Energy Conservation and Indoor Air Quality:

Lessons From the Past Have Relevance for the Future

The relationship between IAQ and the use of energy to heat, cool and ventilate buildings is well documented throughout history. This lesson is at risk of being forgotten as concerns about global warming have once again put energy conservation front and center. What is missing in today's discourse is the understanding that to pursue energy conservation in homes and buildings without taking the quality of indoor air into consideration puts building occupants at unnecessary health risk. Conversely, to pursue good indoor air quality (IAQ) without considering the efficient use of energy may unnecessarily increase energy costs and emissions of greenhouse gases, thereby contributing to outdoor air pollution and possibly even global warming. The two go together.

To underscore this point, this report briefly reviews the history of energy conservation and IAQ, prior to 1970, as they relate to buildings, in particular how their histories became intertwined and their use today interdependent. This review is not meant to be comprehensive, but to offer illustrative highlights. The companion AQS Research Report, *Energy Conservation and Indoor Air Quality: Newer Objectives, Same Health Impact*, highlights studies that demonstrate the benefits of good IAQ and that IAQ and energy are complementary not competing goals. That report also emphasizes that to successfully manage IAQ and energy, both must have the same priority throughout the life of a building. This report is available free from the AQS Aerias IAQ Resource Center (www.aerias.org).

Energy Conservation, Indoor Air Quality: Intertwining Histories

Early on humans strived to find easier ways to work while using less physical energy. The invention of the wheel, for example, was an advance in energy conservation as was reducing the time and effort to find fuels for fires (Wulfinghoff 2000). At the same time, humans also strived to shield themselves from the weather, including keeping warm during cold snaps and cool when temperatures soared. While these two goals are different, humans used the same resource to achieve them: energy.

Fire, Ice, Wind Fuel Early Attempts at Heating, Cooling, Ventilation

The discovery of fire is viewed as one of the most significant milestones in human history, along with language. Pre-historic people used fire to stay warm and provide light and protection from animals, giving rise to the first social gatherings. Egyptians at the time of Moses (1355 BC to 1235 BC) developed a primitive type of bellow to concentrate and enhance heat energy from fires and to disperse smoke from the indoor environment. Around 2500 BC, the Egyptians also employed early attempts at evaporative cooling, and there are records of an 8th century (AD) caliph in Baghdad using snow packed between the walls of his summer villa for cooling (Jaquet 1985, Donaldson and Nagengast 1994).

Central heating in the form of ducts beneath the floors of the King of Arzawa's palace was first used in southwestern Anatolia (present day Turkey) before 1200 BC. The technology disappeared, but was rediscovered and used extensively by the Roman Empire more than 1,000 years later. The Roman design employed under-floor ducts connected to a central chamber that was heated with fire. This method was referred to as *hypocaust*, from the Greek words for "under" and "burning." To prevent smoke from getting into rooms, exhaust was vented through an opening in the hypocaust chamber. Clay tile risers or a network of chimneys built within the walls provided heat distribution. These chimneys were open to the hypocaust chamber at the bottom and the outside air at the top (Sprague de Camp 1963, Donaldson and Nagengast 1994). Roman residences, such as villas or apartments, also were heated with wood or coal-fired braziers that were placed in the middle of the room. Smoke was vented through doors and windows or vents located at the top of the room. (Donaldson and Nagengast 1994).

Other early attempts at natural ventilation used fire to induce ventilation in areas where breezes were not available. This Roman invention was used until the end of the 18th century, when fans where first introduced into the British House of Parliament. In hot climates, natural ventilation took advantage of prevailing winds, through the use of courtyards, open verandas, loggias and porches on the outside. Indoors, large, open stairwells induced vertical air circulation and dome or high ceilings were used to ventilate hot air. Many of these same features are found in southern US colonial architecture (Donaldson and Nagengast 1994).

Despite these early efforts, the concept of ventilation remained poorly understood until the 19th century. There was some awareness, however, that "good" air was healthier than "foul" air, but there was little agreement as to whether the "good" air was indoor or outdoor air. Hippocrates hypothesized that decaying organic matter from marshes and wetlands created an infected air or "miasma" that was a carrier of deadly diseases. For centuries, foul air was considered a natural condition to be avoided by proper city planning and building away from marshes (Addington 2000).

Medieval Period, Renaissance: Open Fires, Fuel Shortages Yields Poor Indoor Air Quality

Until the late 18th century, fires built in open hearths in the center of buildings away from combustible walls, or in stoves without chimneys, were the primary method for cooking. Poor chimney designs often contributed to the problem of smoke removal, which limited the use of open fires for heating. Instead, smoke migrated out through cracks, porous roofs, eaves and louvers. Smoke also was a problem for the outdoor environment. By 1306, for example, soot was so pervasive in London that the burning of coal was temporarily outlawed. Even today in developing countries, open fires and stoves without chimneys are used for cooking and heating (WHO 2005, Addington 2000, Motavalli and Reese 1999).

Also, the scarcity of clean burning fuel, which had an indirect impact on the quality of indoor air, was not uncommon. For example, in response to a severe deficiency of hardwood, caused by a building boom in English cities, Queen Elizabeth I "proclaimed in 1558 that no oak, beech or ash more than one foot square at the stub could be used for purposes other than building." This proclamation further depleted increasingly expensive supplies of dirtier softwoods for fuel (Wright 1964), and prompted all but the wealthiest households to burn coal, dung, sawdust and/ or peat. Charcoal became the fuel of choice for the wealthy, as its lack of smoke made it ideal for burning in braziers in closed rooms without ventilation. The downside, however, is many died from carbon monoxide poisoning (Addington 2000). Of note, the World Health Organization (WHO) reports that more than one-half of the world's population today still relies on dung, wood, crop waste or coal to meet their most basic energy needs, resulting in 1.6 million deaths per year due to poor IAQ (WHO 2005).

Not much changed with respect to managing smoke indoors until the mid-18th century when in 1742 Dr. Benjamin Franklin devised the Pennsylvania fireplace, better known as the Franklin stove, which more was more fuel efficient and more effectively heated rooms than other stoves and fireplaces used at the time. To address the problem of smoking fireplaces, which was detrimental to IAQ, Dr. Franklin published his *Observations on Smokey Chimneys* in 1793, in which he proposed rules for proportioning of fireplaces. He also described the design of multiple flues in a single chimney, which allowed for heating multiple story buildings and apartments. Benjamin Thompson, Count of Rumford, expanded on Dr. Franklin's work, including introducing a smoke shelf to the open fireplace and the regulator, which provided a way to control fresh air intake and the rate of burning fuel in a stove – a key advance in energy efficiency (Donaldson and Nagengast 1994, Addington 2000, NNDB 2007).

While these efforts greatly reduced the amount of smoke indoors, major changes in the understanding of air prompted the realization that smoke was not the only indoor air danger; human expiration of carbon dioxide posed a grave threat as well. This threat also had major impact on how buildings were heated, cooled and ventilated and inspired the promulgation of ventilation standards, beginning in the 19th century.

Urbanization, Industrialization: Population Growth, Steam and Discovery of New Fossil Fuels Drives Demand

But for fire, other primary energy sources, such as water and wind, were not directly involved with the heating, ventilation or cooling of buildings, but instead were used for transportation and shipping, food production, irrigation, smelting and shaping iron, sawing wood and powering a variety of early industrial processes. The exception, of course, is natural ventilation, which relied on prevailing winds. This all changed with the advent of industrialization, the steam engine and the discovery of vast amounts of fossil fuels, which gradually replaced the use of windmills and waterwheels, although the use of wind and water are still used today to generate electricity.

Steam engines were first put into practical application during the 18th century and to a large extent, this power source created modern civilization, by removing time, geographic, climate and size restrictions for the use of energy. The ability to build large steam engines and the growth in their applications also led to a rapid increase in demand for fuel, with the cost of fuel soon becoming a major impediment to this technology. In response, energy efficiency emerged as a key issue, and mechanical engineers went to work to create more efficient steam engines (Wulfinghoff 2000).

Another intriguing factor that greatly influenced the efficient use of energy during the Industrial Revolution is new sources of fuel were discovered in advance of demand. Steam engines, for example, made coal mining much more productive. Thus, burning coal became a popular source of energy, which had a significant impact on both indoor and outdoor air quality in cities (Wulfinghoff 2000). For example, in 1854's *Hard Times*, Charles Dickens wrote of US cities: “It was a town of machines and tall chimneys, out of which interminable serpents of smoke trailed themselves for ever and ever and never got uncoiled.” In parts of the Midwest, the smoke and soot was so dense that Chicago and Cincinnati passed ordinances to control emissions from furnaces and locomotives, becoming the first air pollution statutes in the US (Motavalli and Reese 1999).

Extracting petroleum in quantity also became possible in the mid-19th century, before people knew what to do with it. The development of internal combustion engines soon provided a large market for petroleum, including providing fuel for steam engines. With petroleum came natural gas, at first a dangerous waste product, but its discovery in quantity motivated finding uses for it (Wulfinghoff 2000).

Driven by this wealth of these natural resources, US industries grew dramatically during the late 19th century. As industries grew, so did the towns and cities in which they were located. In many cases, the cities not only expanded outward but also upward as skyscrapers became popular. Specifically, US cities grew by about 15 million people between 1880 and 1900, many of which were immigrants from around the world. A steady stream of people from rural America also migrated to the cities. Between 1880 and 1890, nearly 40 percent of US towns lost population. Many of those who resided in cities lived in rental apartments or tenement housing. This greater population density in cities also brought noise, traffic, outdoor air pollution, and sanitation and health problems (US Library of Congress 2002).

With respect to indoor environments, John Shaw Billings, deputy surgeon general of the US Army, adapted the principle of aspirating ducts (dedicated heat-source such as a kerosene lamp or gas jet inside the duct to establish a convective current of air) for ventilation systems in several public and institutional buildings from the mid-1870s and 1880s (Gouge 1881, Billings 1889). Rather than using a combustion source directly in the aspirating shaft, Billings inserted steam coils and eventually proposed using the same shaft for heating and ventilating. His invention was a key step forward in a more efficient use of energy as it eliminated the redundancy of having separate heating and ventilating systems (Addington 2000).

At about the same time, district steam service arrived in major US cities, which provided a supply of steam to buildings and facilitated the gradual phase-out of direct combustion systems for heating, such as those powered by fossil fuels. In addition, smaller steam engines, which could easily be installed in buildings, were developed and gradually made convectively driven ventilation obsolete in favor of systems mechanically driven by fans. The BF Sturtevant Company adopted Billings' approach for its "blower system," which was comprised of a combustion engine, fan and heater in a single unit. The company promoted this system as providing "free ventilation" with the exhaust steam from driving the fan's engine serving as the supply steam for the heating coils. This approach dominated ventilation system design even after electrical drives replaced steam engines at the beginning of the 20th century (Sturtevant 1896, Addington 2000).

During the later part of the 19th century, concerns about carbon dioxide and depletion of oxygen in public buildings were replaced with fears about "crowd poison," reflecting a growing awareness of the socioeconomic conditions of immigrants and a greater incidence of tuberculosis among those living in city tenements (Tomes 1998). As a result, Thomas Tredgold in 1824 was the first to recommend a ventilation standard, by proposing 4 cubic feet per minute (cfm) of "unvitiated" air per person. Other experts in the US and Great Britain also proposed standards even before many ventilation systems could accommodate the proposed rates (Janssen 1994).

There also was a debate about how disease was transmitted and the role of air in caring for the sick, especially in cities with high population densities. Even though the medical profession had accepted that infectious diseases were spread by physical contact or through water, insects, food, there was still a strong belief that air was a carrier. Frederick A.P. Barnard, president of Columbia University, argued that the carrier itself was not as important as the hygiene efforts used were the same regardless, including disinfection, proper drainage, wholesome food and fresh air (Barnard 1837).

Billings countered by presenting statistics that compared the death rates of men, horses and monkeys in well ventilated with unventilated barracks, ships, prisons and stables. These statistics showed that numerous diseases, including tuberculosis, were cause or made worse by insufficient ventilation (Billings 1893). He recommended a minimum ventilation rate of 30 cfm per person, which was very well received, and by 1915, 21 states had passed laws or ordinances required ventilation in public schools and/or factories, with four of those states requiring ventilation in all buildings types (Ventilation Laws 1917).

Another debate going on during the early part of the 20th century concerned the best conditions for schools: mechanical ventilation or fresh air from open windows. For four years (1913 – 1917), the New York State Commission on Ventilation studied the issue, both in a laboratory and in 20 different schools. After reviewing the performance of 5,500 children, the investigators concluded that temperature in the classroom was the most important variable to control. Ventilation was only needed to remove odors, which could very well be achieved by opening the windows (Milbank 1923). The results of the study were not published until 1923, which by then the American Society of Heating and Ventilating Engineers had established a chart that quantified the environmental dynamics of comfort. Researchers at the Department of Ventilation and Illumination, Harvard School of Public Heath, further refined this comfort chart. In the end, the New York State Commission's findings and efforts to promote those findings did little to stop the use of mechanical ventilation (Addington 2000).

Another factor working against natural ventilation was the 1918 – 1919 influenza pandemic, which killed more people than in World War I. Old fears about the miasmic contamination resurfaced. Undertakers were said to have sung the following rhyme as they buried the dead:

I had a little bird, and its name was Enza. I opened the window, and influenza (Crosby 1997). For more information, see *Understanding the Nature of Indoor Air* below.

Comfort Cooling (Air-Conditioning) Allow Cities in Hot, Humid Climates to Thrive

Popularly believed to have been invented around 1900, early forms of modern air conditioning, also called "comfort cooling", were actually being developed during the 19th century, although these designs were "really hit-or-miss approaches: the air was at least cooled and sometimes dried. But there was little understanding of the science involved in these processes" (Nagengast 1999).

A scientific approach to cooling did not come into play until the late 19th century, when German heating engineers refined the methods of Eugen Péclet of France. In the 1894 first edition of Hermann Rietschel's, professor at the Berlin Royal Institute of Technology, *Guide to Calculating and Design of Ventilating and Heating Installations,* a chapter on room cooling contained a step-by-step approach for calculating cooling plants and elucidated the following points, all of which were to have significant impacts on energy use and IAQ:

- "For calculating heat gain, the highest normally expected outdoor temperature should be used, and the exposure of the outside buildings walls face should be considered."

- "As air is heated it becomes relatively drier, and conversely, as air is cooled, it becomes more dense and relatively more wet. When air is cooled below its dew point, it becomes saturated and water will condense out. Normally, refrigeration systems use very cold heat exchangers that reduce the absolute humidity to a low level. However this cold but saturated air would result in uncomfortable conditions were it to be used for comfort cooling. It is then necessary to mix the cold saturated air with warmer outdoor air to raise its temperature, but lower its relative humidity."

- "The normal heating practice of using 100 percent outdoor air would results in very high cooling system operating costs, because of the latent heat removal encountered in moisture reduction. Therefore, recirculation on the part of the room air is important. Supply ducts should introduce cool air far enough from the room occupants so that the air is thoroughly diffused."

- "An air washer can be used to dehumidify air if the water temperature is sufficiently low. The washed, cooled air can be mixed with recirculated room air and then introduced directly into the room."

- "To calculate the size of refrigerating systems for air cooling, it is necessary to determine the load that includes wall heat gains, heat from occupants and lighting.""

- Only part of the supply air should be cooled to saturation. Some supply air can be bypassed around the cooling coil, mixed with the cooled air of low absolute humidity resulting in an air supply of lower relative humidity" (Nagengast 1999).

Alfred Wolff was the first to successfully apply many of Professor Rietschel's principles in the cooling systems he designed for the Cornell Medical College in 1899, the New York Stock Exchange in 1901 and the Hanover National Bank in 1903. Wolff expressed his conviction about the value of air conditioning to the Stock Exchange's architect George Post:

"What this means in comfort, in ability to transact business, the health and well-being of the members, can scarcely be realized by a mere recital of ... figures, but must be experienced to be thoroughly appreciated…If the refrigeration plant is instituted for the boardroom and the entering air is cooled ... and the percentage of moisture lowered, the result will be that this room will be superior in atmospheric conditions to anything that exists elsewhere. It will mark a new era in the comforts of habitation" (Wolff 1901, Nagengast 1999)

Dr. Willis H. Carrier's innovative work in the early 20th century built on the work of Professor Reitschel and others, including Wolff. His realization that air conditioning could be a profitable business and then capitalizing on it earned him the title, "Father of Air Conditioning." The following list some of his many remarkable achievements that would have a lasting impact on IAQ and energy:

- Discovering the law of constant dew points in 1907 and using it as the basis for automatic control systems

- Presenting his "Rationale Psychrometric Formulae" and chart to calculate dew point control in 1911, which was hailed as the "Magna Carta" of the air-conditioning industry

- Achieving the first residential air conditioning application in 1914 at the Charles Gates mansion in Minneapolis, Minnesota (Donaldson and Nagengast 1994)

- Being the first to air condition a department store, JL Hudson, in Detroit in 1924 (Carrier Corporation 2007)

- Inventing the centrifugal refrigeration machine, which Carrier patented in 1921. The "centrifugal chiller" was the first practical method for air-conditioning large spaces and proved to be safer and more efficient (Bellis 2007).

- Air-conditioning the US House of Representative and US Senate chambers in the Capitol 1928 and 1929 as well as more than 300 movie theaters by 1930 (Encyclopedia of World Biography 2006).

Also, in the early 20th century (1908), GB Wilson wrote the first textbook to use the term "air conditioning", in which "he defined modern year-round air conditioning:

1. To maintain a suitable degree of humidity in all seasons and in all parts of a building.

2. To free the air from excessive humidity during certain seasons.

3. To supply a constant and adequate supply of ventilation.

4. To efficiently wash and free the air of all micro-organisms [sic], effluents, dust, soot and other foreign bodies.

5. To efficiently cool the air of rooms during certain seasons.

6. To either heat rooms in winter or to help heat them.

7. To combine all the above desiderata in an apparatus that will not be commercially prohibitive in first cost or cost of maintenance" (Wilson 1908).

It is important to note that the interest in reducing the cost of operating air-conditioning systems during this time was motivated more by the desire for sales than by an interest in conserving energy. In fact, air conditioning prior to World War II was primarily confined to theaters, industry and other public spaces.

The Metropolitan Insurance Company's headquarters in midtown New York City, for example, was the only commercial building in the city that was fully air conditioned at the time of its construction (Ross 2007). For more information, see *Electricity, Air Conditioning, Modernism Transform Buildings* below.

In the residential sector, air conditioning did not really catch on until the later part of the 20th century. In 1978, for example, only 23 percent of US homes had central air conditioning. By 1997, however, this number had increased to 47 percent. During the same period, the number of homes with window/wall units dropped from 33 percent to 25 percent, and the number with no air-conditioning equipment at all dropped from 44 percent to 28 percent. As expected, the South, with its hot, humid climate, consistently had the highest percentage of homes with air conditioning. By 1997, 93 percent of homes in the South had some type of air-conditioning, compared with 41 percent of homes in the West (US EIA 2000).

Electricity, Air Conditioning, Modernism Transform Buildings

As with air conditioning, electrical power first emerged in the late 19th century. Its first use was for lighting, although other uses were soon found, such as running electric motors, which greatly expanded the use of mechanical power to many applications, including HVAC systems. As a result, “energy” in the form of electricity "quickly became a ubiquitous commodity by the beginning of the 20th century” (Wulfinghoff 2000).

During the 20th century, as available fossil fuel energy supplies grew comfortably ahead of demand, wind and water as power sources diminished in importance yet were still used. Today, about 10 percent of US electricity comes from hydropower. Wind energy also continues to be used to generate electricity, and according the US Department of Energy (US DOE) is the world’s fastest-growing energy source. In addition, nuclear power plants came on line during the last half of the 20th century to generate electricity (US DOE 2005, Wulfinghoff 2000).

As noted above, the 20th century saw an amazing change in buildings, both at the start of the century and at its end. Early on, air conditioning and electric lighting, along with modernism (the power of human beings to create, improve, and reshape their environment, with the aid of scientific knowledge, technology and practical experimentation) transformed building architecture. Permeable masonry was replaced by impermeable curtain walls made of glass, steel, plastics, lighter-weight masonry and concrete panels. Mechanical HVAC systems and electric lighting allowed more of a building’s interior to be used as occupied space, and as a result, internal heat gains rose rapidly, requiring many buildings to be cooled even in winter. Despite these demands, HVAC systems changed very little (Addington 2000, Ross 2007). Air conditioning also allowed the cities in the US South and Southwest to grow into vital economic and cultural centers as the US population moved south and west, especially in the last half of the 20th century.

During this time, interest in ventilation rates diminished. Occasionally, there were questions whether the old ventilation codes, usually specifying a rate of 30 cfm per person, needed to be supplied with outside or recirculated air. Researchers during the 1930s, who conducted studies on odor and ventilation, concluded that if the recirculated air was treated through the air handler, then it could replace one-half of the outside air with no noticeable impact on odors (Janssen 1994, Addington 2000). This debate quieted and did not resurface again until 40 years later.

Lesson From the Past Have Relevance for the Future

The response to the OAPEC Oil Embargos of the 1970s and subsequent energy crises ignored many of the lessons of the past. As a result, as buildings were constructed to conserve energy they had an unintended adverse impact on the health of building occupants and eventually spawned an epidemic of indoor mold growth, which peaked just after the turn of the millennium. Confounding these problems was a shift from natural to synthetic materials used to construct, finish and furnish building interiors, leading to significant off gassing of volatile organic compounds (VOCs), including formaldehyde, which became a major problem for schools using portable classrooms. In addition, electronic office equipment became a mainstay beginning in the 1970s. While electronic office equipment greatly improved worker efficiency and productivity, some copiers and computer printers generate particulates, which can adversely impact on health. For more information, see the companion AQS Research Report, *Energy Conservation and Indoor Air Quality: Newer Objectives, Same Health Impact.*

It is not too late to revisit the lessons from the past and apply them to the future. AQS stands ready to partner with the building owners, designers, specifiers, builders, and operation and maintenance personnel to create and maintain healthy indoor environments. Visit us at www.aqs.com to learn more about how the AQS Building Consulting Group can help you, or call us at (770) 933-0638. Also visit the AQS Aerias IAQ Resource Center to learn more about indoor air quality. Aerias may be accessed from the AQS website or at www.aerias.org. For a listing of products that are certified to emit low levels of VOCs, visit the GREENGUARD Environmental Institute site at www.greenguard.org.

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