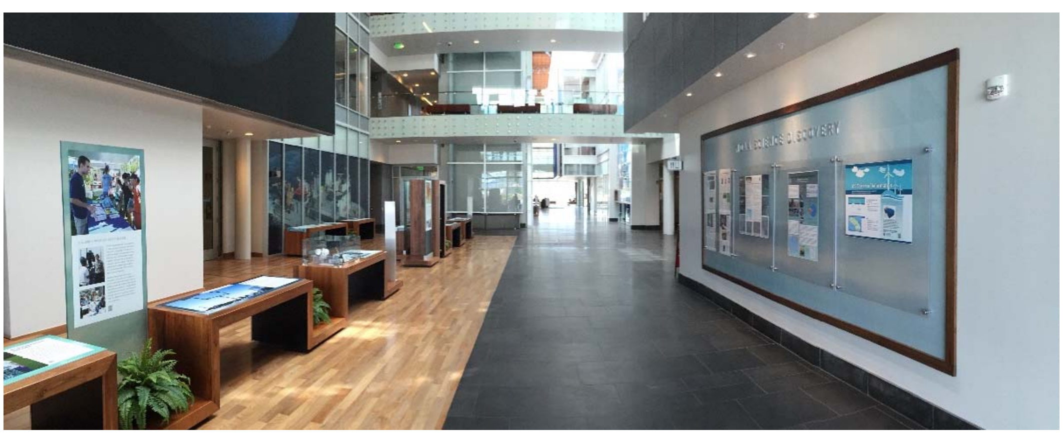
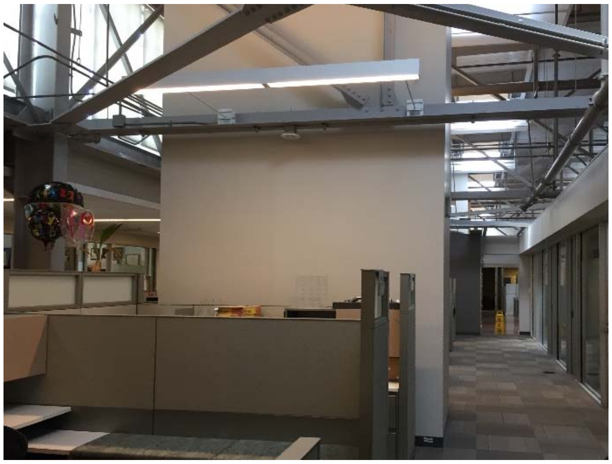
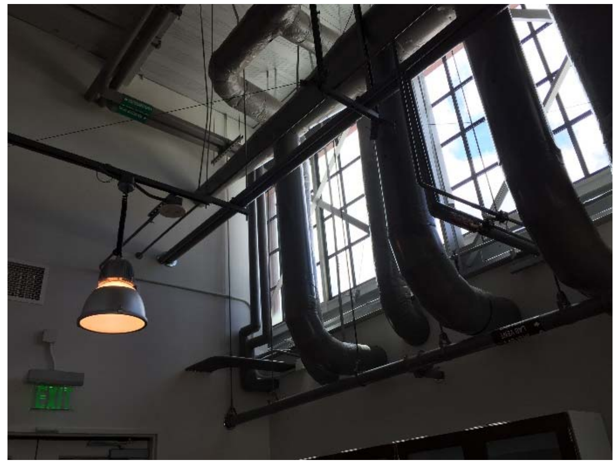


Figure 7.7.4: NOAA building lobby with actively cooled walls providing radiant cooling effect



Shaft connecting the wind “scoop” towers with lower level air distribution; cooling coils in the shaft remove sensible and latent load from the outdoor air supply



Internal ventilation and cold-water pipes

Figure 7.7.5: Internal ventilation and cooling equipment

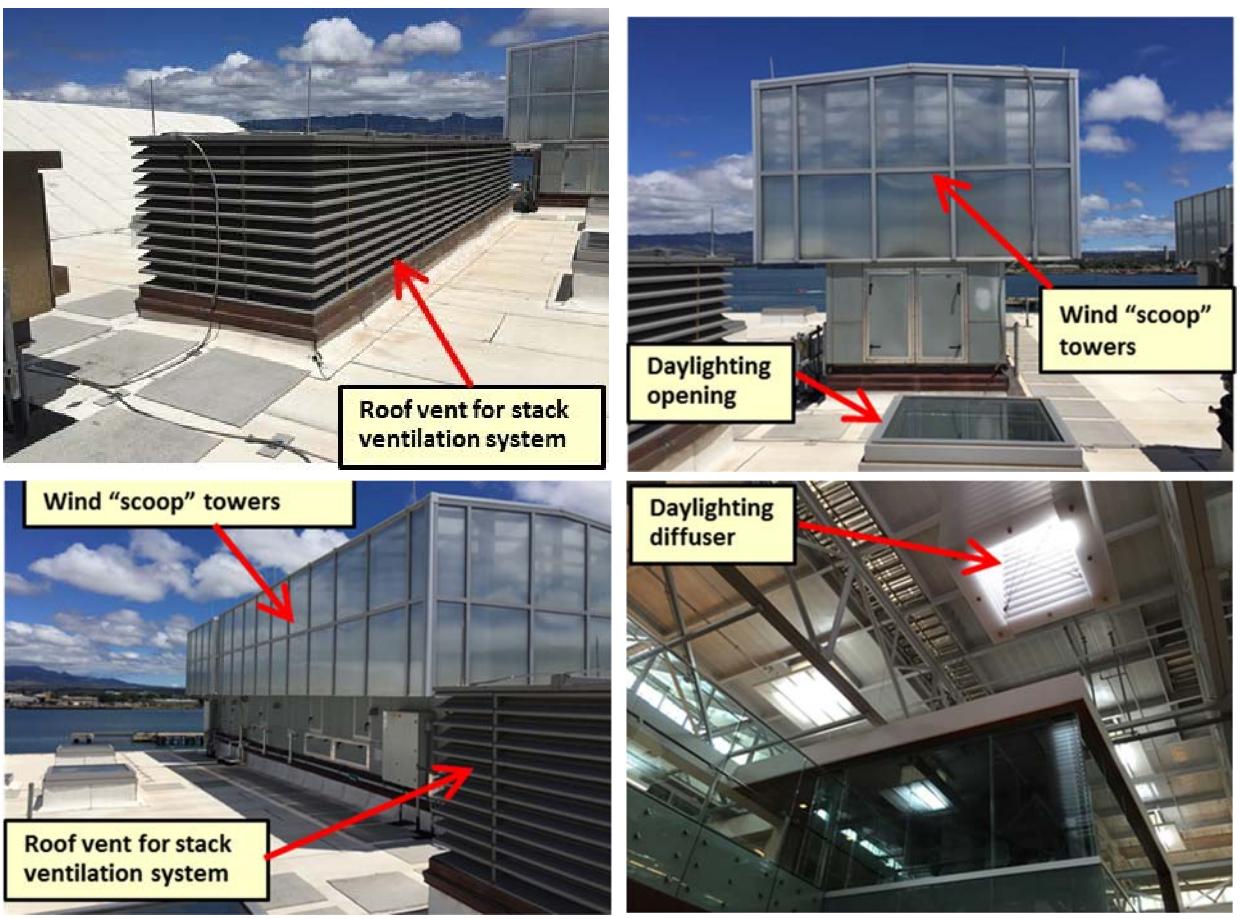
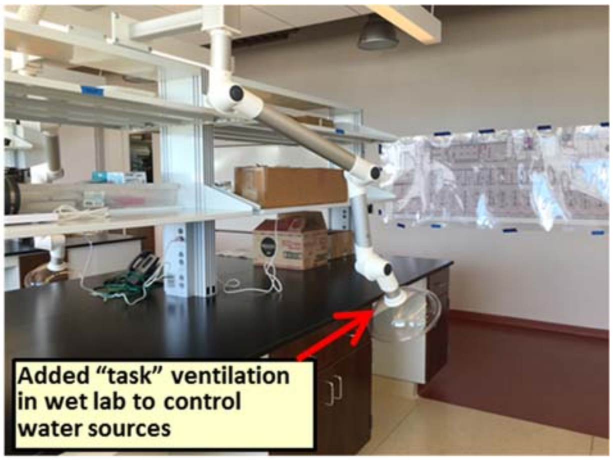
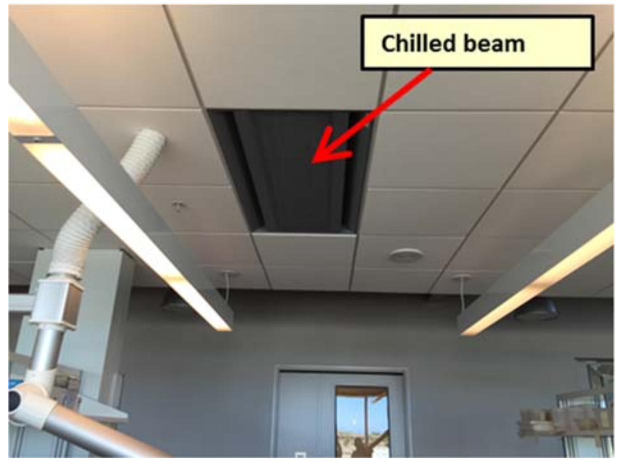


Figure 7.7.6: Passive ventilation equipment located on the NOAA building roof





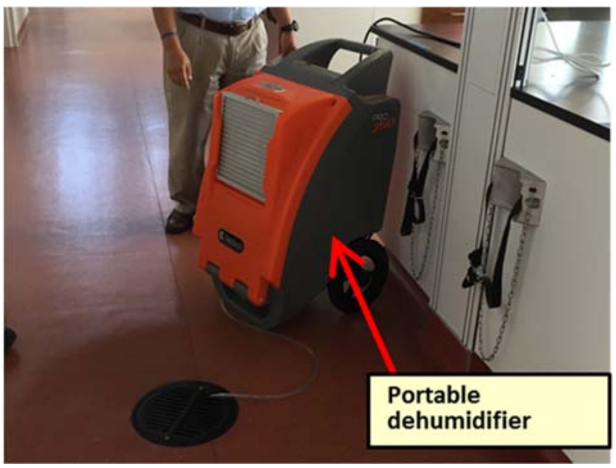


Figure 7.7.7: The NOAA wet lab facilities are equipped with chilled beams and 100% outside air supply.

Periodically dew point reduction is insufficient and minor condensation occurs on the chilled beam equipment. The staff uses portable dehumidifier to lower the dew point to an appropriate value

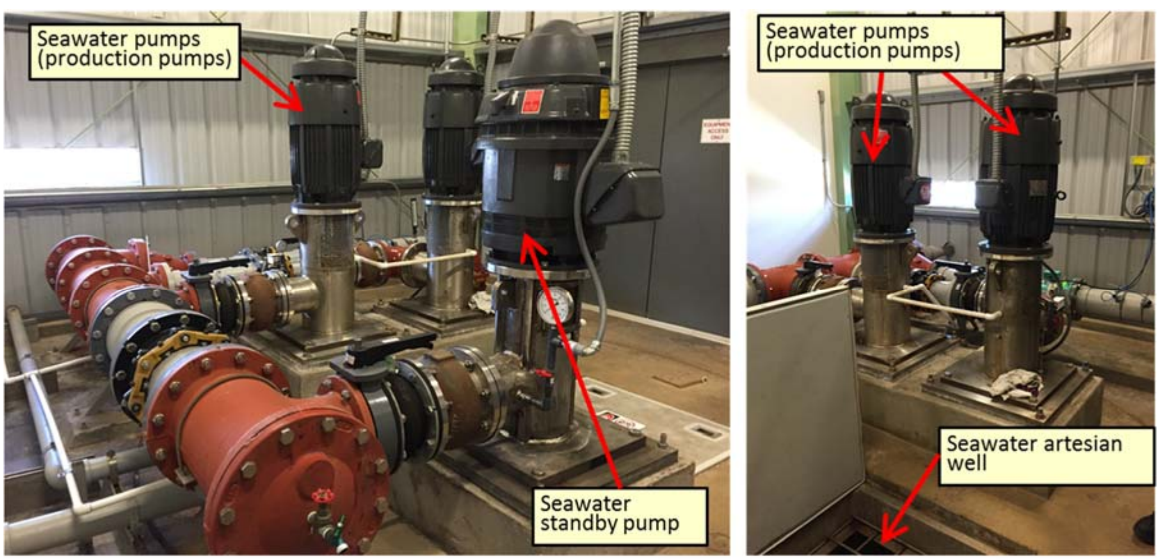


Figure 7.7.8: Seawater cooling system, artesian well with seawater supply pumps

Conclusions of the site visit: The NOAA building features several innovative space conditioning technologies which can be candidate systems components of the proposed hybrid cooling system with liquid desiccant dehumidification. The overall thermal performance of the building provides a comfortable indoor thermal environment. Some portions of the building are somewhat overcooled with occupants wearing sweaters and jackets to avoid too cold indoor temperatures. The dehumidification inside the wet lab appears to have periodic insufficient dew point reduction, since condensation on the chilled beam occurs from time to time. The excess humidity is removed with portable conventional dehumidifiers. The cold seawater that is derived from the 1,500 feet deep well and has an average temperature of 70°F provides inexpensive cooling capacity.

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APPENDIX A

THREE INFORMATIONAL PAMPHLET FOR MEETINGS WITH AGENCY STAKEHOLDERS

Informational Pamphlet A

Introducing a State-of-the-art AC technology for Hawaii's Schools which provides high-quality indoor comfort conditions while saving significant energy

Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control, creates high quality indoor comfort and saves significant energy

Challenge for Hawaii's Schools: Educational facilities need to upgrade building conditioning (e.g. air-conditioning (AC)) systems in a cost-effective way, while providing students, teachers & staff with high-quality indoor comfort at affordable installation and energy cost.

Proposed Solution: Follow the example of educational institutions around the nation to exchange older AC systems with more energy efficient and better comfort AC systems, which use dedicated outdoor air supply (DOAS). DOAS systems were developed several decades ago and are increasingly used because of their many benefits. DOAS AC-systems separate sensible cooling (indoor temperature control) from humidity control. They create a high quality indoor thermal comfort while avoiding energy losses of conventional all-air AC systems.

Proposed prototype installation: The proposed hybrid AC pilot installation (using liquid desiccant dehumidification) uses the many benefits of DOAS, but adds Hawaii specific features, including the use of solar energy and ceiling fans. By going beyond the typical DOAS, a healthy indoor environment results, matching Hawaii's unique climate. The proposed hybrid AC technology uses commercially available products and, while innovative, can rely on technologies and maintenance procedures which have been tested and proven. The prototype installation will familiarize decision makers and stakeholders in classroom facilities with this new cost-saving way to control humidity and temperature, for better cooling than with conventional all-air AC.

Testimonials of two High-Schools that switched from conventional AC to DOAS-AC

These high schools use DOAS AC-technologies and have saved significant costs and boosted attendance rates through better indoor thermal climate:

Clark County Public Schools, Winchester, Kentucky, uses a DOAS Ac system with chilled beams. The School District Superintendent prefers the water-based DOAS system over conventional AC because it rules out possible health risks from refrigeration leaks in classrooms. He states his DOAS systems have three times the lifecycle expectancy of older AC systems, lower installation and maintenance costs, and significant energy savings. His DOAS systems eliminate the loud noise of the conventional AC it replaced. ***".. now I walk into classrooms with the chilled beams and I can't hear any sound from the HVAC system".*** The high school has increased attendance because of the comfortable learning environment created by the DOAS-AC. ***"Rising attendance generally transcends into more productive learning, which will help maintain Clark County Schools' standing as one of the top districts in Kentucky".***

George Rogers Clark High School, Kentucky, uses a DOAS system with heat recovery and chilled beams. The school reports savings of more than 35% in energy costs and significant installation costs savings. The increased attendance earned the school a $200,000 government-awarded attendance incentive.

Benefits for Hawaii's schools and educational facilities:

Reduced energy & maintenance costs' lower installation costs	The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification. It avoids redundant fan power and bulky duct systems. It avoids energy penalties from unnecessarily overcooling the rooms. It ensures that ceiling fans are effectively used for "free" cooling, without reducing comfort.
Creating a healthier indoor and better learning environment	The proposed installation can reduce "sick building" conditions and avoid humidity related problems, such as mold, by separation of cooling and dehumidification controls. Sufficient outdoor air supply results in healthy indoor air. It avoids noise and distracting sounds from conventional air supply fans. It avoids unhealthy drafts from cold air. When external climate conditions allow, the system can use natural ventilation settings

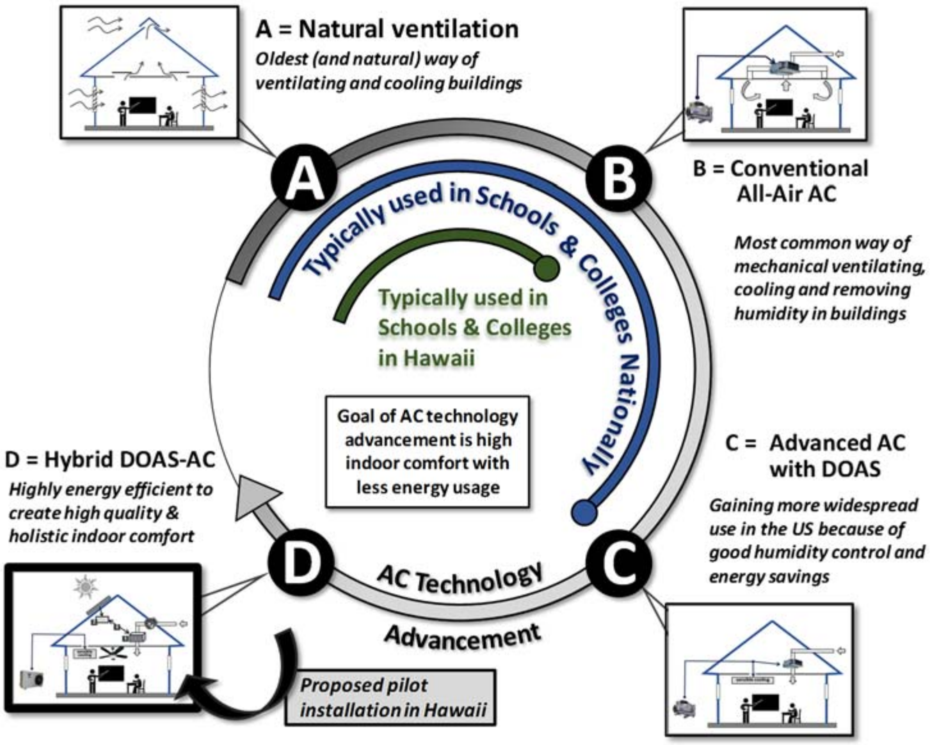


Figure 1

The proposed pilot installation will utilize **system (D)** which - the **Hybrid DOAS-AC.** The system will use liquid desiccant as the technology to remove from and control humidity in buildings and class rooms. Liquid desiccant dehumidifcation is a tested and highly efficient humidity control techology, which offers significant benefits.

The proposed hybrid DOAS-AC pilot installation will use a liquid desiccant dehumidifier, a small electrical water chiller and ceiling fans to provide effective and healthy indoor temperature and humidity conditions. The heat for the regeneration of the liquid desiccant material will be provided by solar heat, if space requirements for the solar panels can be met. In Figure 1 above, the **proposed pilot installation is System D, Hybrid DOAS-AC.** Figure 1 shows how the proposed Hybrid DOAS-AC fits into current AC technology advances in the US and world-wide, and how it compares to three other technologies for indoor thermal control, referred to as Technologies A through C. Table 1 below illustrates the performance characteristics for the four building conditioning technologies A through D.

Table 1 - COMPARISON	**Relative Performance across Systems**			
Important functions of building conditions systems	**A = Natural ventilation**	**B = Conventional All-air AC**	**C = Advanced AC with DOAS**	**D = Hybrid DOAS-AC**
1. Electricity savings relative to conventional AC	**High:** only natural processes used, no electricity	**Not applicable:** savings are relative to conv. AC	**Medium:** more efficient heat removal	**High:** more efficient heat removal & other energy savings
2. Capacity of using renewable and waste energy for AC	**Not applicable:** ventilation requires no electric energy	**Very limited:** some quantities of solar electricity	**Medium:** some solar & waste heat dehumidification	**High:** more solar & waste heat for dehumidification
3. Continuous control of indoor thermal conditions	**Low:** wind induced ventilation is intermittent	**High:** always provides sufficient & continuous cooling	**High:** always provides sufficient & continuous cooling	**High:** always provides sufficient & continuous cooling
4. Continuous control of indoor humidity & mitigation of humidity related problems	**Low: Cannot control** - intermittent outdoor conditions	**Low to Medium:** no separate humidity controls	**High:** separate humidity control	**High:** separate humidity control
5. Providing continuous healthy indoor environment & comfort	**High, but intermittent:** dependent on outdoor conditions	**Low to Medium:** frequent over-cooling, noisy, others comfort impairments	**Medium to High:** fitting temps. & humidity, low noise, others comfort gains	**High:** fitting temps. & humidity, low noise, individual ceiling fan controls
				Pilot Installation

Figure 2 shows the performance characteristics of building conditioning technologies A through D as a relationship of Energy Efficiency and Quality indoor comfort and humidity control ***(see Pages 4 and 5 for detailed descriptions of systems A through D).***

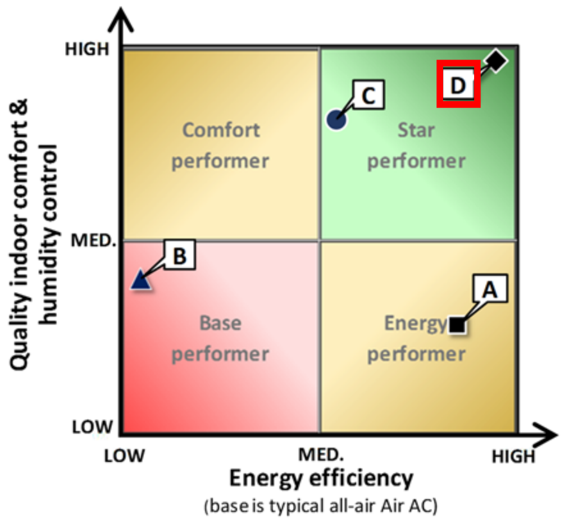


Figure 2: Relationship between energy efficiency and ability to create a healthy indoor climate:

<u>Four performance categories:</u>

Base performer: Low energy efficiency and limited ability to continuously and effectively control indoor comfort and humidity

Energy performer: High energy efficiency but limited ability to continuously and effectively control indoor comfort and humidity

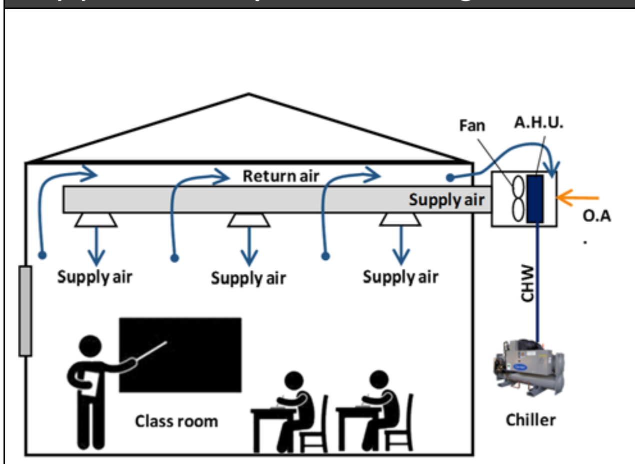
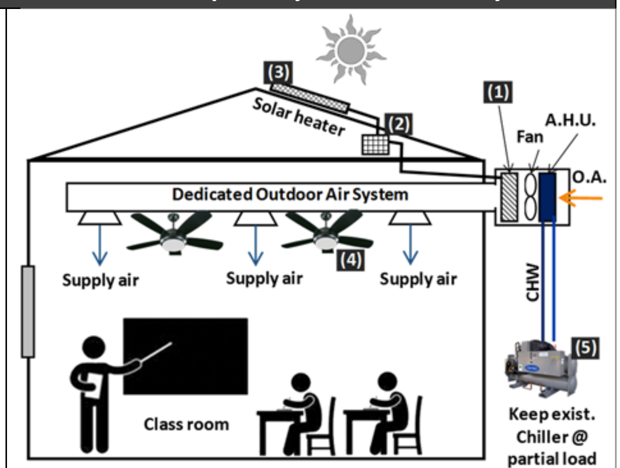
Comfort performer: Low energy efficiency but high ability to continuously and effectively control indoor comfort and humidity

Star performer: Low energy efficiency AND high ability to continuously and effectively control indoor comfort and humidity

<u>**A trough D Space conditioning technologies:**</u>

A = Natural ventilation; **B** = Conventional All-air AC; **C** = Advanced AC with DOAS; **D = Hybrid DOAS-AC (pilot)**

Space Requirements for New Pilot Installation: The <u>pilot installation</u> can either **(A) retrofit** a classroom (or other space) that has an existing central AC, or **(B) install a new Hybrid AC system** in a classroom (or other space) that presently has no AC. Both scenarios (A) and (B) are possible, though the new installation would show better results.

<table>
<tr><th colspan="2">(A) Retrofit of space with existing conventional AC to install the pilot Hybrid DOAS-AC system</th></tr>
<tr><td>
</td><td>
</td></tr>
<tr><td>Existing conditions: The classroom (or other space) has an existing coventional all-air AC system with a duct system that supplies required ventilation rates and supplies chilled air to the room for cooling. The chilled air is recirculated inside the conditioined space. Cooling, dehumidification and ventilation occurs through the recirculated indoor air supply. The chiller provides all chilled water capacity for cooling and dehumidifictation. Cooling based dehumidification works by cooling air below its dewpoint, and removing humidity by condensate on coils. (e.g overcooling)</td><td>Retrofitted conditions: (added equipment 1-5)
(1) <u>Liquid desiccant absorber</u>, removes humidity from the air stream, without risk of overcooling
(2) <u>Liquid desiccant regenerator</u>, reconditions the liquid desiccant solution using heat to restore its capacity to absorb of humidity
(3) <u>Solar panel (heater)</u>, to provide heat for liquid desiccant regeneration
(4) <u>Ceiling fans</u>, increase cost-effective sensible cooling and provide “natural climate feeling” indoors.
(5) <u>Chiller</u>, either run existing chiller at partial load or use new but smaller chiller</td></tr>
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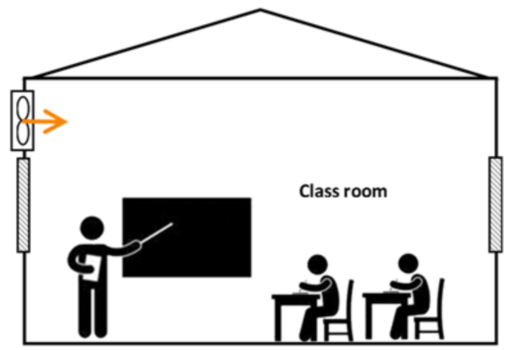
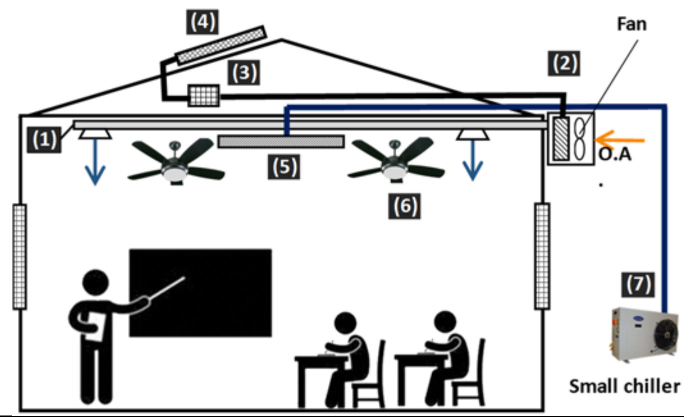
<table>
<tr><th colspan="2">(B) Space without existing AC; New pilot installation of Hybrid DOAS-AC system</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Existing conditions:

The classroom (or other space) is naturally ventilated or has a small air fan that provides the room with ventilation air if wind driven ventilation is insufficient. Cooling of the classroom occurs through introducing external air which rejects heat through convection. The achievable humidity level cannot be lower than that of the external air.</td><td>Retrofitted conditions: (added equipment 1-7)
(1) Add small ventilation duct, sufficient for small DOAS air flow
(2) Add Liquid desiccant absorber, to remove humidity from the air stream
(3) Add Liquid desiccant regenerator - reconditions the liquid desiccant solution using heat to prepare desiccant for absorption of humidity
(4) Add Solar panel, to provide heat for liquid desiccant regeneration, only if space allows installation of solar array.
(5) Chilled beam, proposed approach to remove sensible load, or use air cooling through VAV.
(6) Ceiling fans, to increase sensible cooling
(7) New Chiller, smaller than original chiller</td></tr>
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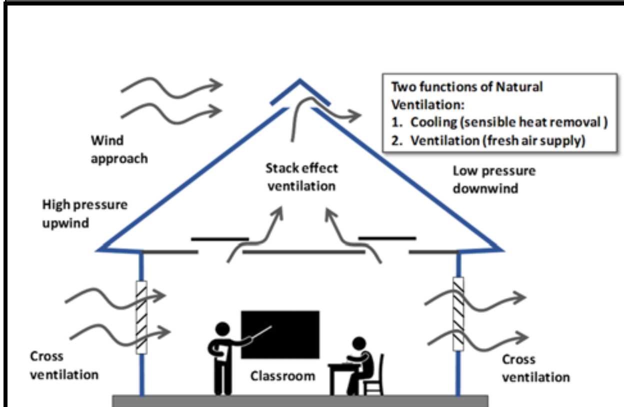
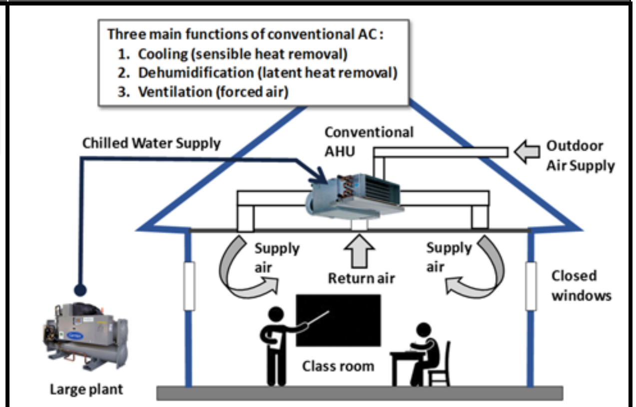
Summary of Comparative Building Cooling Technologies

A - Natural ventilation



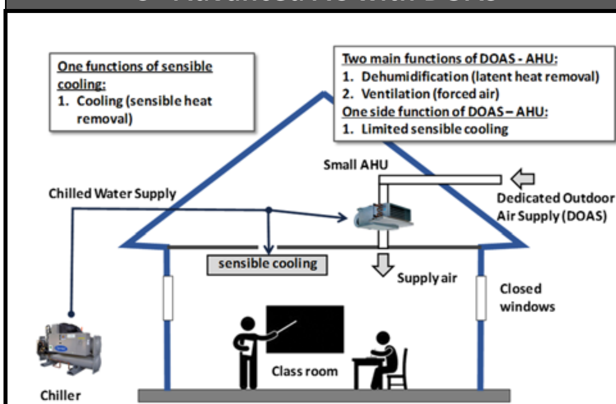
The space is ventilated by a combined action of wind induced cross ventilation and thermally induced stack ventilation. Higher indoor temperatures are reduced by fresh outdoor air supply. Humidity levels cannot be adjusted by natural ventilation, since humidity levels cannot be lower than the outdoor air.

B - Conventional All-Air AC



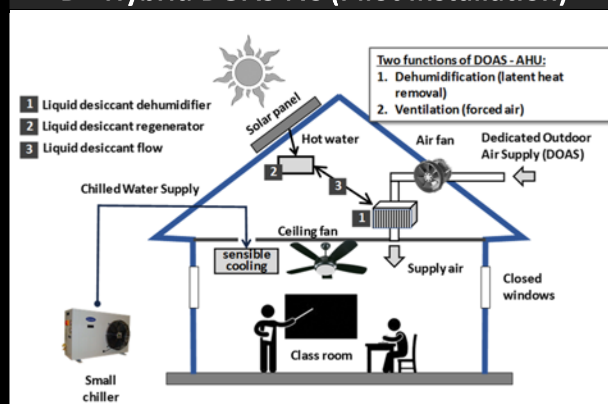
The space is mechanically conditioned. The AC system has a duct system that provides chilled air to the room for simultaneous cooling, dehumidification and ventilation. Air is recirculated throughout the space which can lead to cross contamination. Cooling based dehumidification occurs through reducing the air temperature below its dew point, thereby initiating condensation of humidity on the cooling coils. The system does not provide separation of sensible (e.g. indoor air temperature) and latent (e.g. humidity) loads. Overcooling is always a problem.

C - Advanced AC with DOAS



The space is ventilated by a Dedicated Outdoor Air System (DOAS) which only uses fresh outdoor air and avoids recirculation of air indoors. The DOAS provides dehumidification, where for conventional DOAS humidity is removed with a cooling coil based dehumidification (e.g. the same as conventional AC dehumidification). The sensible cooling occurs through the chilled beams or other suitable sensible cooling technologies. (*Predicted energy costs savings relative to conventional AC are around 25 - 35%*).

D - Hybrid DOAS-AC (Pilot Installation)



The space is ventilated by a Dedicated Outdoor Air System (DOAS), which provides dehumidification through a liquid desiccant system. The regeneration of the liquid desiccant uses solar generated heat, if solar panels can be installed. The liquid desiccant regeneration can be located anywhere in the building, making the system flexible. Sensible cooling occurs through chilled beams or other suitable sensible cooling technologies. Ceiling fans provide additional, low-cost sensible cooling. (*Predicted energy costs savings relative to conventional AC are around 50%, or higher, if solar energy is used for desiccant regeneration*) .

Informational Pamphlet B

Introducing a State-of-the-art AC technology for Hawaii's Schools which provides high-quality indoor comfort conditions while saving significant energy

Proposing a pilot installation at a Hawaii DoE facility of an advanced AC technology which allows effective humidity control while saving significant energy costs

Challenge for Hawaii's Schools: Educational facilities need to upgrade building cooling and ventilation (e.g. air-conditioning (AC)) systems while achieving the following goals:

1. Continuously provide improved thermal comfort in the class-rooms
2. Significantly reduce the energy and other O&M costs for AC and indoor ventilation
3. Provide a healthy indoor environment, which provides a high-quality learning environment and avoids typical humidity related health risks and maintenance problems

Existing conditions: At present, educational facilities use either natural ventilation or conventional AC. Natural ventilation is intermittent since it is driven by the external climate and cannot control temperature and humidity levels inside the spaces all the time. Conventional AC can continuously control thermal conditions but falls somewhat short of effective humidity control in the warm and humid Hawaii climate. In addition, conventional AC, often overcools the rooms and requires significant energy. **Conclusion**: Existing building cooling & ventilation systems fall short of providing continuously good thermal comfort and a healthy environment at reasonable costs.

Proposed prototype installation: The proposed **Advanced mixed mode** space conditioning system overcomes problems and shortcomings of conventional AC and natural ventilation, by combining advantageous aspects and avoiding shortfalls of each. The Advanced mixed mode system uses highly effective humidity control technologies that have been successfully used in industrial and health institutional application for several decades. These outstanding humidity control technologies are now available to control humidity inside buildings in an effective way that is unmatched by conventional AC. Advances in technology also make it possible to use solar energy or waste heat, thus lowering the environmental impact and saving significant energy costs. We are using this advanced humidity control technology and combine it with a temperature and ventilation control that is ideal for people living in the hot and humid Hawaii climate. It avoids too low temperatures with frequent overcooling and provides a soothing and healthy temperatures. The result is an indoor environment that can be enjoyed and creates a very conducive working and learning environment. While being used on the mainland and worldwide, we propose a demonstration pilot installation to showcase this technology's many benefits for educational facilities in Hawaii.

Figure 1 compares the energy and comfort performance of the three types of space conditioning systems, natural ventilation and conventional AC (presently used in Hawaii's schools) and the proposed Advanced mixed mode. We use two ranking metrics; (a) energy efficiency, relative to an optimal operating conventional AC and (b) Continuous thermal comfort & humidity control. Ranking of performance is done on a scale from 5 to 1.

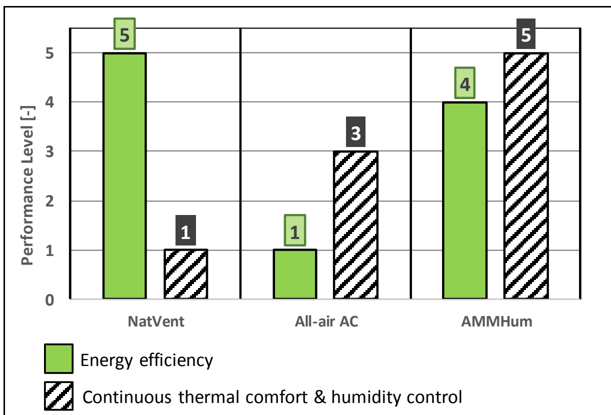


Figure 1: Comparison of three systems
Natural Ventilation (NatVent)
Full conventional all-air AC (All-air AC)
Advanced Mixed mode (AMMHum); **Proposed**

Scale: 5 = Very high to 1=very low, with 3=medium

Conclusion: The proposed Advanced mixed mode has the best performance of the three compared building cooling and ventilation technologies. It avoids intermittency of natural ventilation, but creates an attractive indoor climate with elements resembling natural climate conditions. It avoids the high energy costs of conventional AC, by eliminating electrcil inefficiencies and using solar or waste process heat.

Benefits of Advanced mixed mode for Hawaii's Schools & Educational facilities:

Reduced energy & maintenance costs and lower installation costs	The proposed advanced HVAC system will increase student and teacher comfort, and lower electric energy usage by at least 50%, or more, if solar heat can be used for the desiccant dehumidification. It avoids redundant fan power and bulky duct systems. It avoids energy penalties from unnecessarily overcooling the rooms. It ensures that ceiling fans are effectively used for "free" cooling, without reducing comfort.
Creating a healthier indoor and better learning environment	The proposed installation can avoid "sick building" conditions and humidity related problems, such as mold, by separation of cooling and dehumidification controls. Precisely controlled ventilation of dryer air result in healthy indoor air. The small ducts and fans avoid noise and distracting sounds typical for conventional AC. The better outdoor air supply avoids unhealthy drafts from cold air. When external climate conditions allow, the system can use natural ventilation settings

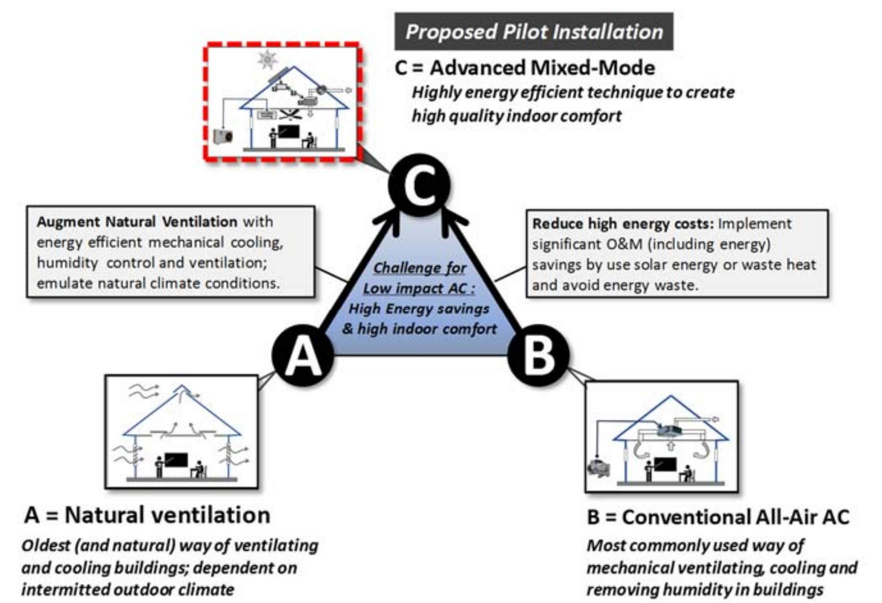


Figure 2:
The proposed pilot installation will utilize **system (C).** The **low impact Avanced mixed mode** system combines benefits of both natural ventilation and conventional AC, but avoids shortfalls, inefficiencies and high energy costs. The new system <u>augments</u> natural ventilation by adding meachnical means of space conditoing. It reduces the high energy demand of conventional Ac and provides a better indoor climate.

Brief description of Advanced mixed mode: The proposed hybrid DOAS-AC pilot installation will use a liquid desiccant dehumidifier, a small electrical or evaporative cooler and ceiling fans to provide effective and healthy indoor temperature and humidity conditions. The desiccant dehumidifies the indoor air independently from cooling to the exact requirements. This avoids overcooling and insufficient humidity control typically found in conventional AC. The heat for the regeneration of the liquid desiccant material will be provided entirely or partly by solar heat, if space requirements for the solar panels can be met, thus significantly reducing electric power needs. The electric or evaporative cooler will regulate the indoor temperature at comfortable and not too cold levels. The ceiling fans will provide cost effective additional cooling and comfort and allow individual controls of air movements.

How can the proposed Advanced mixed mode system pilot system be installed?	
As part of a **RETROFIT**, in spaces where a conventional AC systems will be upgraded:	As a **NEW INSTALLATION**, in spaces that have no existing AC:
The Advanced mixed mode system can use existing ventilation ducts to deliver dry and slightly cooled air. Possible humidity problems in the duct or ventilation system as well as in the spaces will be avoided. The existing chillers can be run in partial mode to control temperatures. Ceiling fans add cost effective cooling.	New air ducts will be installed, which are a fraction of the size of conventional ducts, to deliver dried and slightly cooled outside air at separately controlled temperature and humidity levels. A new electric of evaporative cooler will provide limited cooling. Solar panels provide heat energy for desiccant regeneration. Ceiling fans add cost effective cooling.

Informational Pamphlet C

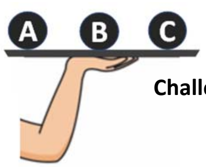
SITUATION ASSESSMENT

Briefing Page 1

Three main challenges and critical issues related to DoE buildings, which need improvements

No.	Issue	Required actions
A	**Thermal comfort**	Improve indoor thermal comfort by effective control of external and internal thermal loads
B	**Energy & Power**	Reduce electric energy and power requirements for AC (space conditioning) and use technology that maximizes cost-effective use of renewables and waste thermal energy
C	Health and IAQ	Avoid unhealthy indoor conditions for occupants (e.g. sick building syndrome) and deterioration of building materials, structure and equipment through effective humidity control

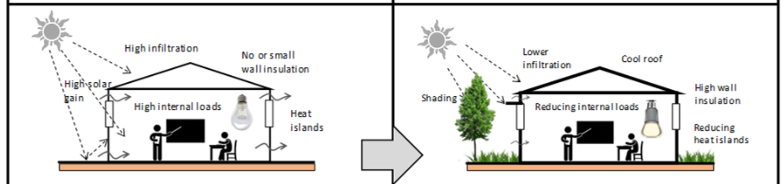
MOST IMPORTANT TASK - BALANCING A THROUGH C



Challenge: To optimize thermal comfort, energy and healthy indoor quality

B Reduce electric energy & power demands for space conditioning

Challenge & Current state	Desired state
No or insufficient cooling HVAC capacity	Install cooling to attain indoor temperature adjusted to Hawaii
Too warm in spaces; cooling (e.g. sensible heat removal) not sufficient for thermal loads	Reduce external thermal loads
	Reduce internal loads
	Use "soft" cooling; i.e. ceiling fans
For PV powered HVAC provide sufficient electric storage to bridge intermittency	Use thermal energy storage, which is cheaper than batteries

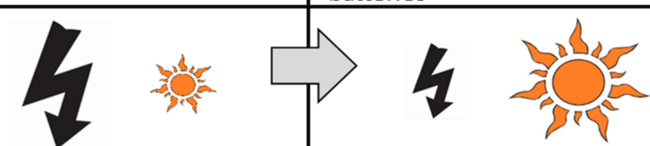


Current buildings: High sensible loads - HVAC system sized to deal with cooling needs	Focus on energy efficiency in cooling - lower external and internal thermal loads

Goal: Provide good thermal comfort while reducing electricity for cooling

A Improve thermal comfort for occupants

Challenge & Current state	Desired state
High energy and power demands for installed and planned HVAC	Reduce by implementing mixed mode wherever possible
Some DoE infrastructure cannot accommodate high electric loads	Reduce HVAC site electrcity demand
Renewables limited to PV-electric which requires costly battery storage	Use also solar heat and waste heat, in addition to PV electric
	Energy storage (heat desiccants) and batteries

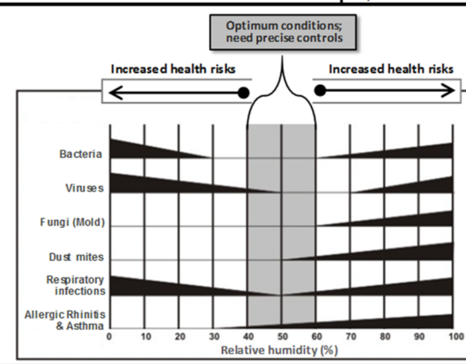


High electric energy and power use; little renewable energy use	Low electric energy and power use; High renewable energy use

Goal: Use Hawaii's climate and increase renewables

C Provide healthy indoor air & environmental quality

Challenge & Current state	Desired state
Often humidity out of healthy range	Accurate humidity control
Not enough ventilation to satisfy code (i.e. too high CO_2 levels)	Well ventilated space
External noise and intrusion of dust and pollutants	Create quite, clean and productive learning space



Goal: Secure indoor health through accurate humility control

Goal: Implement cost-effective humidity control independent of cooling control

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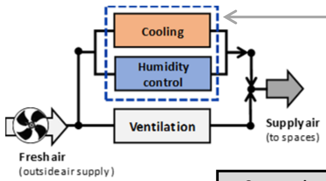
CONVENTIONAL VS MIXED MODE DESICCANT / AC SYSTEM

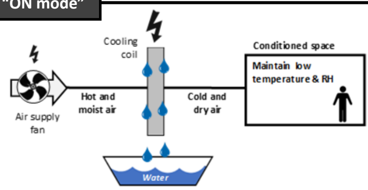
CONVENTIONAL DX –AC WITH COOLING BASED DEHUMIDIFICATION



Cooling (sensible load removal) and humidity control (dehumidification) **CANNOT BE SEPARATED AND THEREFORE CANNOT BE OPTIMIZED INDIVIDUALLY**

Conventional AC controlled by high and low temperature set points:

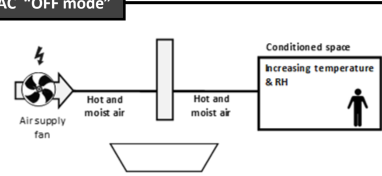
AC "ON mode"



AC functions:

Cooling: Overcooling if thermal loads are smaller than cooling capacity	ON
Dehumidification: Cooling coils below dew point therefore condensationof water vapor in air	ON
Ventilation: Supply sufficient fresh air rate	ON

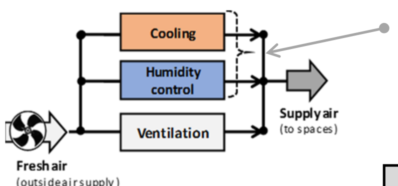
AC "OFF mode"



AC functions:

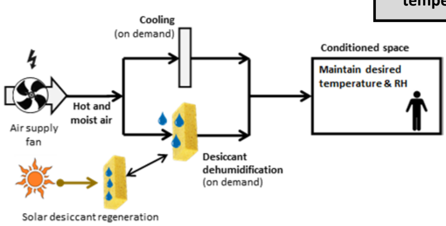
Cooling: No cooling - controlled by HIGH set point	OFF
Dehumidification: No dehumidification on warm coils & reevaporation from wet coils	OFF
Ventilation: Supply sufficient fresh air rate	ON

MIXED MODE AC WITH DESICCANT DEHUMIDIFICATION AND ON DEMAND COOLING



Cooling (sensible load removal) and humidity control (dehumidification) **ARE SEPARATED AND CAN THEREFORE BE OPTIMIZED INDIVIDUALLY**

Advanced Mixed Mode AC controlled by independent temperature and humidity set points



AC functions:

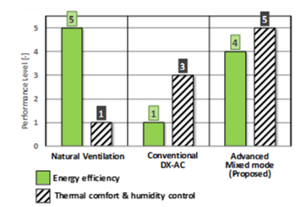
Cooling: Cooling on demand - Controlled by temperature set points	ON / OFF
Dehumidification: Dehumidification on demand - controlled by humidity levels	ON / OFF
Ventilation: Supply sufficient fresh air rate	ON

ADVANTAGES / DISADVANTAGES OF CONVENTIONAL COOLING BASED AC AND AC WITH DESICCANT DEHUMIDIFICATION

Criterion / Parameter	Conventional DX-AC with cooling based dehumidification (combined cooling & dehumidification)	AC with desiccant dehumidification (separate dehumidification & cooling)
O&M costs	High	Low
Energy source	Electric (limited solar electric)	Electric, solar, heat
Control over humidity	Limited	Very Accurate
Indoor air quality	Average to low	High
Indoor thermal comfort	Average to high	High; good integration of low impact comfort measures (e.g. ceiling fan
Installation / type and costs	Conventional and average costs	Requires new but proven methods, therefore higher costs

PROPOSED ADVANCED MIXED MODE

Proposed Advanced Mixed Mode combines advantages of natural ventilation and forced HVAC



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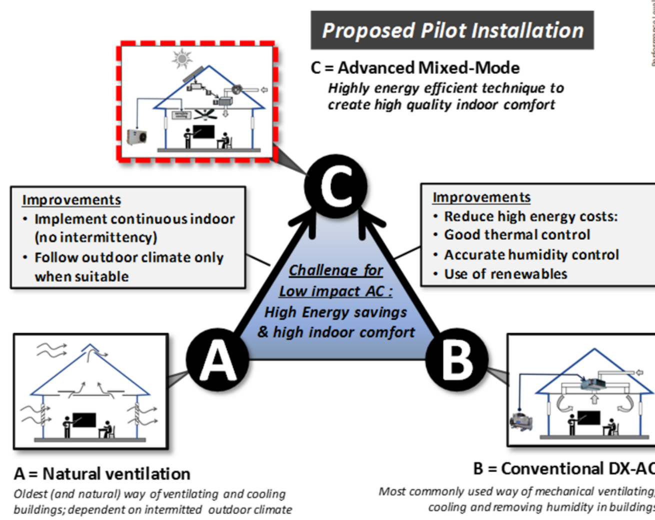

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BRIEFING PAGE 3

PILOT INSTALLATION IMPLEMENTATION OPTIONS

LIQUID DESICCANT DEHUMIDIFICATION IS A PROVEN INDUSTRIAL TECHNOLOGY

Since 2000 intensive technology development for liquid desiccant **HVAC applications**

Low flow Liquid desiccant (LD) conditioner and LD regenerator for HVAC application:

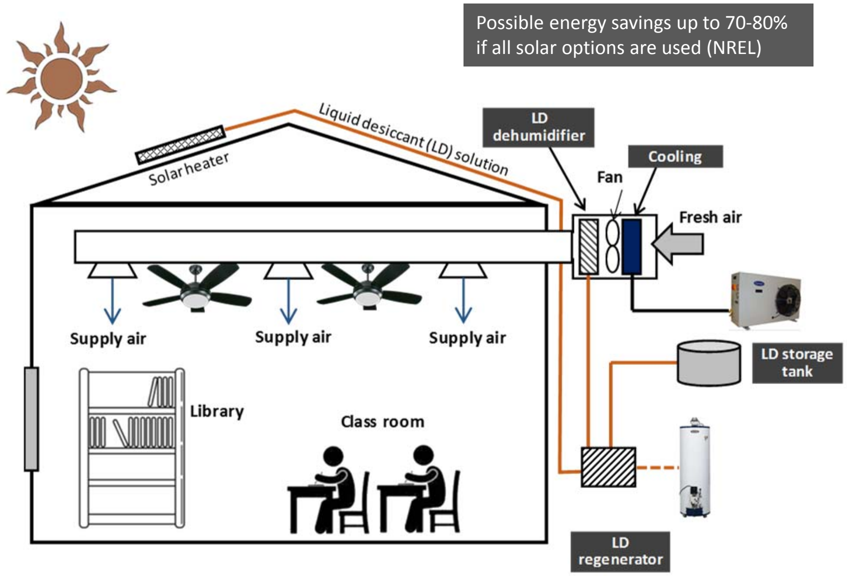
Improvements over industrial desiccant systems:

- Simpler operation for smaller HVAC applications
- Lower maintenance and less material problems
- Energy savings
- Use of low grade heat (i.e. solar, waste heat)
- Flexible integration into building infrastructure

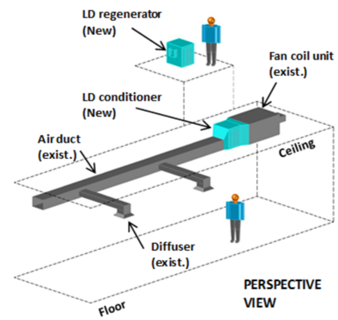
Conventional Liquid desiccant (LD) dehumidification technology has been used for over 70 years for precise humidity control in industrial and institutional applications, such as pharmaceutical industry, storage, archives, museums, hospitals. - Industrial & institutional liquid desiccant applications was precise but costly and maintenance intensive

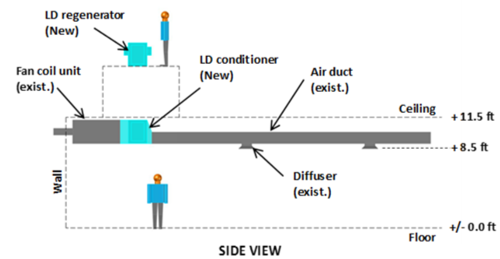
PROPOSED PILOT LIQUID DESICCANT (LD) INSTALLATION FOR DOE

Possible energy savings up to 70-80% if all solar options are used (NREL)



OPTION: LD CONDITIONER INSIDE SPACE INSTALLED IN EXISTING DUCT



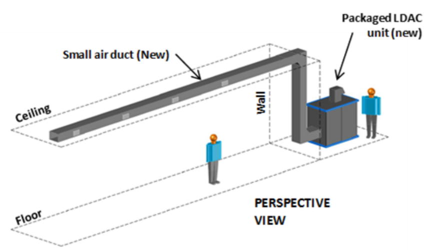


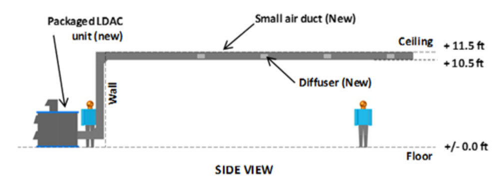
The liquid desiccant(LD) conditioner (dehumidifier) and the LD regenerator (desorption unit) can be installed apart form each other. This provides extra flexibility & requires less space for integration of the LD conditioner into the existing HVAC ducts.

The following components are used :

1. Liquid desiccant (LD) conditioner: removes humidity and provides for separate humidity control of space
2. Liquid desiccant (LD) regenerator: Thermal treatment of desiccant to drive out humidity and recharge desiccant solution
3. Thermal source for desiccant regeneration: can be solar array, electricity or gas
4. Thermal sink for desiccant conditioner (either fans or cooling tower)

OPTION: PACKAGED LD UNIT OUTSIDE OF SPACE





For this type installation of a liquid desiccant air condition (LDAC) unit it is assumed that the space has either no existing AC system or an old AC system that needs total replacement. The new installation will include a packaged LDAC with a LD conditioner and a LD regenerator housed inside one unit. The heat sink and source for the LD conditioner and LD regenerator are located externally.

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