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ABSTRACT

Building design and construction that helps deliver both superior air quality and occupant thermal comfort, while minimizing energy consumption, are examined. The paper explores an integrated building systems approach that combines the principles of "directed air flow control" and "demand controlled ventilation" where ventilation is effectively delivered to the occupant, based on loading, that can be applied to all types of indoor air quality situations in all types of buildings. Highlighted are savings and return of investment data for the traditional "green building" general design strategy. Case studies provide examples of this high performance IAQ design. Finally, key differences and advantages of a displacement ventilation design classroom versus conventional mixing ventilation systems are examined along with data of expected benefits of a heating, ventilation, air conditioning school displacement design. (GR)

# Healthy Building Design For The Commercial, Industrial, and Institutional Marketplace

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In recent years we have seen a rapidly growing interest in the creation of "greener" buildings for our clients that are both "affordable" and "sustainable". With this type of design priority, Indoor Air Quality and Energy Conservation considerations must go hand in hand as major focal points in a facility. Too much "general dilution ventilation" with Outdoor Air can result in excessive energy costs, and will likely result in undesirable moisture problems for the occupants, the building shell, and the mechanical systems. Simply using the often traditional approach of minimum code required for toilet exhaust, and minimum general ventilation for "dilution" of indoor generated contaminants as the primary methods of providing good indoor air quality in a building, often results in unacceptable indoor environments. This is because the use of the conventional approach of code driven minimum dilution ventilation, results in occupants often being exposed to a variety of materials that can cause irritation prior to their being sufficiently diluted to acceptable levels. Alternately; excessive general dilution to lower airborne material concentrations to acceptable levels where irritation is unlikely to occur, will be energy intensive. Based on our forensic work, other common issues that also accompany poor indoor air quality typically include: lighting, acoustics, preventive maintenance, moisture control, and thermal comfort. Thus to be successful, a high performance design must also address these issues.

## Healthy Building Design: Indoor Air Quality

**HVAC Design:** Achieving a design that will deliver both superior air quality and occupant thermal comfort, and minimize energy consumption, requires the design team to take an "integrated building systems approach" for proper Indoor Air Quality and HVAC design. This "Healthy Buildings" approach needs to consider the use of "green building" type low emission rates materials (reduced source strengths), and include a careful look at where and when the undesirable air contaminants "sources" could be generated (either within the facility itself, on the rooftop, or immediately adjacent to the site), and to use "directed air flow control" to minimize the occupants' exposures to the emissions. Additionally, appropriate general dilution levels need to be provided "at the times they are needed"; i.e., utilizing a demand controlled strategy. The two design principles of "directed air flow control" and "demand controlled ventilation" where ventilation is effectively delivered to the occupant, based on loading, can be applied to all types of Indoor Air Quality Design situations ranging from Office Buildings to Industrial Settings, including School Classrooms and the Hospitality Industry. Proper application of both principles will both enhance the indoor air quality, and keep energy costs lower; desirable ingredients for a "Healthy Building" design.

## Healthy Buildings: Material Selection and Application:

Other traditional "green building" general design strategies, in addition to HVAC considerations, also need to be considered. They include selecting low emission composite materials and low emission finishes, and minimizing the application of liquid finishes and adhesives inside the facility once it is closed-in during construction and fit-up.

## Healthy Buildings: Economics

| ANNUAL SAVINGS | | | | | |
|---|---|---|---|---|---|
| Operating Cost per sf/yr. | | % Savings/yr. | | $ Savings/yr. | |
| | | High | Low | High | Low |
| Energy | $ 2.00 | 15% | 5% | $.30 | $0.10 |
| Maintenance | $2.00 | 5% | 1% | $.10 | $.02 |
| Productivity | $200.00[1] | 7%[2] | 2% | $14.00 | $4.00 |
| | | | **Savings Total:** | **$14.40** | **$4.12** |

Additional Cost per sf for Healthy Building Construction[3] $3.75 $3.75

| RETURN ON INVESTMENT | | |
|---|---|---|
| | High | Low |
| Simple Payback Period (in months) | 3.13 | 10.92 |
| IRR [6] | 387% | 113% |
| NPV[7] | $95.38/sf | $24.61/sf |

Notes:

[1] $200.00/sf cost for a $40K employee occupying 200 square feet.

[2] Data from Johnson Controls

[3] (5%[4] x $75.00[5])

[4] 5.00% premium for "Healthy Building" components and systems per Turner Group

[5] $75.00/sf cost of construction per R.S. Means for 2-4 story office building.

[6] Period = 10 years, inflation @ 3%, Salvage Value = 0

[7] Discount Rate @ 10%, same as #6 above.

The economics of Healthy Buildings are obvious - the investment has a very short payback, not to mention the improvement in general office morale which will be generated by a more comfortable environment.

## Healthy Buildings:

## Case Studies: Examples of Our High Performance IAQ Design

In the remainder of this article we will focus on the application of High Performance IAQ/HVAC design to the various market sectors that we deal with, utilizing a case study approach for each design, to illustrate the two basic principles of directed air flow and demand controlled ventilation.

### School Classrooms: Boscawen Elementary School

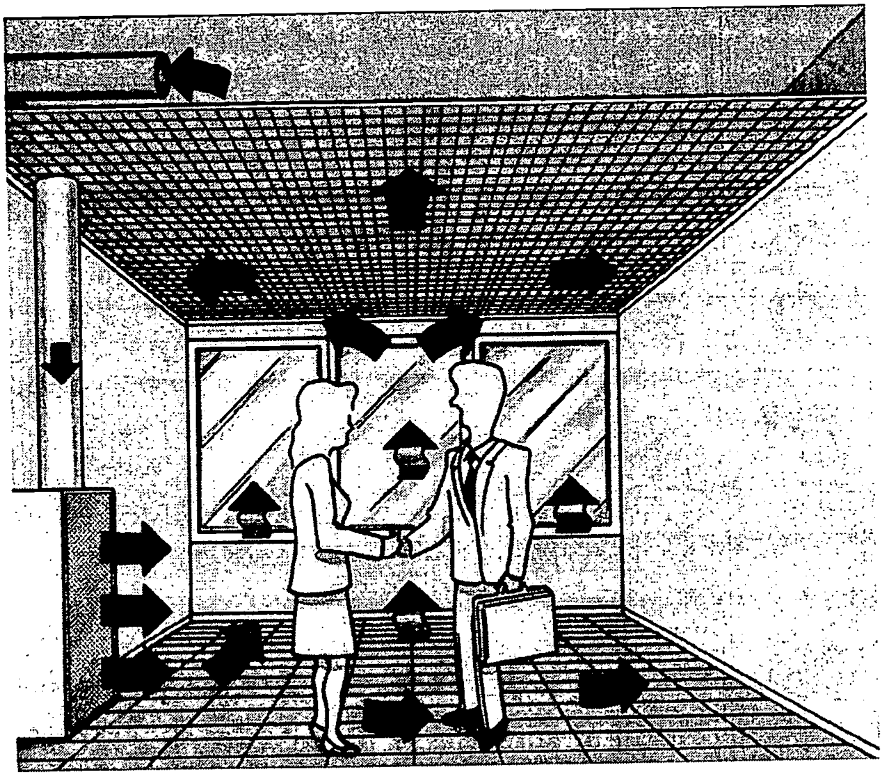
In 1996, a new 48,000 sf, (4,460 square meter) Elementary School was occupied with 400 students and staff located in Boscawen, New Hampshire. Designed by our firm, this school is the first in the United States to utilize the concept of displacement ventilation (a form of Directed Air Flow Control), and Demand Controlled Ventilation (ventilation that monitors carbon dioxide levels and adjusts fan speeds and damper positions) as the primary means of providing high performance design aimed at both good indoor air quality and thermal comfort, and reduced energy costs. The integrated "sustainable" design concepts of the facility address other important factors including: siting, programming (specific design elements that consider the educational plan), social dynamics, lighting, acoustics, energy efficiency, classroom computer usage, and good access that allows for planned HVAC preventive maintenance. Ventilation and thermal comfort objectives are achieved through a combination of 100% outdoor air which is delivered near the floor in the classroom and exhausted at the ceiling (the directed air principal), and demand control (providing the correct amount of ventilation air when it is needed.

A unique ceiling/roof structure that provides a 14 foot (4.3 meters) high vaulted ceiling was incorporated into the classroom design to enhance both the classroom space use and to provide room volume to enhance the performance of the displacement distribution system. An elevation of the room design is presented in the following figure. This approach also facilitates appropriate lighting and acoustical design.

**Healthy Buildings:**

**Presentations of Some Key Differences and Advantages, Displacement Ventilation Design Classroom Versus Conventional Mixing Ventilation Systems:**

As designed by our team, the vertical displacement ventilation concept is different from conventional ventilation, mixing ventilation systems in several important ways. These differences offer many potential benefits over most conventional HVAC systems typically found in public or private schools.



Displacement Ventilation Design Differences

*No Drafts.* Air is supplied near the floor in the space at extremely low velocity which results in no "throw" of air and subsequently little risk of "drafts".

*Stratified Room Air.* Supply air is purposely not uniformly mixed throughout the space. It is intentionally stratified vertically to provide a better quality of air in the occupied part of the room. Supply air is delivered during occupancy at temperatures just slightly lower than desired room temperature. The supply air moves horizontally across the floor until it naturally rises from the floor, driven by convective currents as it warms due to internal heat from people, lights, computers, etc. The stratification as observed in representative carbon dioxide monitoring data is illustrated in Figure #1.

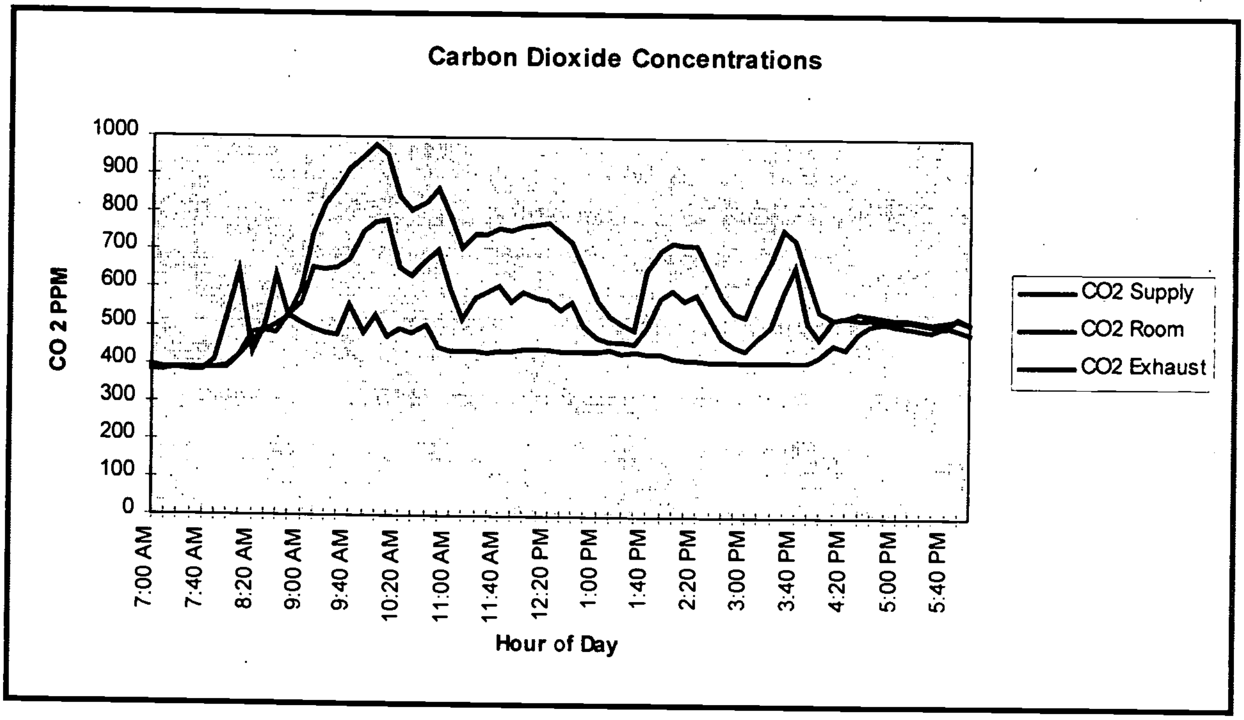


Figure 1

In addition to the stratification of Carbon Dioxide, there is rapid flushing of the room as the students leave, confirming the achievement of displacement air movement. **This room achieves**

**this superior air quality with an overall room ventilation rate of only 1.5 air changes per hour, which is less than half the ventilation rate that would be needed with a conventional design, drastically lowering electrical energy use through reduced fan horsepower consumption due to less air movement.**

*Improved Effective Ventilation.* Because of body heat, convective currents and warm human breath, there is a general upward flow of exhaled breath and other human bio-effluents above the occupied zone, as long as it is not greatly disturbed by fan forced air streams (as happens in conventional mixing distribution systems). Air also rises from the lower level of the room around stationary occupants due to the development of a convective current over the human body. This means that occupants will breathe air closer to supply air conditions (in this case conditioned outdoor air), rather than the condition of the air being exhausted from the space at the ceiling level, improving ventilation effectiveness. This principle would also apply to a designated smoking area in the Hospitality Industry,, and is discussed later in the article.

*No Recirculated Stale Air.* In this design approach, all supplied air is "preconditioned" 100% outdoor air. All air removed from the classroom is exhausted outdoors -- none is recirculated. Only the sensible and latent energy is captured from the exhaust air stream and recycled when needed.

*Individual Room VAV Not Needed.* When there are few or no internal loads, such as an unoccupied room with the lights off and little solar gain, the room air will be displaced upward by the air beneath it. In this case, the room will eventually be approximately the same temperature as the supplied air, which is only slightly cooler than the desired room temperature, thus the need for individual room VAV to prevent overcooling is virtually eliminated. "Demand control" of the total air supply via temperature and Carbon Dioxide sensors is utilized to minimize energy use and fan horsepower during cold weather or low occupant density, and to supply higher rates of ventilation only when needed.

*Reduced Cooling Capacity Needed.* Thermal stratification also allows some reduction of internal cooling requirements, because about 50% of the heat from the lights and other sources located above the occupants does not reach the occupied zone and, in this design, is exhausted outdoors when not needed.

*Less Fan Horsepower Needed.* In this design, supply air flows needed to achieve temperature control and provide adequate ventilation are approximately 35% to 70% of conventional system flows (dependent on season and solar gains). Thus, much lower fan horsepower than conventional mixing type systems is needed. Low velocity supply of air cannot be accomplished using conventional ceiling mounted mixing type diffusers, conventional horizontal unit ventilators, or non-ducted fan coils.

*Less Room Noise.* With reduced total air flow quantities and low exit velocities, there is reduced noise when compared to mixing type systems because there is no need to forcefully mix air in the room, and less total air flow is needed.

*Less Inter-zone Pollutant Transport.* The supply air quality to individual rooms as well as the individuals in the rooms is also improved because the supply air is not mixed with contaminated air already within the room as it enters. With no recirculation, the supply air does not contain contaminants which have been transported from other rooms or zones of the building.

*Summary of Costs and Benefits* : Table #1 presents a brief technical summary of the HVAC features incorporated into the school design, including actual equipment costs and assumptions about the calculated benefits, and the expected reduction of greenhouse gas generation by each feature. The data reveals that all of the listed technical items utilized to enhance the comfort and sustainability of the school offer attractive simple payback periods for a publicly funded facility with a life expectancy of 30 years or more. The economics of these features would be enhanced further if summer operation were included, or the facility was located in a climate with a longer cooling period.

## TABLE #1

## EXPECTED BENEFITS OF HVAC SCHOOL DISPLACEMENT DESIGN

| HVAC SUSTAINABLE FEATURE and Cost | SIMPLE PAYBACK OF INVESTMENT | ANNUAL FUEL SAVINGS | ANNUAL COST SAVINGS | ANNUAL $CO_2$ REDUCTION |
|---|---|---|---|---|
| # 1 Tightened building shell, 0.08 Vs 0.24Ach<br>$ 8,000.00 | S. pay: 4.4 yr.<br>S .pay 3.1 yr. | oil 2,272 gal<br>ng 3,181 therm | $ 1,818.00<br>$ 2,545.00 | = 30 tons<br>= 19 tons |
| # 2 Latent Heat recovery 70 % eff.<br>$ 29,000.00 | S. pay: 10.4 yr.<br>**See Note#1**<br>S. pay: 7.1 yr. | oil 4,002 gal<br>ng 5,602 therm | $ 2,797.00<br>$ 4,077.00 | = 53 tons<br>= 34 tons |
| # 3 Variable frequency drive HVAC motors, ventilation savings<br>$ 6,000.00 | S. pay: 5.2 yr.<br>S. pay 3.7 yr. | oil 1,429 gal<br>ng 2,001 therm | $ 1,143.00<br>$ 1,601.00 | = 19 tons<br>= 12 tons |
| # 4 Variable Freq. Motors Electric savings<br>$ 15,000.00 | S. pay: 4.0 yr. | 46,338 kWh<br>oil<br>ng | $ 3,707.00 | = 50 tons<br>= 31 tons |
| #5 Displacement Dehum. Vs mix. AC<br>$ -18,000.00 savings | S. pay: NA<br>**See Note #1** | 4,067 kWh<br>coal<br>oil | $ 325.00 | = 5 tons<br>= 1 tons |
| #6 two switch, high efficiency lighting<br>$ 2,500.00 | S. pay: 0.5 yr. | 64,800 kWh<br>coal<br>oil | $ 5,184.00 | = 77 tons<br>= 70 tons |
| total investment<br>$ 42,500.00 | ----------------- | ----------------- | annual est. total savings<br>$ 17,400.00 | |

| **Additional Cost** | **Annual Savings** | **Reduced $CO_2$** |
|---|---|---|
| | | **190 tons/yr.** |
| **$1.00/sq.ft.** | **$ 0.40/sq.ft. yr.** | **9 lb./sq.ft./yr.** |

**Note #1: The School does not currently operate in the summer. The savings would be much greater if it did, or if it was located in a more hot/humid climate.**

*Expected Lower Maintenance Costs And Higher Reliability With Central HVAC* Inadequate preventive maintenance issues have frequently been observed as a problem with dispersed air handling systems such as unit ventilators, fan coils, window mounted air conditioners, and water source heat pumps. This has especially been the case when the equipment is located in ceiling plenums above occupied spaces, where it is hard to access. With centralized systems, the location of air intakes can be carefully selected, unlike with unit ventilators, where air is usually drawn near the ground pulling in vehicle exhaust fumes, plant and insect materials, and soil type odors. Centralized systems also allow for improved (medium efficiency) particle air filtration, which is not possible with unit ventilators.

The displacement HVAC system and other associated design features installed in the Boscawen School, and subsequently others, has generally performed as designed, and the occupants report satisfaction with the resultant indoor environment. Decreasing the likelihood of Indoor Air Quality problems, and enhancing the learning environment in any facility must begin with sound, well conceived building system designs, and include a cost effective easy to maintain HVAC systems. Incorporating displacement ventilation into school design, along with the other features described, has resulted in a facility that appears to be highly functional and cost effective. The cost to construct the new Boscawen Elementary School (exclusive of site costs) was \$65 per $ft^2$ (SI \$701/$m^2$.); HVAC and plumbing systems making up \$11 per $ft^2$ (SI \$118/$m^2$) of the total construction budget. Costs in smaller schools have been as high as \$85 per $ft^2$. (SI \$800/$m^2$.) US currency.

**Commercial Office Space:**

In July of 1998, we will occupied our own new corporate headquarters in Concord, New Hampshire. Designed and constructed by our firm, this office building is the first in the United States to exclusively utilize the concept of displacement ventilation (similar to the Boscawen School approach), and Demand Controlled Ventilation as the primary means of providing high performance design aimed at both good indoor air quality and thermal comfort, and reduced energy costs. As with our school designs, the integrated "sustainable" design concepts of the facility address other important factors including: siting, programming, social dynamics, lighting, acoustics, energy efficiency, and access for planned HVAC preventive maintenance.

Unlike the school design, which is dominated by high density classroom occupancy, only the large conference room training area utilizes demand controlled 100% outdoor air. The remainder of the facility is served by a displacement design concept, which will provide a minimum of 25% Outdoor Air during design heating and cooling conditions, and up to a maximum of 100% Outdoor Air during most daytime operation. However, very unlike conventional office design, all of the air that leaves spaces where known irritants are likely to be generated will always be exhausted out of the facility after passing through an energy recovery exchanger; i.e., whenever the facility is occupied, emissions generated from reprographics, major printing operations, and food prep are captured at their source and removed from the space.

As with our school design, a unique ceiling/roof structure provides a high vaulted ceiling in many areas. Additionally, reflected daylighting is delivered to most core areas. With this design we have combined a radiant floor heating system along with the use of the vertical displacement ventilation concept. This approach will enhance all of the expected benefits of the classroom design such as: *No Drafts, Stratified Room Air for improved Ventilation Effectiveness, Enhanced comfort with minimal VAV zones, Reduced Cooling Capacity Needs by 1/3 over conventional design., Less Fan Horsepower Needed during normal or design condition operation.*

Where the office design does not use 100% outdoor air, we have incorporated the use of *95% (ASHRAE Dust Spot*) efficiency particle air filters in both central Trane IAQ Package air handlers. We also chose to incorporate integrated Direct Digital controls supplied by Trane Company as most system components (including controls) will be assembled and tested at the factory. Only the radiant floor controls will require major field installation at each of the tubing manifolds.

Decreasing the likelihood of Indoor Air Quality problems and enhancing the working environment in an office facility must begin with sound, conceptual building system designs, and include a cost effective, easy to maintain HVAC system. In an office facility, the use of 100% outdoor air is generally not justifiable due to the cost of energy. With an office where all known office process emissions are removed with point-of-use exhaust systems, and the building is designed for 20 cfm (minimum of outdoor air per person; heat recovery; enthalpy control; and dehumidification of outdoor air in the cooling season, it works.

### Industrial Assembly Area

In January of 1997, we were asked to work with a major manufacturer of laminate products to assist them with improvements in air quality in an assembly area. After careful analysis of the situation, including the temperatures of the materials that were being assembled, the need for full climate control in the assembly area, and the needed locations of the operators, we chose a directed airflow concept approach. For this situation we were able to use the same exhaust rates which currently were in use. The major change that we implemented was to use directed air flow to blanket the assemblers with clean, conditioned 100% outdoor air, and to move the emissions generated in the assembly process away from the operators. This concept performed so well that all assembly and press operations in the plant are being changed to the same concept. This approach has drastically lowered operator exposures to product emissions, and will improve product quality. By utilizing a modified displacement (directed air flow ) concept, we were able develop a High Performance HVAC System compared to other conventional approaches that had been attempted.

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