A SURVEY OF HIGH-PERFORMANCE OFFICE BUILDINGS IN THE UNITED STATES

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ABSTRACT
This paper presents the results of a survey of high-performance commercial office buildings to determine the components that could best improve building performance in hot and humid climates. The case studies reviewed include high-performance buildings, high-performance components, and measurement tools. It also includes an analysis of whether or not the building systems and components can be modeled using today’s simulation programs. In addition to the general survey, this paper focuses on the most promising characteristics of high-performance office buildings in hot and humid climates.

INTRODUCTION
In the United States, buildings consume more than one-third of the total energy and more than two-thirds of the total electricity use (EIA, 2004). It is, therefore, important to design buildings that consume much less energy than existing buildings. In recent years, some owners and designers have achieved great advances in changing the energy consumption patterns of buildings (Torcellini et al., 2004).

Efforts to improve energy efficiency of new commercial buildings have been reported in many studies (Stein et al., 2000; Case and Wingerden, 1998; Brohard et al., 1998; Peterson and Eley, 1996; Kaplan et al., 1992; Diamond et al., 1992 and 1990). However, energy conservation is still the easiest and readily verifiable way to achieve a high performance building. For commercial buildings, energy conservation is a straightforward “green” benefit that can be shared between owner and tenant (Traugott, 2000).

A high performance commercial building is a substantially better building than standard practice in terms of energy, economic, and environmental performance. To build a high performance building, it is necessary to consider the whole-building commercial design concept during the design phase that integrates all the subsystems of the building to work together. To accomplish this, the design team should include architects, engineers, occupants, owners, and energy efficiency specialists (NREL, 2005; EERE, 2003; and Crosbie, 2000).

CASE STUDIES OF HIGH-PERFORMANCE BUILDINGS
High performance buildings have been reported in a number of different climates. All were constructed using high performance building components and systems in all stages of the design, which allowed them to consume considerably less energy than conventional buildings. In this survey, a total of 35 high-performance building case studies were selected, reviewed, and then summarized in Table 1. Table 1 includes information about building characteristics, high-performance strategies, Energy Use Indices (EUIs), and energy savings. Also, climate zones, in which the buildings are located, are included according to the map (USDOE, 2002) in Figure 1.

Currently, the USDOE’s Office of Energy Efficiency and Renewable Energy (EERE) contains the largest database of case studies of high performance buildings (EERE, 2005). In this database are more than twenty case studies of high performance commercial buildings in the United States. The energy savings of these case study buildings were calculated mainly with utility bill comparisons or DOE-2 simulations (LBNL, 2002). The savings results varied from study to study, depending upon the unit of measure and the reference buildings.

Figure 1: Map of Climate Zones in United States for Energy Design Guidelines (USDOE, 2002)
### Table 1: Literature Summary of High-Performance Building Case Studies

<table>
<thead>
<tr>
<th>No.</th>
<th>Authors</th>
<th>Building Name</th>
<th>Climate Zone</th>
<th>Building Location</th>
<th>Org Type</th>
<th>Contraction Date</th>
<th>Base Area</th>
<th>Energy Use Intensity (kBtu/ft²)</th>
<th>Energy Savings (%)</th>
<th>High-Performance Strategies</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dec et al. (2009)</td>
<td>Pecos Resource Department of Public Facilities' Building</td>
<td>Cool &amp; Humid</td>
<td>Arlington, TX</td>
<td>Commercial office</td>
<td>2011</td>
<td>13,000</td>
<td>DOE-2</td>
<td>20%</td>
<td>HVAC system, lighting, HVAC controls, lighting controls, building envelope, water systems, renewable energy, compressed air systems, solar panels, pumps, and energy management systems.</td>
</tr>
<tr>
<td>2</td>
<td>Dec et al. (2009)</td>
<td>Higher Education Improvement Center</td>
<td>Cool &amp; Humid</td>
<td>Arlington, TX</td>
<td>Commercial office</td>
<td>2011</td>
<td>5,400</td>
<td>DOE-2</td>
<td>20%</td>
<td>HVAC system, lighting, HVAC controls, lighting controls, building envelope, water systems, renewable energy, compressed air systems, solar panels, pumps, and energy management systems.</td>
</tr>
<tr>
<td>3</td>
<td>Smith et al. (2009)</td>
<td>The Chicago Gay Foundation, Philip Merrill Environmental Center</td>
<td>Cold &amp; Dry</td>
<td>Silverthorne, UT</td>
<td>Commercial office</td>
<td>2010</td>
<td>10,000</td>
<td>DOE-2</td>
<td>20%</td>
<td>HVAC system, lighting, HVAC controls, lighting controls, building envelope, water systems, renewable energy, compressed air systems, solar panels, pumps, and energy management systems.</td>
</tr>
<tr>
<td>4</td>
<td>Taylor et al. (2009)</td>
<td>The National Park Visitors Center</td>
<td>Cold &amp; Dry</td>
<td>Chet Holifield Building</td>
<td>Commercial office</td>
<td>2010</td>
<td>6,500</td>
<td>DOE-2</td>
<td>20%</td>
<td>HVAC system, lighting, HVAC controls, lighting controls, building envelope, water systems, renewable energy, compressed air systems, solar panels, pumps, and energy management systems.</td>
</tr>
<tr>
<td>5</td>
<td>Taylor et al. (2009)</td>
<td>Thermal Felt Facility at the National Renewable Energy Laboratory</td>
<td>Cold &amp; Dry</td>
<td>Philip Merrill Environmental Center</td>
<td>Commercial office</td>
<td>2010</td>
<td>6,400</td>
<td>DOE-2</td>
<td>20%</td>
<td>HVAC system, lighting, HVAC controls, lighting controls, building envelope, water systems, renewable energy, compressed air systems, solar panels, pumps, and energy management systems.</td>
</tr>
</tbody>
</table>

*Note: DOE-2 stands for the Department of Energy's EnergyPlus software, which is used to simulate building energy performance.*
When comparisons were made with conventional buildings, savings of 52-64% were reported. Savings of 24-40% were reported for buildings that were compared to ASHRAE Standard 90.1-2001 (ASHRAE, 2001) compliant buildings. Finally, savings of 40-50% were reported for buildings that were compared to California’s Title 24 Standards (CEC, 2001).

In one significant study, Torcellini et al. (2004) analyzed the performance of six High-Performance buildings. These buildings were originally built with goals of energy efficiency and sustainability without compromising environmental elements. To achieve these goals, high-performance systems were implemented in the buildings, which included improved thermal envelopes, daylighting, radiant heating, natural ventilation, mixed-mode ventilation, ground source heat pumps, photovoltaic, and passive solar systems. Torcellini et al. used computer simulation tools (DOE-2 and EnergyPlus) to evaluate the performance of the buildings. The results showed that all buildings performed significantly better than the minimum code requirements; i.e., energy cost savings from 44% to 67% compared to ASHRAE Standard 90.1-2001 or the Federal Energy Code 10 CFR 435.

As shown in Figure 2, five of the studies (14%) had EUIs less than 30 kBtu/ft²-yr, eleven studies (31%) had EUIs between 30-50 kBtu/ft²-yr, three studies (9%) had EUIs between 50-70 kBtu/ft²-yr, six studies (17%) had EUIs between 70-90 kBtu/ft²-yr, three studies (9%) had EUIs between 90-110 kBtu/ft²-yr, and four studies (11%) had EUIs greater than 140 kBtu/ft²-yr.

As shown in Table 1, however, no high-performance buildings were identified in hot and humid climates except the Robert E. Johnson Building in Austin, TX (Sylvester et al., 2002). Sylvester et al. developed a baseline simulation model calibrated to the measured whole-building energy consumption to determine the independent and combined effect of the stated efficient components installed in the building. They showed that the energy savings resulting from the new design reduced the energy use by 46% when compared to similar state office buildings. Although there have been studies on energy-efficient buildings in hot and humid climates, it is necessary to design and construct high-performance buildings using high-performance HVAC systems and components, which are best optimized for hot and humid climates.

### HIGH-PERFORMANCE SYSTEMS AND COMPONENTS

High-Performance systems and system components have also been reported in a number of different climates. In the survey of high-performance systems and components, a total of 17 papers or reports were selected and reviewed. Table 2 is a summary of the literature and shows system types, applications, climate zones, and energy savings obtained from using high-performance systems or components. The climate zones were indicated using the map of Figure 1. In the literature, energy savings were calculated primarily with the DOE-2 simulation program. The results of energy savings by implementing the high-performance systems and components varied from 22% to 80% compared to energy codes or conventional buildings as baselines. The major systems or components implemented in the studies were Under Floor Air Distribution (UFAD) systems, Ground Source Heat Pump (GSHP) systems, natural ventilation systems, photovoltaic systems, dual-path systems, and ground coupled systems. It is interesting to note that most of these...
systems cannot be simulated with the DOE-2.1e program without modifications.

One noteworthy integrated analysis was performed by Parker et al. in 1997. In this study they presented the energy performance of the new Florida Solar Energy Center (FSEC) building using the DOE-2.1e simulation program to make it a maximum energy efficient building in Florida’s hot and humid climate. The DOE-2.1e simulation program calculated the building energy consumption by implementing ten high-performance systems, which included lighting, glazing, daylighting, HVAC (Heating, Ventilating, and Air-Conditioning) system, humidity control, Energy Star equipment, a reflective roof, variable speed fans and pumps, demand controlled ventilation, and an Energy Management System (EMS). Because of the regional characteristics (hot and humid), careful attention was given to the humidity control. Overall, the optimized building with the implementation of ten high-performance systems showed an energy reduction of 62% and cooling capacity decrease by 52% compared to the energy use of the base-case building that has conventional commercial building characteristics for Florida. The base-case building was simulated using DOE-2.1e program and had an EUI of 71 kBtu/f2-yr, with a cooling capacity of 128 tons (i.e., 320 f2/ton).

### Table 2: Literature Summary of High-Performance Building Systems and Components

<table>
<thead>
<tr>
<th>No.</th>
<th>Authors</th>
<th>Classification</th>
<th>Application</th>
<th>Climate Zone</th>
<th>Location</th>
<th># Bldgs Analyzed</th>
<th>Size (f2)</th>
<th>Energy Use Analysis</th>
<th>Energy Savings (%)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Parks &amp; Taylor (2000)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Temperate &amp; mixed</td>
<td>San Francisco, CA</td>
<td>1</td>
<td>350,000</td>
<td>DOE-2 Simulation</td>
<td>6%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>2</td>
<td>Kamin et al. (2000)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Warm</td>
<td>Columbia, SC</td>
<td>1</td>
<td>98,000</td>
<td>DOE-2 Simulation</td>
<td>6%</td>
<td>UFAD System</td>
</tr>
<tr>
<td>3</td>
<td>Griffith et al. (2006)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Hot &amp; Dry</td>
<td>Denver, CO</td>
<td>1</td>
<td>95,000</td>
<td>DOE-2 Simulation</td>
<td>6%</td>
<td>HVAC System, High-Efficient Chillers, Lighting, and EMS Controls, HVAC and Building Automation System, HVAC Controls and Zoning, Roof Insulation</td>
</tr>
<tr>
<td>4</td>
<td>Deru et al. (2006)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Humid</td>
<td>Edmonton, AB</td>
<td>1</td>
<td>36,000</td>
<td>DOE-2 Simulation</td>
<td>6%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>5</td>
<td>Deru et al. (2006)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Dry</td>
<td>Silverthorne, CO</td>
<td>1</td>
<td>44,400</td>
<td>DOE-2 Simulation</td>
<td>6%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>6</td>
<td>Griffith et al. (2006)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Humid</td>
<td>Amherst, MA</td>
<td>1</td>
<td>32,000</td>
<td>DOE-2 Simulation</td>
<td>29%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>8</td>
<td>Tavakkoli et al. (2005)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Dry</td>
<td>Seattle, WA</td>
<td>1</td>
<td>7,000</td>
<td>DOE-2 Simulation</td>
<td>62%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>9</td>
<td>parker et al. (2006)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Dry</td>
<td>Cocoa, FL</td>
<td>1</td>
<td>41,000</td>
<td>DOE-2 Simulation</td>
<td>62%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>11</td>
<td>Lippe (1997)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Humid</td>
<td>New York, NY</td>
<td>1</td>
<td>1,600,000</td>
<td>DOE-2 Simulation</td>
<td>62%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>12</td>
<td>Roth et al. (2002)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Dry</td>
<td>Greenville, SC</td>
<td>1</td>
<td>647,000</td>
<td>DOE-2 Simulation</td>
<td>62%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
<tr>
<td>17</td>
<td>Kamin et al. (2000)</td>
<td>HVAC System</td>
<td>UFAD System</td>
<td>Cool &amp; Humid</td>
<td>Chicago, IL</td>
<td>1</td>
<td>40,000</td>
<td>DOE-2 Simulation</td>
<td>62%</td>
<td>HVAC System, Primary multi-zone VAV, High-Efficiency Chillers, Ground-coupled Systems, Primary-only Variable Flow, High-Efficiency Cooling Towers with Air-Cooled Water- cooled deciding 2</td>
</tr>
</tbody>
</table>

In another study, “Energy Consumption Characteristics of Commercial Building HVAC Systems”, Roth et al. (2002) reported fifteen high-performance commercial building systems and components that have energy savings potential. The study included a detailed evaluation for each of the fifteen technologies. For example, five of the fifteen technologies used dedicated outdoor systems (or

dual-path systems), displacement ventilation, enthalpy/energy recovery heat exchangers, liquid desiccant systems, and/or radiant ceiling cooling systems. Roth et al. also included energy savings potentials from these technologies, including: 15-20% savings of space cooling energy from Dedicated Outdoor Air Systems (DOAS) compared to conventional VAV systems, 9-69% savings of cooling energy use from Displace Ventilation (DV) systems implemented in office buildings in five U.S. cities (Albuquerque-23%, Chicago-21%, Fort Worth-9%, New York-23%, and San Francisco-69%) compared to conventional VAV systems, 35% savings of annual heating and cooling energy consumption from enthalpy/energy recovery heat exchangers applied in a New York office building, 20-25% savings of outdoor air cooling energy from liquid desiccant systems (in combination with a DOAS) compared to conventional systems, and 15-20% of space cooling energy from radiant ceiling cooling systems (in combination with a DOAS) compared to conventional VAV systems.

There are many high-performance technologies for the construction of high-performance buildings. However, not all high-performance systems and components mentioned in these studies are applicable for high-performance buildings in hot and humid climates. Also, even the technologies, which have been proven to improve building energy performance, need further demonstrations of the benefits of savings. For example, the dual-path system (or DOAS) was verified in a couple of studies (Khattar et al., 2003 and Khattar and Brandemuehl, 1996) as a high-performance system for good humidity control and improved Indoor Air Quality (IAQ); therefore, it should be a good choice for hot and humid climates. However, there is still a need for additional demonstrations for its application to the office buildings in hot and humid climates.

HVAC ENERGY USE OF COMMERCIAL BUILDINGS IN HOT & HUMID CLIMATES

Westphalen and Koszalinski (2001) analyzed total HVAC primary energy use and Energy Use Intensity (EUI) by five regions (Northwest, Midwest, South, Mountain, and Pacific) based on the Commercial Buildings Energy Consumption Survey (CBECS, 1998) report. As shown in Figure 3 and Figure 4, the HVAC energy use was clearly dependent on the geographic regions. The categories here are different from those shown in Figure 1. However, it is reasonable to consider the South region as hot and humid climate area since the climate condition of the South region is mainly hot and humid.

In Figure 3, the South region was the area showing the highest total HVAC energy use since the region has the largest conditioned floor space compared to the other regions. In the South, due to the climatic characteristics (hot and humid), it makes sense that cooling energy use was the major contribution to the total HVAC energy use. Figure 4 shows the average HVAC EUIs by region. Although the South also showed the highest average EUIs, the total EUIs for the five regions did not vary much except one region, the Pacific, which has mild, year-around climate. In the South, however, the cooling portion remains higher than any other regions. It is interesting to note that although there is such a large total HVAC energy use in the South as shown in Figure 3, in Table 1 only a few studies demonstrated specific ideas for reducing energy use in the South.
SUMMARY

In this paper, a literature review revealed not only case studies that deal with high performance buildings, high performance components, and measuring tools, but also experimental research that deals with the development of specific energy-efficient HVAC systems and components in various climates. Based on the survey of high-performance buildings, this study identified 35 case studies of high-performance buildings and 17 papers about high-performance systems and components.

In the case studies of high performance commercial buildings, there were many ‘Green’ strategies to enhance building performance; e.g., wall insulation, displacement ventilation, ground-coupled system, daylighting, underfloor air distribution system, ventilation system, PV systems, roof insulation, high performance window, and so forth. The energy savings of high-performance buildings were substantial, ranging from 15-83% compared to energy codes or conventional constructions as baseline. The savings from individual systems or components varied from 22-80% compared to the energy consumption of conventional systems or equipment.

For the energy savings analysis, the DOE-2 program has been mainly used as the evaluation tool for the energy performance of case studies. Although DOE-2 is a powerful simulation program that is capable of simulating specific systems and components and showing energy impacts of them on buildings as well, there are still HVAC systems that the DOE-2 (or other) simulation programs cannot simulate (e.g., Under Floor Air Distribution System, Dual Path System, Displacement Ventilation, and Natural Ventilation).

Hot-dry and hot-humid climates consume the most HVAC energy use in United States compared to other climate areas due to the large amount of conditioned floor space and the extreme climatic conditions (hot and humid). Also, the cooling energy use is dominant in the energy use required for HVAC in hot-dry and humid-humid climates. So it is necessary to design and construct high-performance buildings using special high-performance HVAC systems and components for south climates. Unfortunately, however, there were only few high-performance buildings identified and reported publicly in hot and humid climates.

There are many technologies to make a building a high-performance building using high-performance systems and components. However, not all high-performance technologies are applicable for buildings in hot and humid climates. Moreover, even for the technologies applicable in the climates, more demonstrations are needed for designers and engineers to be able to implement them with confidence.

Finally, the most promising characteristics of high-performance office buildings in hot and humid climates are as follows.

- Solar thermal and PV systems
- Dual-Path systems (or dedicated outdoor air systems) to control high humidity
- High efficiency chillers
- High-Albedo roofs
- Daylighting systems
- High-performance glazing

Therefore, there is an opportunity to continue to explore alternatives for high-performance office buildings in hot and humid climates.

REFERENCES


Lippe, P. 1997. Lessons Learned 4 Times Square: An environmental information and resource guide for the commercial real estate industry.


