AIR

Swegon Air Academy

Part D

The indoor environment – in a wider sense

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A PLEASANT

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SENSES

[William Shakespeare *Macbeth*]

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FOREWORD

Our need for fresh air, essential to our functioning as human beings, is not normally contested by anyone. This is because we have basic physiological needs - om brains and the cells in our bodies need oxygen so that they can develop and perform properly. However, the air we breathe contains more or less harmful substances and these cause more problems than most of us can probably imagine or understand. On their own, these substances might be troublesome - but collectively, they could be disastrous! Remember, that while we need about 0.75 kg of food and about 1.5 kg of liquid per day, we need at least 15 kg of air!

It is quite reasonable to compare an air handling system in a building to our own respiratory system with its airways and lungs, as both systems have enormous significance for our health and well-being. And, as the air is often used to supply or remove heat, this makes the importance of the air handling system even greater, as it significantly affects our comfort, well-being, productivity and efficiency. Buildings, too, need a continuous change of air to feel good.

LACK OF COMMON POINT OF VIEW

Bearing in mind all of the above, it is rather odd that those involved in lanning a building rarely see things from the same point of view. Short-term economic interests ~re often allowed to determine the choice of technical solutions and, when costs are not critical, buildings are all too often designed in such a way that they are neither pleasant to occupy nor energy-efficient. And, up to now, it has been rather difficult to acceptfeedback and learn from expensive mistakes, and thereby avoid repeating them.

PUBLIC HEALTH, ENERGY AND ENVIRONMENTAL ISSUES - AND ECONOMIC REALITIES

This book focuses on three main areas: Public health, energy and the environment. We are also convinced that economical aspects must be considered as well and this is a recurring topic throughout the book. No matter how efficient and health-promoting an investment might look, it would most probably never be carried out if it were not shown to be economically viable. Today, reliable research results show that there is a clear connection between poor indoor climate and ill-health. And ill-health costs a great deal of money. In other words, there is a real incentive for property owners to invest in good indoor climates now, as future tenants will almost certainly step up their demands.

CONTROL, REGULATION AND MONITORING - THE DECIDING FACTORS

In this electronic age, it is becoming increasingly obvious that control, regulation and monitoring will play a decisive role when it comes to maintaining good indoor climates and ensuring energy-efficient operation of buildings, with subsequent minimal impact on the outdoor environment. The importance of providing solutions that give the clientmaximum freedom of choice and flexibility is illustrated in Chapter 31/The intelligent building- a matter of choice, which discusses centralized building management systems, so-called BMS systems, for control, monitoring and management.

COMPLEX RELATIONSHIPS

- SIMPLE EXPLANATIONS

In this book, *Swegon Air Academy* has compiled ideas and points of view from a wide range of experts. The aim of the book is to put a spotlight on factors and circumstances that are important in the quest for pleasing - indoor environments and comfortable indoor climates, with due regard to energy issues and the outdoor environment. Our ambition has been to explain complex relationships in an intelligible way. It is our profound belief that it is possible to radically improve poorly functioning systems - if we can explain the whys and wherefores.

The passage of air through an air handling system is described, from the outdoor air intake, via an air-conditioned room and into our lungs, with a full account of what happens on the way. The physiological aspects, as well as the comfort, energy and environmental aspects, are examined. How different building designs affect the opportunities for creating good indoor climates is also discussed. Here, the effects that different factors have on each other are not always self-evident or discernable, nor are their specific effects on the indoor climate and total costs. We have, therefore, chosen to illustrate a number of them in greater detail and hope that this will contribute to future developments, for the benefit of all concerned.

TARGET GROUPS

This book is intended not only for clients, property owners and engin-eers, who can influence the design, layout and indoor climate of a build-ing, but also for everyone who would like to learn more about the air we breathe and how it affects us.

Increased insight will make it possible to avoid unnecessary costs, both in the investment stage and in the operational stage of a building project. Attractive premises are a must for survival on a competitive property market.

THE AUTHORS

This book blends theoretical knowledge from the academic world with practical market experience. Our ambition has been to portray the present-day situation and the opportunities in store in an objective and unprejudiced way, by engaging highly distinguished experts and writers from a representative cross-section of the industry.

Proceeds from the sales of this book will be reinvested in the activities run by *Swegon Air Academy*, i.e. in objective transfer of know-how and exchange of information via seminars, technical articles and publications. The contents of this book are available to schools and training programmes connected to the heating and ventilation industry at a subsidized rate.

Enjoy the book!

CONNY NILSSON
Director of the *Swegon Air Academy*

[AIR *Swegon Air Academy*]

AIR

Swegon Air Academy

Part D

The indoor environment - in a wider sense

D. THE INDOOR ENVIRONMENT - IN A WIDER SENSE

CONNY NILSSON *Swegon Air Academy*

When those of us who are normally engaged in the subject of indoor air turn our attention to the indoor environment, we often refer exclusively to the temperature, humidity, speed , purity and quality of the room air, and to the room's acoustics. Unfortunately, this is a rather narrow way of looking at things. An indoor environment comprises so much more, as it also depends on the building's architecture, light sources, colour schemes, furnishings etc.

When designing a building, it is the architect's job to fulfil the client's requirements and intentions with respect to the functions of the building. Consequently, the architect has an enormous influence on the aesthetical aspects of the building, exteriorly and interiorly, as well as the functioning of the building and its energy performance. Different architectural and structural solutions have widely varying effects on the complexity of the installations required to achieve the indoor climate stipulated in the requirements specification. It is, therefore, very important to maintain an open and working dialogue between the architect and the engineering consultants. Their common ambition must be to create a building that will work as an integrated whole.

We do not have to look too far to find that people experience temperature in very different ways. One's own family will suffice - some members think that it is too warm indoors while others, most probably female, think that it is too cold. This everyday example illustrates just how difficult it can be to agree on what is regarded as an acceptable temperature. A compromise is often reached, and no one is really satisfied. Most people would like to be able to adjust the room temperature in their workplace and practical solutions are now available to do just this. In systems with so-called climate modules or chilled beams, separate settings can be made, either for individual rooms or groups of rooms. These are examples of products that allow office staff to enjoy individual temperature control, which has a great effect on their productivity and work efficiency.

Acceptable sound levels in homes and at work could be regarded as being a natural right. Unfortunately, this is not always the case. Even here, the architect plays an important role, being responsible for the overall design of the building, the choice of windows and building materials, etc. The siring of the building is also important - it is obviously harder to create a good acoustic environment in a busy downtown area than in the countryside.

All mechanical installations in a building affect the acoustic environment to some extent. Fans, pumps and lifts - to name a few - are often sources of irritation. Most people who work in office environments and who experience what happens when the ventilation system shuts down at the end of the day know how the ensuing silence produces a feeling of relief. Constant efforts are being made to reduce the amount of energy used for running fans, which means designing for lower air speeds in the ventilation system. Fortunately, this also means lower noise levels - a perfect example of an energy-saving measure going hand-in-hand with improved comfort.

The title of this book is *AIR* and the reader might wonder how the airtightness of a building comes into the picture. In Chapter 12/ Airtightness - for energy efficiency and moisture protection, it becomes perfectly clear: Air must be prevented from finding its way through the building envelope, for the sake of the occupants and the building itself. The airtightness of a building affects thermal comfort, acoustics, moisture resistance, ventilation, energy requirements, etc, and is a key factor with regard to how a building is experienced and how it actually functions.

Another key factor that determines our experience of the indoor environment is the availability of light and in Chapter 13/People and buildings - both need light, it can be seen how important natural daylight is to our health and well-being. Solar radiation also creates heat in a room and this often means that we need even more cooling, which is highly undesirable, as we want to reduce our energy use. Fortunately, improved window designs and different types of sun shading can help limit the adverse effects of solar radiation.

Our experience of the indoor environment is a complicated subject and we often have completely different ideas about what constitutes a good indoor climate. With the world's present focus on energy issues, it is even more urgent that all those engaged in indoor environment issues maintain a working dialogue and cooperate to the full. No one can be an expert about everything but, by working in close cooperation and with mutual respect, it should be possible to make important steps towards better indoor environments and more efficient use of energy.

9. THE HISTORY OF AIR

Architects SAR/MSA **RASMUS WAERN** and **GERT WINGÅRDH**
Wingårdh Arkitektkontor AB, Stockholm/Gothenburg

Why is it that outdoor air almost always represents something heavenly, while indoor air is described as having varying degrees of hellishness? Even noticeably foul air is tolerated outdoors, while the same air indoors is completely unacceptable. The smell of urban air is something for which many are prepared to pay dearly, just as long as it remains outside the dwelling. It is as if the actual stagnation, the fact that the volume of air is at least perceived to be uniform, arouses our sense of nuances that are not otherwise noticed.

These values do not remain the same over time. We are equipped with an immeasurably acute sensitivity, which allows us to perceive changes in that which pertains to our survival. In Torgny Lindgren's novel *Merabs Skönhet,* the well digger describes the nuances in the taste of the water so critically that he is allowed to determine the location of the dwelling site. Since the dawn of industrialisation, air quality has had a decisive influence on Europe's urban planning. Where a westerly wind prevails, the westernmost town quarters have always been preferred by those who have been able to choose. East of the city, where factories and chimneys discharged their waste into the air without a care, lived the workers. Thus, the air itself contributed to a division of the built environment.

These motives persist, but take on new expression. When the chimneys are moved to Asia, it is the traffic that causes people to choose where they wish or do not wish to live. Before the advent of elevators, dwelling status sank with building height; later, the opposite relation would apply. The free air of height is irresistible. The higher, the freer. It is the uppermost floors that make the high-rise attractive. The high-rise is the post-industrial chimney. Instead of sending up smoke, people take the elevator to the freedom of heavenly heights.

The changes in the atmosphere which are now affecting the climate are not, as yet, something that can be directly perceived by people. The distribution of the main constituents of air, oxygen and nitrogen, is essentially constant. Indoor air, on the other hand, has changed drastically. A description of the development of indoor climate is aided by British engineering historian Bill Addis's excellent book, Building: 3000 Years of Design, Engineering and Construction, [Phaidon, 2007], which defines the present situation. The following history is based largely on his presentation.

FIRE AND TOWERS

The earliest problems with ventilation as a means of creating reasonable conditions for people were encountered when mines were sunk so far into the ground that the air did not circulate on its own. The cool mine air does not rise, which is why technical solutions for air exchange were directly decisive for mine operation. The simplest method involved the use of fire. With the warm air, oxygen-deficient, and sometimes poisonous, air was ventilated out and the negative pressure drew fresh air in from the surface, sometimes via special shafts. Capacity was limited, however, and significant amounts of wood were consumed. In his tract, De re Metallica from 1556, the father of mineralogy, Georg Agricola, described several alternatives involving different types of fan systems for mines.

At the same time, the emergence of the new bourgeoisie society brought about a need for secular meeting places. Earlier, churches had provided social meeting places, but with the growth of urban prosperity, the demand for public meeting spaces arose. The church structure's height, in combination with the church tower with its sound vents, was ideally designed to accommodate huge crowds; but for the meetings of political life, the church was not a suitable model. To utilize the same chimney effect, the new assembly buildings, such as the assembly hall in Bruges from 1534–37, or the town hall in Antwerp from 1561–65, were equipped with roof-mounted ventilation outlets. That this first became customary in northern, Protestant Europe is no accident. The need to separate church and state was more acute than in Roman Catholic countries. By the 18th and 19th centuries, these ventilation chimneys adorned innumerable public buildings throughout Europe.

In the 1600s, attitudes as to what constituted good and bad air were not always the same as they are today. There was a widespread understanding that the poor outdoor air should be prevented from entering the buildings, where smoke from fires and candles would make the air salubrious. Consider the smoke sauna, for example. It was not until scientists began to be interested in the composition of air and became aware of the significance of oxygen that air exchange became an important consideration. In 1670, Robert Hooke demonstrated that the requirements for air for breathing and combustion were the same, and in 1713, the significance of fire for ventilation was reported in Mechanism of Fire by Nicolas Gauger. Shortly thereafter, in 1744, John Theophilus Desaguliers described a ventilation system that would evacuate "air that has been fouled by the exhalation of many people and the vapours from candles" in Christopher Wren's newly built House of Commons.

During the Enlightenment, knowledge surrounding heat, humidity and gases grew with the advent of new measurements instruments. At the same time, urban density increased with the addition of many very poor-standard dwellings. Consequently, in the mid-1700s, doctors, scientists, philosophers and reformists began to show an interest in issues of public health and the underlying causes of contagion. A widespread theory was that contagious disease spread via the air from rotting meat or diseased humans and animals. It was an acknowledged fact that illness flourished in enclosed environments such as ships, barracks, prisons and, ironically, hospitals. Since it was believed that diseases were transmitted via the air, attempts were made to ventilate buildings where disease was known to occur or to isolate carriers of the disease. This, however, was seldom practical.

In 1752, British scientist Stephen Hales convinced authorities at London's Newgate Prison to open ventilation ducts in the walls and install a large fan to force in fresh air. Mortality and diseased were radically reduced, and Hales' principles won widespread acceptance and were incorporated in the many new public buildings then being erected. As is still the case today, the choice was between two principles: natural or mechanical ventilation.

The Royal Navy hospital at Stonehouse, Plymouth, was designed as a number of narrow pavilions, whereby each ward could be ventilated with a cross draught. Positive experiences of ventilation soon spread in both England and France.

THE VENTILATOR EVOLVES

Mechanical ventilation driven by heat or fans had long been applied in mines. Even though heat-driven ventilation had been applied with a degree of success in the House of Commons in 1705, it was difficult to create sufficient draught with the principle. In an attempt to improve the ventilation there, Desaguliers installed a hand-driven fan with a diameter of more than two metres. Desaguliers thereby coined the term "ventilator", but in this case, he was referring to the person who operated the wooden apparatus.

At the same time, Hales was experimenting with bellows that would force air into a granary and thus prevent the grain from rotting. The principle was successfully applied on the navy's large ships. As larger ships were built and voyages grew longer, problems of ventilation became more acute, especially since the use of fire onboard ships was discouraged. Hales likened the ship to a whale and the ventilator its lung and his principles soon became popular. Hales' system was installed on all Royal Navy vessels. Hales' version of the manually operated ventilation fan was installed in Naples, St. Petersburg and Lapland. Since these devices so dramatically improved the environment in prisons, hospitals and barracks where they were installed, complaints about the work involved in operating them were minimal. In these institutions, the work of operating the fan was part of daily routine, while in other contexts, mechanical ventilation remained a luxury. As late as the 1840s, for example, two people were required to run the fan that supplied Queen Victoria's opera box with fresh air. Textile factories, which always stood near a source of water power, were provided with water-propelled fan systems that extracted the dust, thereby eliminating a fire hazard. Otherwise, mechanical ventilation did not become popular until the advent of the small steam engines in the mid-1800s.

By the 1810s, the quality of air was beginning to be defined and principles for determining the speed of throughput of air began to emerge. During this period, in England, the Derbyshire General Infirmary was erected. This hospital incorporated all the latest technology in heating and sanitation. The driving force behind the project was a medical doctor, Erasmus Darwin, who, together with engineers William Strutt and Charles Sylvester, created a structure with a ventilation system that spread warm air in the winter and cool air in the summer. The air flow was improved with the addition of rotating hoods on the tops of ventilation chimneys, which increased the draught in the ventilation ducts. Air was brought in via a 70-metre-long, 1.2-metre-wide tunnel in which the temperature remained relatively constant the year round. In winter, air was heated in furnaces on each floor. The laundry was steam-heated and equipped with a steam-driven laundry machine. The wet laundry was hung on racks that were rolled on rails out to a special drying room. Strutt also developed flushing toilets that filled with water when the user opened the door. Innovations also included new, adjustable beds, a meat grill in the kitchen, and foot warmers. These successes made the building and its designers famous and in demand all over Europe and even in North and South America. Even ships that were designed for Arctic exploration were heated and ventilated with Strutt & Sylvester's systems.

Desaguliers' innovative House of Commons burned down in 1834, and when parliament was temporarily moved to the House of Lords, this building was equipped with a sophisticated system designed by the Scottish chemist and engineer David Boswell Reid. One chamber was allocated to "moistening, drying, cooling and other alterations to the air, besides those achieved by the hot water apparatus". In warm weather, the air was cooled by large blocks of ice placed in the ventilation ducts. Even though the term did not yet exist, Reid's device was a full-fledged air conditioner. Soot was removed from the air with filters, after which it was washed in both water and limewater, while acid was neutralised with ammonia. Finally, the air was disinfected with chlorine. The vitiated air was expelled via the ceiling, where glass plates concealed gas lamps which aided the draught while at the same time providing lighting for the room. The inclined glass plates also improved the acoustics.

Reid soon made further advancements with the installation of the world's first large-scale mechanical ventilation system in St. George's Hall in Liverpool. It was designed and built between 1841 and 1854. Three fans, each three metres in diameter, drew in fresh air and also supplied the large concert organ. Capacity could be varied from 100 to 5000 spectators, and the maximum ventilation capacity was 50 000 cubic feet per minute. After filtering, heating or cooling and humidification, as required, the air was distributed along the walls via thousands of tiny holes near the floor. The advanced system functioned for nearly 130 years.

FROM ICE TO COOL AIR

Although heating and ventilation systems were well developed by the mid-1800s, no effective means of cooling the air was devised until the close of the century. The traditional method of cooling air was based on the fact that heat is released when water evaporates. Ponds, and still better, fountains, cool the surrounding air. Ice was used to refrigerate food, and trade in ice was a major industry in the 1800s.

The American "Ice King" Frederic Tudor sold ice from Boston not only throughout the USA, but also to Cuba, Central and South America, to China, the Philippines, India and Australia. In the 1860s the ice industry reached a peak, with 200 000 tons of natural ice being exported from the USA.

The principles of refrigeration in a closed process were first developed by the American inventor and steam engineer, Oliver Evans, in 1805. However, the first refrigeration machine to successfully produce cooled air in large amounts was not built until nearly half a century later. Competition from the ice trade, however, impeded development. Until the latter half of the 19th century, water curtains or ice were still mainly being used to cool inflowing air. By placing blocks of ice on wooden stands in the air ducts, the air could be cooled by about 10 degrees. The cooling capacity could be calculated. In the 1880s, for example, Madison Square Theater in New York used four tons of ice every evening. The great change came about when it became possible to cool air directly with refrigeration machines. The need for theoretical models thereby increased, and in 1887 a heating and ventilation research institute was founded in Berlin by Hermann Rietschel, the world's first professor of heating and ventilation technology. His manual for calculation and design of ventilation and heating systems is still in print. Another historic figure is Richard Mollier, whose lucid Mollier diagram is still used to describe the relations governing air temperature, humidity and energy content. To be able to maintain a stable indoor climate it was essential to be able to control humidity. Textile engineer Stuart Cramer was the first to present a viable solution to this problem. It was he who coined the term "air conditioning" to describe his devices for achieving the correct temperature and humidity in the spinning mills. Cotton fibres become brittle if exposed to air that is too dry (which is one of the reasons why the textile industry emerged on Britain's damp west coast), and trials with water vapour caused the machines to rust.

In the 1920s, air conditioning systems became a standard feature in American factories, hotels, theatres and, not least, cinemas. The fact that cinemas could offer filmgoers a few hours of cool relief strongly influenced the growth of the American film industry. All the while, cooling machines were being refined, and Electrolux presented the first system that was driven by heat, a seemingly paradoxical method of running a refrigerator that later became well known to many caravan owners. The first small single-room units were introduced in the 1930s. These were the predecessors of the boxes that are now mounted on the walls of buildings the world over. However, it was not until the post-war years that air conditioners became commonplace in American offices. Everywhere, the process was the same. Once the proportion of offices with air conditioning reached 20 percent, all other property owners were soon compelled to follow suit in order to compete in the rental market.

The great change that has taken place in the past half century is the realisation that buildings can and should conserve energy. Here, the foremost technical innovation is the heat pump, a device that can be used both to heat and cool a building. The principle was developed by William Thomson, later Lord Kelvin, (the man behind the absolute temperature scale) in the 1850s, but the first heat pump was installed by engineer Thomas Graeme Nelson Haldane in his own home and office. This uncommonly efficient principle, by which more than twice the energy input is returned, achieved a degree of success and was employed, for both heating a cooling, in 1951 in the Royal Festival Hall on the Thames. However, low oil prices impeded technical development.

As energy conservation has become an ever more important element of architectural design, greater focus has been placed on building operation and use, whereas previously, more attention had been paid to the form and construction of the building. Naturally, buildings in extreme climates attract particular interest. As early as the 1950s, architect Ralph Erskine's ideas on sub-arctic construction engendered international interest, even though human wellbeing, rather than energy use, was what interested Erskine most. Today, energy-efficient indoor climatization in tropical climates, as exemplified by solutions by architects like Ken Yang and Renzo Piano, are applied throughout the world. In a global perspective, cooling now accounts for greater energy use than heating.

ATMOSPHERE IS MORE THAN AIR

The history of indoor air, as described here, is largely the history of the triumphs of mechanical ventilation. At the same time, modern ecological building has brought about a renaissance for the technology of natural ventilation. That the British Houses of Parliament were at the forefront of technical development in a country that was the birthplace of industrialism is only logical. But even though the technology had been refined 150 years later, British architect Norman Foster chose a solution based on natural ventilation for the new German parliament in Berlin. From a user perspective, well-functioning natural ventilation is unsurpassed. No noise from fans, and stable systems that are always in operation. In Germany, offices are more often ventilated by opening windows than by mechanical ventilation systems. This is probably energy-efficient in a country with a relatively mild climate. If energy use is to be reduced in cold countries, there is no alternative to extracting heat from vitiated air leaving the building in order to heat the inflowing air. Today, when buildings are equipped with advanced fan systems, it is more for the sake of humanity than for human wellbeing.

In a long-term perspective, our way of creating indoor climate seems hopelessly primitive. Energy-efficient, complicated and with dubious quality. In addition, we are not accustomed to buildings in which the temperature is essentially constant year-round and at all hours of the day and night. Furthermore, we are not accustomed to building them. In times past, ventilation focused almost exclusively on getting rid of indoor air vitiated by human activity. But air quality can also be compromised by materials or by ventilation itself. The fatal components are often very marginal compared to the total volume. Glue, paint, plaster and plastic can give great cause for discomfort, even in there original state; but unlike wood, stone and metal, there is no telling what can happen when they are exposed to heat and moisture. Good indoor air often begins with sound building technology.

In the early 1990s, "sick houses" and the reasons for their ailments became a major topic of discussion. At this time, Wingårdhs were commissioned to design a secondary school in Ale, north of Gothenburg. There, we attempted to maximize use of the natural air dynamics in order to make the indoor environment as good as possible. The air flows in through long culverts under the building, so large particulate matter falls to the floor and can be easily vacuumed up each week. From the culvert, the air rises through vertical shafts that open under each window. Therefore, the windows are staggered on the façade, so that the shafts are always perfectly straight and therefore easy to clean. In the classroom, the air is heated by lamps and thirty warm pupils before flowing out through the sound trap above the door in one opposite corner of the room, and then continues up into lanterns of the atrium. There, a window can always be opened on the leeside, where the wind eventually draws the air away. Thus, the building is in principle ventilated without fans, but by making dual use of the fans that were installed for the chemistry lab fume hoods, the entire building can be kept under constant negative pressure. The principle is, above all, silent; however, to eliminate pollen and other light particulate matter, the air must be pushed through a filter or over a heat exchanger when it is coldest. When the

Municipality of Ale subsequently compared figures, it was noted that the school consumes considerably less energy than its other schools.

Expectations with respect to a completely stable indoor climate are still characterized by novelty. Not long ago, this was a luxury enjoyed by few. In addition, an indoor climate offers sensual qualities that can be allowed to vary: to be able to sleep in a cool room, or to be able to feel the warmth of a fire. Actually, only long-term sitting requires an even temperature and airflow. There is good reason to believe that technological development can open the way for variations in indoor climate over time and space. This would be both energy-efficient and sensual.

Saving energy often means accepting nature. Scandinavians live in a part of the planet that is favourable in many ways. It is seldom necessary to cool the air. The student union building at Chalmers University is one of the buildings that Wingårdhs has designed in which mechanical ventilation and natural airflow work hand-in-hand. If one can accept that it will be a little warmer in the building during the few days of the year when the temperature in Gothenburg exceeds 23 degrees Celsius, then the savings, in terms of both building and usage, are considerable. Ventilation solutions that take advantage of architecture are most easily realized in structures in which the high, public spaces can draw the air out of low ceilinged rooms. This is how both Ale and Chalmers work, as do Universeum and the tall new office building at Astra Zeneca in Mölndal. The air moves diagonally through the smaller rooms and out into the atriums where it naturally finds its way towards the roof and out into the open. The large room is not merely an architectural expression; it contributes to good air quality and silent spaces at low cost.

The history of air has largely concerned the solution of problems caused by the buildings themselves. Even though the choice of natural or mechanical ventilation influences the architecture, technology is still expected to fulfil the task, unnoticed, of supplying rooms with reasonably good air. We know that this in not always the case, but what is more – the air can be transformed into a real, sensual quality – part of what we call atmosphere. Just as the air by the seaside, in pine forests or in high mountain areas has its own particular qualities, there is indoor air that can be inhaled with pleasure. Greenhouses, cool stone churches and log houses have an atmosphere that is directly related to our experience of air. Scent is significant. Coffee roasteries, spice warehouses and root cellars can make nostrils flare inquisitively or noses turn up in repulsion. But even if attempts are made to perfume indoor air, much more can be done with the room's material, volume and structure – that which creates atmosphere. Air should always be light, while atmosphere can have any density. Architecture, wrote the Austrian architect Adolf Loos in 1925, is all about emotions. The architect's task is to make these emotions precise.

REFERENCE

Building: 3000 years of Design Engineering and Construction, Phaidon 2007.

10. THERMAL CLIMATE

Associate Professor **LARS E. EKBERG** Ph.D.
CIT Energy Management AB, Gothenburg

Indoor temperatures in modern buildings are often regulated within very close limits. In fact, a number of the guiding principles in this field are based on the insight that our perception of thermal climate becomes more positive, the more constant the temperature is maintained. The main challenge now, however, is how to deal with personal thermal comfort preferences in an occupied room, when everyone is dressed differently and has their own individual pattern of movement.

A number of different standards are available that provide guidelines for acceptable thermal indoor climate. No matter which standard we choose to follow, if we even make a choice, we are forced to realize that when a number of people are subject to a particular climate some of them will always prefer it to be warmer while others will prefer it to be cooler. It's a question of creating a climate that 90% can be content with or, conversely, only 10% will be dissatisfied with.

In order to find the best thermal climate, there are two questions that have to be answered:

1) What type of climate is required so that we feel neither too cold nor too hot?
2) How do we avoid discomfort caused by draughts and thermal radiation?

It is quite possible to experience local discomfort, for instance, due to a draught, while at the same time regarding the temperature, on the whole, as being acceptable. Acceptable, in this sense, means our body's heat balance being at a suitable level, i.e. we are not inclined to sweat to get rid of surplus heat or to get goose pimples to reduce heat losses from the body.

The factors that affect a person's heat balance and, consequently, their perception of the thermal climate are:

- Their clothing
- Their level of activity
- The air temperature
- The temperature of surrounding surfaces
- The velocity of the air
- The humidity of the air

Clothing, level of activity and temperature of the air and surrounding surfaces are important factors, while the humidity of the air, in most cases, is less important for a person's heat balance. Factors that can cause local discomfort include cold floors, chilled beams and cold down-draughts near windows. Rapid air movements, at low air temperatures, are also perceived as draughts.

If there are any surfaces that are very cold, or very hot, then the proportion of thermal radiation can be significant. In such instances, it is not sufficient to measure the temperature of the air alone, which is only a measure of the amount of heat transferred by convection. A unit that combines the effects of convection and radiation is called the *operative temperature*.

OPERATIVE TEMPERATURE

If surfaces in a room have approximately the same temperature as the air, it will suffice to determine the room temperature by measuring the temperature of the air itself. However, in many instances, for example in buildings with large glass facades, the heat balance of an occupant will be strongly influenced by the thermal radiation from or to surrounding surfaces. It will then be necessary to determine the thermal climate by also taking into account the temperatures of these surfaces. These can, of course, be measured and their effects on a person's heat balance can then be calculated. This is, however, a rather time-consuming process. Instead, a special type of sensor can be used to measure the operative temperature, which is a weighted average temperature of the air and the surrounding surfaces, or, in other words, a unit of temperature that takes into account thermal transfer via both convection and radiation.

METHOD FOR DETERMINING THE THERMAL CLIMATE

In many situations, determination of the thermal climate is based on Professor Fanger's comfort equation developed in the 1970s [Fanger, 1970]. Fanger's theories are fundamental to the international standard that is still applicable in this area, ISO 7730. This standard has also been adopted as a European standard and, in many other countries, as a national standard. The standard specifies a method based on the so-called PMV index, determined by questionnaire replies or by carrying out calculations that take into account people's clothing and activities as well as the physical environment. PMV is an abbreviation of Predicted Mean Vote and is simply a measure of the way a large group of test participants would be expected to assess a particular thermal climate on a seven-point scale from –3 to +3. The limit values on this scale correspond to what people would regard as unacceptably cold or unacceptably hot conditions. The zero value means that they would not like it to be colder or hotter.

In practice, a PMV index of zero means that some people will think that it is a little too cold and some a little too hot. However, most of them are, or are expected to be, satisfied and the average assessment is that the climate is acceptable. The temperature of this particular climate is called the *optimal operative temperature*. A PMV index that is determined by calculation is, of course, only valid in the specific conditions assumed regarding clothing and activities. The equation for the PMV index as a function of clothing, activity, temperature, air speeds etc is quite complicated and requires a time-consuming calculation process. The equation is not given here, but can be found in the ISO 7730 standard.

PERCEPTION OF THERMAL CLIMATE

The operative temperature is acceptable if the PMV index is close to zero. The criterion that the PMV index should lie between −0.5 and +0.5 is often used. According to Professor Fanger, results within these limits correspond to a 90% acceptance rate by the people subject to the climate in question. This can also be expressed as a dissatisfaction rate of 10%. According to the standard, this is denoted by the so-called PPD index, Predicted Percentage Dissatisfied, which in this example would have the value 10%.

The relationship between the PPD index and the PMV index is shown in Figure 1.

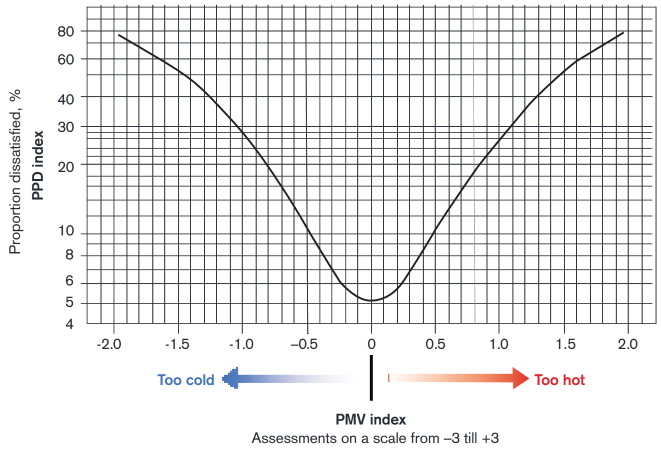

FIGURE 1. Relationship between the PPD index and PMV index according to ISO 7730.

MEASURING LEVELS OF ACTIVITY AND THERMAL INSULATION OF CLOTHING

Slapping your arms against your sides will help if you are cold, as will putting on an extra jumper. How much these alternatives will help is described in two international standards, ISO 8996 and ISO 9920. The level of a person's activity can be measured in SI units and is given in watts, W, or, as in Table 1, in watts per square metre body area. In order to calculate the PMV index using Fanger's comfort equation, the heat developed by a body is given in mets, Met, as in metabolism. Examples of values for different levels of activity are given in Table 1.

TABLE 1. Examples of body heat development and corresponding Met values for different activities. Current standards assume a typical body area to be 1.8 m^2.

Activity	Metabolism	
	W/m^2	Met value
At rest, lying down	46	0.8
Relaxed, sitting down	58	1.0
Office work, sitting down	70	1.2
Light activity, standing up	93	1.6
Household work or similar	116	2.0
Physical work, low intensity	220	3.7
Physical work, medium intensity	350	6.0

TABLE 2. Examples of thermal resistance of clothing (1 Clo = 0.155 °C·m/W)

Clothing	Clo value
Naked	0
Tropical clothes	0.3
Light summer clothes	0.5
Light working clothes	0.7
Indoor clothing, in winter	1.0
Suit, waistcoat, shirt and light underwear	1.7

The thermal resistance of clothing can also be measured in SI units and is given in °C · m/W. In order to carry out thermal climate calculations using the PMV index, the unit Clo, as in clothing, is used. Table 2 shows thermal resistances for different types of clothing.

Typical Clo values for individual pieces of clothing are given in ISO 9920 and it is also possible to calculate their accumulative effect. For example, the difference between a shirt with long sleeves and one with short sleeves is just less than 0.1 Clo. When carrying out office work, this could mean a difference in desired temperature of about 0.5 °C. Taking off or putting on a jumper can change the desired temperature by between 1 and 2 °C. This means that there are significant opportunities for us to influence our perception of temperature by changing our clothing. And we can also note that the assumption regarding clothing can play a significant role when it comes to requirements specified for a building, if the requirements are based on PMV/PPD concepts, i.e. Professor Fanger's comfort equation. Similar reasoning can be applied to the level of activity: If clothes corresponding to 0.7 Clo are worn, an increase in activity level of 0.1 Met will have the same effect as an increase in operative temperature of 0.8 °C.

People have different metabolic rates and, to a certain extent, dress differently and we can conclude that it is difficult to find a general temperature level to satisfy everyone. On the other hand, if there is a practical opportunity to regulate room temperatures according to personal preferences, this is usually highly appreciated.

CHOICE OF SUITABLE OPERATIVE TEMPERATURE

As mentioned above, a normal criterion for good thermal climate is that the PMV index lies in the interval −0.5 to +0.5, which, in turn, coincides with a PPD index of 10%. To illustrate the corresponding operative temperature, depending on dress and level of activity, a diagram as shown in Figure 2 can be drawn. If clothes corresponding to 0.5 Clo (typical summerwear) are worn and the level of activity corresponds to 1.2 Met (typical sedentary office work), the optimal operative temperature will be about 24.5 °C. The diagram also shows that the temperature can vary by about ±1.5 °C from this value without the PPD index exceeding 10%. Consequently, a temperature interval between 23 and 26 °C is often stipulated as the summertime operative temperature in, for example, offices. Working at a higher level of activity means that the temperature ought to be lowered and vice versa.

In winter, it is often assumed that clothes corresponding to 1.0 Clo are worn. If the level of activity remains at 1.2 Met we can see from the diagram that the room temperature in an office should be 22 °C ±2 °C.

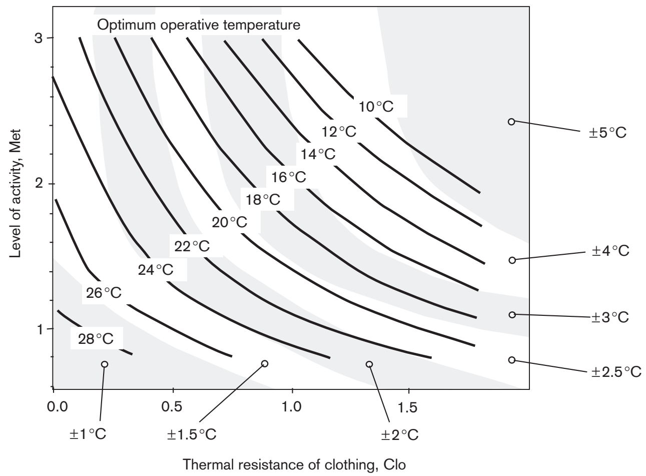

FIGURE 2. The effect of clothing and level of activity on the optimal operative temperature, according to ISO 7730. The diagram also shows the maximum deviations that can be accepted if the PPD index is to be kept below 10%. The diagram is valid for a maximum air velocity of 0.1 m/s.

The diagram in Figure 2 is applicable, if it is assumed that the velocity of the air is less than 0.1 m/s. If the velocity of the air relative to an occupant is closer to 0.2 m/s, then the optimal operative temperature will increase by about 1 °C with other factors remaining unchanged.

Sometimes a more restrictive criterion is specified, for example, that the PPD index must not exceed 6%. The corresponding operative temperature can be read from a diagram similar to that in Figure 2, plotted for a PPD index of 6%.

If clothing and level of activity then correspond to 1.0 Clo and 1.2 Met respectively, the PPD index of 6% will indicate an operative temperature in the interval 21 to 23°C. This more restrictive criterion means that the temperature must be kept with ±1.0°C instead of ±2.0°C. It does not necessarily follow, however, that this more precisely maintained temperature will lead to any real improvement of thermal comfort. If people exert themselves more than or less than 1.2 Met, a different temperature interval will be desired. And, correspondingly, people whose clothes deviate from the assumed 1.0 Clo will also want a different interval.

Another way of providing a higher degree of satisfaction is to aim for a PPD index of 10% and, at the same time, offer the tenants the opportunity to make individual climate adjustments. This is suggested in the guidelines for specifying indoor climates drawn up by the Swedish Society of Heating and Air Conditioning Engineers [VVS Tekniska Föreningen, 2006]. Finally, it would be a great advantage if occupants of a building realized that they could change their perception of the indoor climate by wearing appropriate clothes.

LOCAL THERMAL DISTURBANCES

Thermal radiation towards a cold surface, or strong air movements in combination with low temperatures, can cause local cooling of parts of your body. Even if your body's heat balance is not affected to any great extent, and you therefore do not actually want the room temperature to be warmer, this radiation can lead to discomfort in the form of draughts. A corresponding problem can arise if the surface of a floor is too cold or if a large temperature difference is experienced between floor and head level. In this latter case, it is often said that the vertical temperature gradient is too large. Some examples of criteria, for avoiding local thermal disturbances, are given in Table 3.

STANDARDS

As mentioned above, Professor Fanger's theories formulated in the 1970s are those on which the current international standard, ISO 7730, are based. The standard is based on the PMV/PPD concept, generally outlined above. The concept has received a wide degree of acceptance and has been spread extensively since the standard was adopted as a European standard and in many other countries as a national standard. It was updated in 2006 and one of the new inclusions is the choice of three quality levels, A, B and C. Level A corresponds to a PPD index of 6%, level B to an index of 10% and level C to an index of 15%. In earlier editions of the standard, it was recommended to keep the PPD index below 10%. The standard also presents guidelines for the reduction of risks of thermal disturbances.

TABLE 3. Examples of criteria (target values) in order to avoid local thermal climate disturbances.

Factor	Target value, °C	Notes
Vertical temperature gradient, measured between 0.1 m and 1.1 m above floor level	<3	The measured value should reflect the temperature difference between the ankles and neck of someone sitting down
Radiation temperature asymmetry – from a warm ceiling – towards a cold wall – towards a cold ceiling – from a warm wall	 <5 <10 <14 <23	The figures show that we are more sensitive to radiation from a warm ceiling than from a warm wall
Floor temperature	19 to 26	The level depends on whether the room is meant for children or not
Air velocity	<0.10 m/s at 20°C <0.15 m/s at 26°C	The risk of experiencing draughts increases as the velocity of the air increases and the temperature decreases

In 2004, the American standard in this field [ASHRAE, 2004] was updated and is now also based on the PMV/PPD index concept. Since the 1980s, this standard has been based on at least 80% of the tenants being satisfied with the thermal climate, i.e. also accepting 20% dissatisfaction. These figures, however, are the result of a summation of the effect of the body's heat balance in general and the occurrence of local thermal disturbances, such as draughts. As in ISO 7730, the ASHRAE Standard 55 states that the PPD index should have a maximum value of 10%. The remaining 10% of the 'accepted' dissatisfaction is presumed to be caused by local thermal disturbances.

WARMEST SUMMER DAYS

Providing a technical solution, to avoid unacceptably low room temperatures in winter, is quite simple and is a question of designing the heating system correctly. The room temperature should not be allowed to fall below 20 °C, except when it is extremely cold outdoors. In summer it is often necessary to accept temperatures above those regarded as comfortable when the PMV/PPD index concept is applied.

When drawing up a requirements specification for thermal climate in a building project it must be clearly stated, along with the desired temperature interval and target values for temperature gradients etc, to what extent higher temperatures can be accepted on hot summer days. This can be seen as a compromise between good thermal climate and the cost of the technical solutions required to satisfy the tenants' demands. At the same time, the room temperatures should be allowed to rise slightly when it is hot outdoors. If they are not allowed to do so, the contrast between the outdoor and indoor climates might be perceived as being too uncomfortable. In buildings with comfort cooling, for example, a solution might entail keeping room temperatures about 3 °C lower than the outdoor temperature when it rises above the summer design temperature. In working spaces such as offices, it would be reasonable to allow temperatures above the upper limit according to the PMV/PPD index concept for, say, 80 working hours per year. It should be compulsory for the HVAC design engineer to explain to the client how theses different requirement levels affect the cost and complexity of the installations.

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11. BUILDING ACOUSTICS

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This chapter discusses the properties of buildings that affect the indoor acoustics. How sound is created and attenuated in HVAC installations is discussed in Chapter 26/Sound and sound attenuation. This chapter looks at the theory behind the creation and propagation of sound and vibrations and how sound can be dampened, and explains the terminology, units and quantities that are common to both chapters.

SILENCE IS IN SHORT SUPPLY

Silence is becoming an increasingly rare commodity. When an HVAC system is designed and installed to provide a better thermal climate this must not be done at the expense of a quiet environment. Plant that causes noise inside and outside buildings is justifiably criticised. Condenser fans and heat pumps are typical culprits of the latter type.

These effects are completely unnecessary and must be prevented. Equal attention must be paid to creating systems that are quiet as to making systems that are functional and energy-efficient.

Levels of outdoor noise are also increasing – there is more traffic and traffic noise, more infill development in towns and we find ourselves increasingly closer to external sources of noise.

One of the primary functions of a building is to shield against and dampen external noise. The number and intensity of sources of noise are, unfortunately, also multiplying indoors – we use an increasingly large number of building services to create a good indoor climate, but the price is often less silence.

Disturbing noise has a number of negative consequences – in homes it can affect opportunities for rest, recovery and sleep. Noise can also make it more difficult to carry on a conversation and we might even have to raise our voices; it can cause stress, reduce our sense of well-being and increase risks of heart and vascular disorders. In extreme cases – when all efforts to combat noise have failed – it could lead to hearing damage.

IT ALL STARTS AT THE PLANNING STAGE

In residential buildings, bedrooms are located on the quiet sides of the buildings to avoid, as much as possible, the higher levels of noise affecting the most exposed sides. In blocks of flats this can be sabotaged at a later point in time if noisy pieces of equipment, such as extraction fans, air-cooled condensers and heat pumps, are installed on the quiet side, for example, when ground floor space is converted into business premises. In all types of buildings – dwellings, office blocks, hospitals etc – efforts must be made to locate noisy installations and equipment as far away as possible from occupied rooms.

The prerequisites for having quiet building services installations are created during the planning and design stages of a building. Discovering noise problems at a later stage in the building process is both unfortunate and unprofessional. It is also considerably more difficult and expensive to be forced to carry out remedial measures that would have been much simpler and cheaper had they been carried out from the beginning.

Noise attenuation measures can require a lot of space, space that at a later stage might not be readily available. Fan and equipment rooms should therefore not be located above or close to sound-sensitive spaces, for example, bedrooms, meeting rooms and hotel rooms. Doors, walls and floors with high sound reduction properties should be used to prevent noise from disturbing neighbouring rooms. Airborne sound can easily pass through small gaps and cracks. Pipes, cables and ducting passing through sound-insulated walls must be fitted with adequate seals. All these problems are easier to solve if noisy plant and equipment are located as far as possible from sound-sensitive rooms.

WHAT IS NOISE?

A popular definition of noise is “unwanted sound”. If a sound is to be classed as noise, then it will depend on a subjective opinion, i.e. whether hearing it creates pleasurable sensations or not. Parents and children might have different opinions when it comes to classifying different types of music. On the other hand, they will most probably agree that noise from building services, for example, is annoying.

Physically, noise or, more strictly, sound is defined as the propagation of pressure in an elastic medium, usually air, created by a sound source. If the pressure change is to be regarded as sound, then there must be, besides the source and the medium, a listener who can sense the sound.

Sound is often a mixture of a number of different and more or less irregular vibrations. If the sound comprises a complete mix of all tones that are equally strong, then this is called noise.

PROPAGATION OF SOUND IN GASEOUS, LIQUID AND SOLID MEDIA

Sound is the result of mechanical vibrations in an elastic medium. If the medium is made to vibrate, the pressure variations will spread from the source by transferring energy from one molecule of the medium to the next.

This phenomenon is normally illustrated by the pattern created when a stone is dropped onto a calm water surface and concentric waves spread across the surface, at a certain speed, from the point of impact. Note that it is not the particles comprising the medium that are transported away from the source by the waves but energy from the sound source. The particles only vibrate around their centres of equilibrium.

The distance that a wave travels during a complete wave cycle is its *wavelength* λ and this, in turn, is determined by its *propagation velocity c* and *frequency f*. The equations for sound in air are:

$$\lambda = \frac{c}{f} \text{ and } c = f \cdot \lambda \tag{1}$$

where:
λ is the wavelength of a sound wave in m
c is the speed of sound in the medium, i.e. its propagation velocity, in m/s
f is its frequency in Hz or s^{-1}

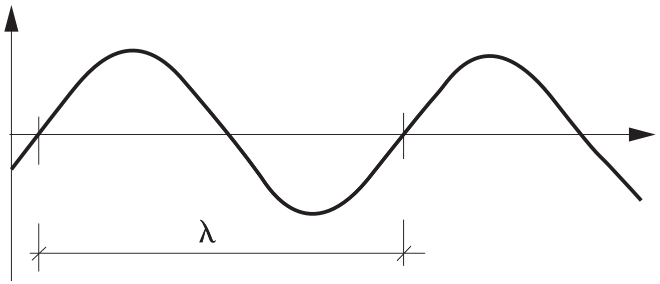

FIGURE 1. The wavelength λ of a pure tone.

The *propagation velocity c* of sound in a given medium varies with the elasticity and density of the medium. The following relationship, derived by Laplace, describes how the velocity of sound varies in an ideal gas:

$$c = \sqrt{\frac{p \cdot \kappa}{\rho}} \tag{2}$$

where:
p is the static pressure of the gas in Pa
κ is the ratio of the specific heat of the gas at constant pressure to its specific heat at constant volume, i.e. c_p/c_v
ρ is the static density of the gas in kg/m^3

For diatomic gases, of which air is mostly comprised, the expression can be simplified to:

$$c = 20 \cdot \sqrt{T} \tag{3}$$

where:
T is the absolute temperature of the air in K

This means that at 0 °C (273 K), c ≈ 331 m/s and at normal room temperature, 20 °C (293 K), c ≈ 340 m/s.

The same basic relationship applies to sound propagation in solid and liquid media.

In liquids:

$$c = \sqrt{\frac{K}{\rho}} \tag{4}$$

where:
K is the coefficient of compressibility in Pa
ρ is the density of the liquid in kg/m^3

In solids:

$$c = \sqrt{\frac{E(1-\nu)}{\rho(1-\nu-2\nu^2)}} \tag{5}$$

where:
E is Young's modulus, the modulus of elasticity, in Pa
ρ is the density of the medium in kg/m^3
ν is Poisson's ratio

ν is often 0.2 which means that in Equation (5):

$$\sqrt{\frac{1-\nu}{1-\nu-2\nu^2}} = 1.05$$

A good approximation is thus:

$$c = \sqrt{\frac{E}{\rho}} \qquad (6)$$

For liquids (with K in the region of $1 \cdot 10^9$ Pa and ρ in the region of $1 \cdot 10^3$ kg/m^3) the velocity of sound will be approximately 1000 m/s:

TABLE 1. The speed of sound in different liquids.

Liquid	Temperature, °C	Speed of sound, m/s
Water	0	1 407
Water	10	1 449
Water	20	1 484
Water	30	1 510
Salt water	15	1 470
Alcohol	20	1 213

The speed of sound, derived from Equation (6), in a number of building materials is as follows.

TABLE 2. The speed of sound in a number of solid materials used in building construction.

Material	E MPa	Density g/m³	Speed of sound m/s
Concrete	35 000	2200	4000
Brick	13 000	1700	2800
Glass	70 000	260	5200
Steel	210 000	7800	5100
Aluminium	68 000	2700	5000
Lead	16 000	11 300	1200
Rubber	3.6	1450	50
Cork	50	200	500
Wood (pine) along the grain	55	470	3400
Wood (pine) across the grain	30	470	2500

SOUND INTENSITY

Sound intensity is measured in *sound power per unit area* and is proportional to the square of the locally dominant sound pressure. Neither sound power nor sound intensity can be measured directly. They can only be determined indirectly.

The basic equation for sound intensity can be written as:

$$I = \frac{P}{S} = \frac{p^2}{\rho \cdot c} \qquad (7)$$

where:
I is the sound intensity in W/m^2
P is the sound power in W
S is the area over which the sound is distributed in m^2
p is the sound pressure in Pa
ρ is the density of the medium in kg/m^3
c is the speed of sound m/s

If a point source of sound, of power P, emits sound uniformly in all directions (spherically), the intensity of sound I at a distance r from its source will be:

$$I = \frac{P}{4\pi \cdot r^2} \qquad (8)$$

Spherical sound propagation assumes that the spherical sound source is located at a large distance from objects that could otherwise hinder its

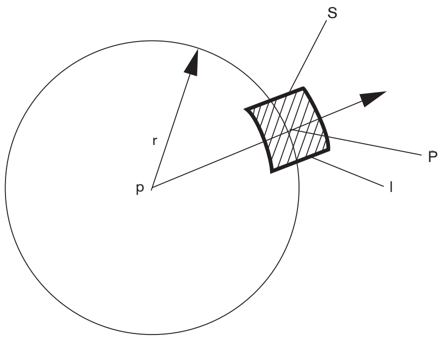

FIGURE 2. Spherical sound propagation from a point source.

propagation. In practical circumstances sound sources are nearly always more or less directionally dependent and sound propagation will vary depending on direction.

The weakest sound pressure *p*, known as the threshold of hearing, that we can detect at a frequency of 1000 Hz is 20 μPa. The sound power *P* that is required to achieve this pressure, in spherical propagation, at a distance that corresponds to a sphere with a surface area of 1 m^2, i.e. at a distance of 0.28 m, is 1 pW (1 picowatt) or $1 \cdot 10^{-12}$ W. Both the sound pressure and sound power are extremely small compared to what we are normally used to. At the other end of the scale, we can hear sound at a sound pressure of 20 Pa, i.e. at a sound pressure that is one million times stronger, at a level known as the threshold of pain. These values, 20 μPa for sound pressure and 1 pW for sound power are used as reference values when expressing sound values in decibels, see below.

AUDIBLE SOUNDS AND FREQUENCIES

Young people and those who are not hard of hearing can hear sounds in the frequency range of approximately 20 Hz to 20 000 Hz. The upper frequency limit falls as people get older – and this can quickly deteriorate if the person in question is subject to dangerously high noise levels. Hearing damage often means having a greatly impaired upper frequency limit – not being able to hear tones above 1000 Hz is not unusual. Sound at lower frequencies than 20 Hz is called *infrasound* and sound above 20 000 Hz is called *ultrasound*, see Figure 3.

We respond logarithmically and not linearly to changes in frequency of a tone. Frequencies are therefore expressed using a logarithmic scale that is divided up into octaves in which the ratio of the upper frequency limit to the lower frequency limit is 2:1 (in a similar way to a piano keyboard). The values of the octave bands are defined in international standards and are denoted by their geometric centre frequencies: 31.5, 63, 125, 250, 500, 1000, 2000, 4000, 8000 and 16 000 Hz.

The relationship between the geometric centre frequency and the limit frequencies is given by:

$$f_{centre} = \sqrt{f_{lower} \cdot f_{upper}} = f_{lower} \cdot \sqrt{2} = \frac{f_{upper}}{\sqrt{2}} \qquad (9)$$

where:

f_{lower} is the lower frequency limit of the octave band in Hz

f_{upper} is the upper frequency limit of the octave band, or $2 \cdot f_{lower}$, in Hz

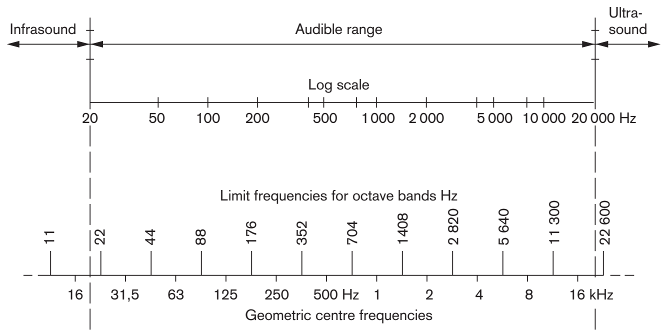

FIGURE 3. Audible frequencies and geometric centre frequencies of different octave bands.

Sometimes, for example in building acoustics, the frequency bands are divided into one-third octave bands where $f_{upper}/f_{lower} = \sqrt[3]{2}/1$. The one-third octave bands form the same series that is used for diameters of spiral tubes for ventilation ducting: **63**, 80, 100, **125**, 160, 200, **250**, 315, 400, **500**, 630, 800, **1000**, 1250, 1600 etc. Every third one-third octave band will have the same middle frequency as the full octave bands, shown in bold type.

WHAT IS A DECIBEL?

Sound pressure within the audible range can vary within very wide limits – at a frequency of 1000 Hz it varies from its weakest, i.e. at the threshold of hearing at about 20 μPa, to its strongest, i.e. at the threshold of pain at about 20 Pa, which corresponds to a ratio of about $1{:}1 \cdot 10^6$. In a similar way the sound power of a normally audible sound can vary from $1 \cdot 10^{-12}$ W to $1 \cdot 10^5$ W. Just like frequencies, we perceive changes in sound intensity logarithmically.

This means that a conventional linear scale would be unsuitable and, as in electronics, a scale with the unit decibel dB has been introduced. A decibel is generally defined as: $10 \cdot \log_{10}\left(\frac{X}{X_0}\right)$ where *X* is the measured value and X_0 is a reference level expressed in the same units. In the following expressions and equations, for the sake of simplicity, log to base 10, i.e. $\log_{10}(x)$ is written as log(x). In this way the scale is conveniently compressed. The reference level X_0 above which a certain unit is measured could be chosen arbitrarily but, in order to be able to compare values, it has been decided to standardize the reference levels for the units used. In acoustics, the following levels (ISO) are used:

Sound power	$1 \cdot 10^{-12}$ W = 1 pW (p, pico, is a prefix denoting the factor 10^{-12})
Sound intensity	$1 \cdot 10^{-12}$ W/m^2 = 1 pW/m^2
Sound pressure	$20 \cdot 10^{-6}$ Pa = 20 µPa (µ, micro, is a prefix denoting the factor 10^{-6})

This means that instead of sound power the term *sound power level* L_w is used and this is the logarithmic ratio of the measured sound power to the reference power:

$$L_w = 10 \cdot \log \frac{W}{W_0} = 10 \cdot \log \frac{W}{10^{-12}} \text{ dB(relative to 1 pW)} \qquad (10)$$

where W is the sound power in W.

In a similar way the *sound intensity level* L_I is expressed as:

$$L_I = 10 \cdot \log \frac{I}{I_0} = 10 \cdot \log \frac{I}{10^{-12}} \text{ dB(relative to 1 pW/m}^2\text{)} \qquad (11)$$

where I is the measured sound intensity in W/m^2.

However, for sound pressure levels the ratio between the sound pressures has to be squared to correspond to the power relationship. The expression for *sound pressure level* L_p will therefore be:

$$L_p = 10 \cdot \log \left(\frac{p}{p_0}\right)^2 = 20 \cdot \log \left(\frac{p}{20 \cdot 10^{-6}}\right) \text{ dB(relative to 20 µPa)} \qquad (12)$$

where p is the measured sound pressure in Pa.

To differentiate between different types of decibels, dB, the reference level above which the unit is measured is given in brackets afterwards. When sound power levels are mentioned verbally it is always assumed that the dB level is measured above the reference level 1 pW.

The sound pressure level at the threshold of hearing, 20 µPa, will then be:

$$L_p = 20 \cdot \log \frac{p_0}{p_0} = 0 \text{ dB(relative to 20 µPa)}$$

And, for the threshold of pain, 20 Pa, it will be:

$$L_p = 20 \cdot \log \frac{20}{20 \cdot 10^{-6}} = 120 \text{ dB(relative to 20 µPa)}$$

The internationally recognized reference values for sound pressure level, 20 µPa, and for sound power level, 1 pW, are explained in their definition:

When there is spherical propagation from a point sound source with a sound power of 1 pW the measured pressure at a radial distance corresponding to a sphere with a surface area of 1 m^2 will be 20 µPa.

At this distance and under these conditions the sound pressure level in dB(relative to 20 µPa) and the sound power level in dB(relative to 1 pW) will have the same numerical value. This can be shown by using Equation (13), which is the basic equation for calculating the sound pressure level at different radii r from a sound source with a sound power level L_w. The equation is only applicable to spherical sound propagation:

$$L_p = L_w - 10 \cdot \log (4\pi \cdot r^2) \qquad (13)$$

If the spherical area is 1 m^2 (corresponding to a sphere with a radius of 0.28 m) the following relationship can be derived:

$$L_p = L_w - 10 \cdot \log 1 = L_w$$

ADDING SOUND FROM DIFFERENT SOURCES

In the previous section we could see that we perceive changes in sound levels logarithmically and not linearly.

When sound levels from different sources are added together this must also be done logarithmically. If a number of sources emit sound simultaneously, the increase in sound power level, compared to a single sound source, is given by:

$$L_{tot} = L_1 + \Delta L = L_1 + 10 \cdot \log n \qquad (14)$$

where:
L_{tot} is the sum of the sound levels in dB
L_1 is the sound power level of a single sound source in dB
ΔL is the increase in sound level in dB
n is the number of similar sound sources

TABLE 3. Logarithmic addition of similar sound sources.

Number of sound sources n	2	3	4	5	6	8	10	20
ΔL in dB	3	5	6	7	8	9	10	13

SOUND PROPAGATION IN A FREE FIELD

At other distances r and different locations of the sound source it is possible to calculate the sound pressure levels as shown below. Equation (13) can first be simplified as follows and can also be illustrated graphically as in Figure 4:

$$L_p - L_w = -10 \cdot \log(4\pi \cdot r^2)$$
$$= -10 \cdot \log(4\pi) - 20 \cdot \log r = -11 - 20 \cdot \log r \qquad (15)$$

At a distance of 1 m, $\Delta L = L_p - L_w$ will be – 11 dB, i.e. the sound pressure level has a numerical value that is 11 dB units lower than the sound power level.

From Equation (15) it can be seen, for example, that the sound pressure level will fall by 6 dB when the distance is doubled:

$20 \cdot \log 2 = 20 \cdot 0.3 = 6$.

The reduction in sound pressure level in spherical propagation in a free medium will then be as shown in Figure 4. An example of a sound

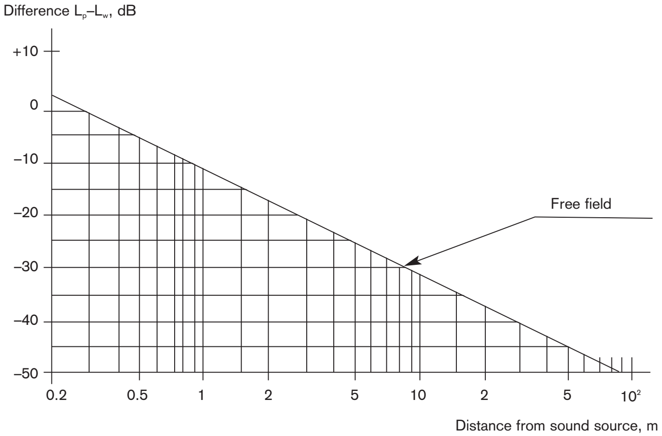

FIGURE 4. Sound propagation in a free field, Equation (15) shown diagrammatically. The difference between sound power level in dB(relative to 1 pW) and sound pressure level in dB(relative to 20 μPa) is plotted against the distance from the sound source. At a distance of 0.28 m the difference is 0 dB.

source with spherical propagation is the exhaust noise emitted from a high chimney.

SOUND PROPAGATION IN CLOSED ROOMS

When sound is propagated semi-spherically the sound power is distributed across half the area and the intensity of the sound is therefore doubled. An example of a sound source with semi-spherical propagation is a supply air terminal device located in the ceiling of a room. Here, at a distance of 1 m, $L_p - L_w = -8$ dB.

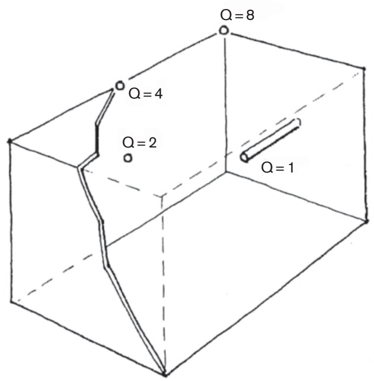

FIGURE 5. Directivity factor Q for sound propagation from sources at different locations indoors and outdoors. Q = 1 for a spherical source and Q = 8 for a 1/8 spherical source.

In a similar way, by gradually halving the area over which the sound is distributed, it is possible to obtain values for 1/4 spherical propagation, for example, when a supply air terminal device is placed on a wall next to the ceiling: $\Delta L = -5$ dB, and for 1/8 spherical propagation, for example, when a device is placed in a corner next to the ceiling: $\Delta L = -2$ dB at a distance of 1 m. The sound pressure level will therefore vary depending on the location of the source and a directivity factor, normally expressed as Q, is used. Every time Q is doubled close to a sound source this will result in a sound pressure level increase of 3 dB:

$$\Delta L = 10 \cdot \log Q \qquad (16)$$

Q can be included in Equation (13) above:

$$L_p - L_w = -10 \cdot \log \frac{4\pi \cdot r^2}{Q} = 10 \cdot \log \frac{Q}{4\pi \cdot r^2} \quad (17)$$

Standard values of Q are given in Table 4.

TABLE 4. Directivity factor Q for different locations of a sound source.

Propagation, spherical fraction	1/1	1/2	1/4	1/8
Directivity factor, Q	1	2	4	8
ΔL at r = 1 m in dB	–11	–8	–5	–2

When sound is propagated in a room it will meet a number of obstacles, such as the boundaries of the room, i.e. the walls, floor and ceiling. Depending on the properties of the surfaces, a large or small proportion of the sound energy will be absorbed by them – the particle vibrations are converted into frictional heat within the materials – while the rest of the energy will be reflected into the room to become mixed with the sound coming directly from the sound source.

The relationship between the absorbed sound intensity and the total incident sound intensity of a material is called the *sound absorption coefficient* α:

$$\alpha = \frac{I_i - I_r}{I_i} = \frac{I_a}{I_i} \quad (18)$$

where:
α is the sound absorption coefficient of the material
I_i is the intensity of the incident sound in W/m²
I_r is the intensity of the reflected sound in W/m²
$I_i - I_r = I_a$ the intensity of the absorbed sound in W/m²

Another expression that is used in indoor acoustics is the *equivalent sound absorption area of a room.* This is an expression of the partial products of the room's boundary areas and their respective absorption factors.

The absorption of a surface can be expressed as $\alpha \cdot S$, where α is the absorption coefficient of the material and S is its surface area in m².

The total absorption of a room can be found by adding together the surface absorptions, based on the respective areas and absorption coefficients:

$$A = \alpha_1 \cdot S_1 + \alpha_2 \cdot S_2 + \ldots + \alpha_n \cdot S_n = \sum_1^n \alpha_n \cdot S_n \quad (19)$$

where:
A is the total absorption of a room, also called the *equivalent sound absorption area of* the room, in m².
α_n is the absorption coefficient of an individual boundary surface.
S_n is the area of an individual boundary surface in m².

All the boundary surfaces in the room are converted into one equivalent area with an absorption coefficient of 1 (equivalent sound absorption area), which means that at a given frequency and energy intensity it will absorb sound energy as quickly as the actual surface elements in question.

The mean absorption coefficient for the boundary surfaces in a room can be expressed as:

$$\bar{\alpha} = \frac{\sum_1^n \alpha_n \cdot S_n}{\sum_1^n S_n} = \frac{A}{S} \quad (20)$$

where:
S = is the total boundary surface area in m²

Typical approximations for the mean absorption coefficient $\bar{\alpha}$ in different types of buildings are shown in Table 5.

TABLE 5. Mean absorption factors $\bar{\alpha}$ at a frequency of 500 Hz.

Type of room/building	**Mean absorption factor $\bar{\alpha}$**
Radio studio, music room	0.30–0.45
TV studio, department store, reading room	0.15–0.25
House, office, hotel room, conference room, theatre	0.10–0.15
Classroom, nursing home, small church	0.05–0.10
Factory, indoor swimming pool, large church	0.03–0.05

An alternative way of expressing the acoustic properties of a room is to specify its reverberation time, see below.

SOUND ABSORBERS

Three different types of sound absorbers can be used to reduce the sound level in a room:

- **Porous absorbers.** If a material is soft and porous, air molecules will penetrate the material and their kinetic energy will be converted into heat due to friction inside the material (in a similar way to a pressure drop in an air filter). Typical porous absorbers are mineral and fibreglass insulation boards, often installed in fan room ceilings, and acoustic boards, curtains and carpets used in occupied rooms.

- **Membrane absorbers,** which comprise massive boards placed at a distance from a wall and which are made to vibrate by the incident sound energy. This is then converted into heat energy, primarily in the edge mountings but also in the material itself. The board becomes a vibrating mass and the contained volume of air acts as a spring. Maximum absorption is achieved at the resonance frequency of the system which, in air at a normal state, is given by:

$$f_0 = \frac{60}{\sqrt{m \cdot d}} \qquad (21)$$

where:
m is the mass of the board in kg
d is its distance from the wall in m

Typical membrane absorbers in a room are windows, thin wall and ceiling boards, and raised floors.

- **Cavity absorbers,** also called *Helmholz resonators*, use a third principle for sound absorption. They can be described as bottles that are built into a building element with their necks opening into a room. They can be used in walls as well as ceilings. An incident sound wave enters a bottle via its neck and causes the air in the neck to oscillate. The air is compressed as it enters the bottle and is slowed down, and when it leaves the bottle it is held back as the air in the bottle is thinned out, creating an under-pressure.
  Sound reduction in absorbers like these is selective, i.e. it is only effective within a limited frequency range. This is determined by the diameter of the neck of the bottle, the length of the neck and the volume of air enclosed in the bottle. In more qualified circumstances cavity absorbers can be made adjustable to suit advanced requirements for different types of performances in concert halls or theatres. Perforated ceiling boards can be regarded as a simple form of cavity absorber.

Sound absorption coefficients α for a number of typical materials are shown in Table 6.

TABLE 6. Sound absorption coefficients α for typical materials used in buildings.

Material	Middle frequences of different octabe bands in Hz					
	125	**250**	**500**	**1 000**	**2 000**	**4 000**
Ceilings, walls and floors						
Concrete, unplastered	0.01	0.01	0.02	0.03	0.03	0.03
Marble, glazed tiles	0.01	0.01	0.01	0.01	0.02	0.02
10 mm soft carpet on concrete	0.09	0.08	0.21	0.26	0.27	0.37
Needle felt carpet on a hard floor	0.05	0.08	0.20	0.30	0.35	0.40
13 mm gypsum board on studs c/c 400 mm	0.29	0.10	0.05	0.04	0.07	0.09
Raised wooden floor above large air volume	0.40	0.30	0.20	0.17	0.15	0.10
Insulation etc						
Rock wool board 25 mm thick	0.09	0.23	0.53	0.72	0.75	0.77
Rock wool board 50 mm thick	0.20	0.53	0.74	0.78	0.75	0.77
Rock wool board 100 mm thick	0.68	0.84	0.82	0.78	0.75	0.77
16 mm wood board on 40 mm battens	0.18	0.12	0.10	0.09	0.08	0.07
Window glass	0.35	0.25	0.18	0.12	0.07	0.04
Heavy curtains	0.06	0.10	0.38	0.63	0.70	0.73
Light curtains 25% folded	0.04	0.23	0.41	0.57	0.53	0.40
Water surface in a swimming pool	0.01	0.01	0.01	0.015	0.02	0.02

REVERBERATION TIME

If the source of a sound in a room is suddenly switched off, the sound will not disappear immediately. The direct sound will stop but reflected sound will continue to reverberate in the room while it is reflected from its boundary surfaces. The time taken for the sound to die out in a room is called the reverberation time and depends on the size of the room (the greater the distance between the reflecting surfaces, the fewer the number of reflections per unit of time) and on the absorption coefficients of each of the surfaces: the higher the absorption factor, the more energy is converted into heat per reflection and the faster the remaining sound field in the room decreases.

The reverberation time *T* is the time, in seconds, it takes for the sound intensity to fall to a one-millionth ($1 \cdot 10^{-6}$) of its original value. This is equivalent to the echo effect that can be heard in a quiet room when a strong sound source is switched off. This reduction in sound intensity is equivalent to lowering the sound pressure level in the room by 60 dB: $\Delta L_p = 10 \cdot \log(10^{-6}) = -60$.

In normal, not heavily soundproofed rooms the reverberation time can be calculated using Sabine's reverberation equation:

$$T = 0.163\,\frac{V}{A} \qquad (22)$$

where:

V is the volume of the room in m^3

A is the equivalent sound absorption area of the room in m^2, from Equation (19)

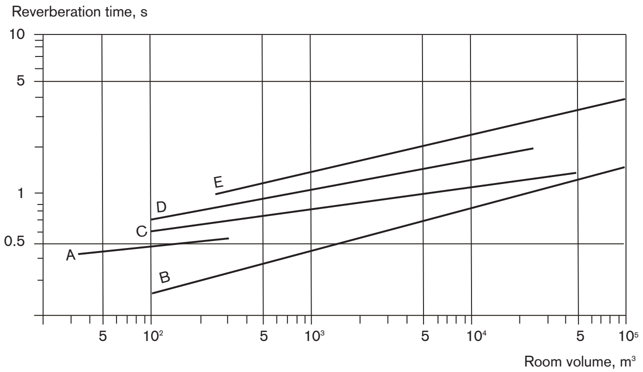

FIGURE 6. The reverberation time T in seconds varies with the size of the room and the materials used in the walls, floor and ceiling. The diagram shows the approximate values for different types of rooms. A – offices and habitable rooms, B – TV and film studios, C – classrooms, lecture theatres and cinemas, D – music studios, E – churches.

NEAR FIELDS AND REVERBERATION FIELDS

When a sound source emits a sound in a room a receiver/listener in the same room will be subject to two types of sound, *direct sound* and *reflected sound* from the boundary surfaces.

Direct sound decreases with increased distance from its source, see Equation (17) and Figure 4, while reflected sound will have the same value at all points in the room on condition that the absorption coefficients of the boundary surfaces are not too high.

Close to the sound source, the direct sound will dominate and the receiver/listener is said to be in the *near field*. It is here that the direction of the sound source can be determined, even if the subject is blindfolded. When the sound is equally strong in both ears the sound source will lie at a point along a line that is perpendicular to the line between the listener's ears. When the distance to the sound source is increased, the direct sound will eventually be drowned by the reflected sound, and the subject will be in the *reverberation* field in the room.

If the two sounds, i.e. the direct sound that is dependent on the distance to the source and the reverberation sound that is independent of the distance, are added together, it is possible to calculate the difference between the sound pressure level and sound power level at an arbitrary point in the room using Equation (23).

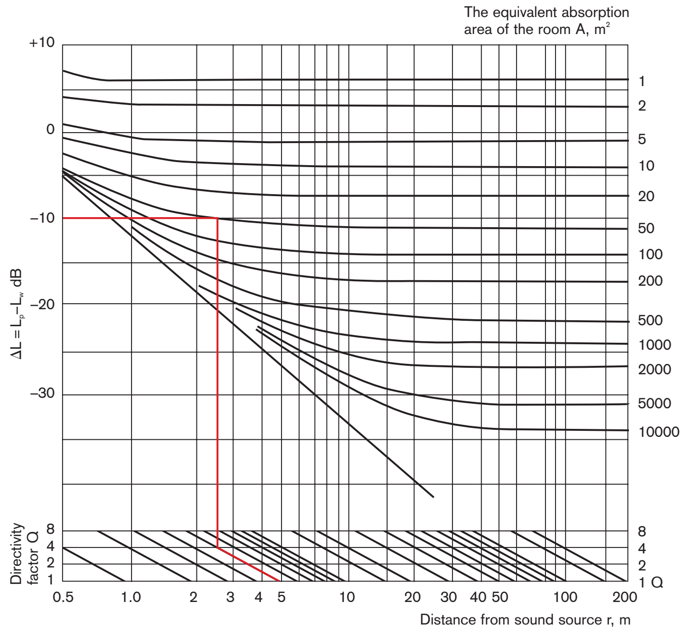

FIGURE 7. Equation (23) shown diagrammatically. The difference between the sound pressure level and sound power level ΔL, expressed in dB, is shown as a function of distance in r in m, the directivity factor for the sound source Q, and the equivalent sound absorption area A of the room in m^2.

EXAMPLE:

The distance between a sound source with a sound power level of 80 dB(relative to 1 pW) and a listener is 5 m, the directivity factor Q = 4, and the absorption area of the room A = 50 m^2. From the diagram, the resulting sound pressure level will be 80 − 10 = 70 dB(relative to 20 mPa).

$$L_p - L_w = 10 \cdot \log\left(\frac{Q}{4\pi \cdot r^2} + \frac{4}{A}\right) \quad (23)$$

where:
L_p is the sound pressure level at a distance r from the sound source in dB(relative to 20 μPa)
L_w is the sound power level of the sound source in dB(relative to 1 pW)
Q is the directivity factor of the sound source
A is the equivalent sound absorption area of the room in m²

This relationship can be used to calculate how the sound pressure at a point in the room varies with the power of the sound source, the distance between the sound source and the receiver, the directivity factor of the sound source (i.e. if it is not propagated spherically) and the effect of the room caused by reflections.

THE PROPAGATION OF SOUND IN BUILDINGS

Sound can be propagated in different ways in a building. Distinctions are made between the following terms:

- *Airborne sound* – sound that is emitted from a sound source into the surroundings via the air and that can be propagated further, for example, by walls that are made to vibrate and thereby create new airborne sound on their far sides.
- *Impact sound* – sound that is created, for example, by walking across a floor and that is transmitted through the building element to a point on its far side where new airborne sound is created.
- *Drum sound* – sound that is created within a room, for example, when walking across the floor.
- *Structure-borne sound* – sound that is created by vibrations in rotating machinery fixed to the building structure and subsequently transmitted through the structure.
- *Flanking transmission* – sound that takes an indirect route, for example, via a floor, instead of taking the shortest path between two rooms.

AIRBORNE SOUND INSULATION

When calculating and measuring the airborne sound insulation between two rooms the following terms are used:

- *Airborne sound insulation,* which is a measure of the ability of a separating structure to reduce sound that reaches it via the air. The term *sound reduction index R,* measured in dB, is used. The index is the difference in the sound pressure level between the source room and the receiving room. The value of the index is corrected with regard to the sound absorption A_m of the receiving room and the area of the separating structure S.
- *The laboratory sound reduction index* R_w measured in dB, is the value of the airborne sound insulation in a building element when measured in a laboratory. It is measured in one-third octave bands and is defined by:

$$R_w = L_s - L_r - 10 \cdot \log \frac{A_m}{S} \quad (24)$$

where:
L_s is the mean air pressure level in the source room in dB
L_r is the mean air pressure level in the receiving room in dB
A_m is the equivalent sound absorption area of the receiving room in m²
S is the area of the building element in m²

The resultant sound pressure level in the receiving room is often required and this can be calculated using the following equation:

$$L_r = L_s - R - 10 \cdot \log \frac{A_m}{S} \quad (25)$$

WALLS WITH WINDOWS AND DOORS

Walls often comprise a number of flush parts, for example, doors or windows, and the total sound reduction index will be affected to a great extent by the part that has the poorer index.

The following sound reduction calculation can be made:

$$R = R_0 - 10 \cdot \log\left[1 + \frac{S_1}{S_0}\left(10^{\frac{R_0 - R_1}{10}} - 1\right)\right] \quad (26)$$

where:
R is the sound reduction index of the complete wall in dB
R_0 is the sound reduction index of the wall only in dB
R_1 is the sound reduction index of the door, window etc in dB
S_0 is the total wall area including the window, door etc in m²
S_1 is the area of the window, door etc in m²

The calculation can also be performed graphically, see Figure 8.

If the sound reduction index is given as R´ then this is a value that has been measured on site.

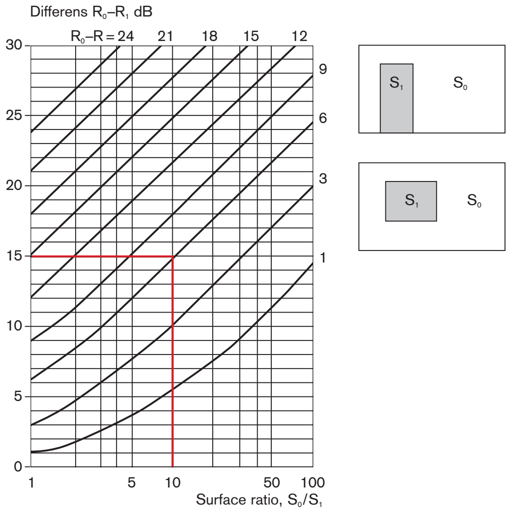

FIGURE 8. Diagram for calculating sound reduction indices for walls with windows and doors.

Example:
A 4 m × 2.5 m wall has a 1 m^2 window:
$S_0 = 10\ m^2$ and $S_1 = 1\ m^2$
$S_0/S_1 = 10/1 = 10$
Sound reduction index:
$R_0 = 40$ dB and $R_1 = 25$ dB
$R_0 – R_1 = 40–25 = 15$ dB
From the diagram:
$R_0 – R = 6$ dB
giving $R = R_0 – 6 = 40 – 6 = 34$ dB

REFERENCE Andersson J. Akustik & Buller – En praktisk handbok, 4:e upplagan, AB Svensk Byggtjänst, Stockholm

12. AIRTIGHTNESS – FOR ENERGY EFFICIENCY AND MOISTURE PROTECTION

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INTRODUCTION

The extent to which a building should be airtight is an often-debated subject, not least in connection with so-called ecological building. Good airtightness is a key property of a building that is expected to fulfil very high demands regarding thermal comfort, moisture protection and energy efficiency. Modern building techniques are often characterized by optimization of the building structure, which means, for example, that every sub-function in an external wall is only fulfilled by one layer of material. This, in turn, means that every layer of material must completely fulfil the demands made on it. For example, there is often only one layer of material in an external wall – usually plastic sheeting – that fulfils the demands for airtightness. If there are any holes in the sheeting or if its edges are not properly secured and sealed, the wall will not be airtight. This can put the structural and functional integrity of a building element at risk. The functions of modern design and buildings are often more sensitive to adverse loads and put far greater demands on the construction process that at any time in the past.

The term 'climate barrier' can be used in a number of contexts, though in building regulations the more specific term 'building envelope' is used. The building envelope comprises the parts of a building that form a boundary to the outdoor air. External walls, windows, doors and roofs thus form parts of the building envelope. Basement floors, via the ground beneath them, also function as a boundary to the outdoor air in the same way as other building elements next to unheated spaces. The quality of the building envelope in any particular climate will, to a large extent, determine how much energy is used in the building. Very well-insulated, well-designed and constructed detail solutions as well as a high degree of airtightness are the most important cornerstones for achieving energy-efficient and sound buildings. This so-called passive building technique is characterized by the fact that if a building is constructed properly from the beginning, the solutions will be durable and very little maintenance will be required during the lifetime of the building. It is therefore highly desirable to have a long-term perspective when choosing the technical solutions employed in the building envelope. Hopefully, the envelope will continue to function for decades to come, without having to be rebuilt or modified. Only the exterior layers will, in certain cases, require maintenance. Any other changes will, as always, be very expensive.

This chapter focuses on explaining how questions regarding airtightness can be dealt with during the building process. The reasons for having good airtightness are discussed as well as the consequences of poor design and workmanship. There are also examples of technical solutions to illustrate how much care must be taken when planning so that satisfactory final results can be achieved. The execution of functional inspections is discussed at the end of the chapter.

WHY IS AIRTIGHTNESS AN ISSUE?

Airtightness is the property of a building that prevents air flows through its structure or fabric, i.e. by infiltration – from the outside to the inside, or by leakage – from the inside to the outside. Airtightness is sometimes confused with wind protection: the purpose of wind protection is to prevent air movements within the fabric of a building, so that its thermal insulation properties can be retained even when subject to wind forces. Wind protection is installed to ensure that the thermal insulation can function properly. The demands made on wind protection depend on the properties of the insulating materials used.

The most important reasons for making a building as airtight as possible are to reduce the use of energy in the form of heat, to provide comfort for the residents or users, to provide the right conditions for good ventilation and to avoid moisture problems. Good airtightness also contributes to preventing outdoor air that might be polluted, for example, by pollen or particles, from making its way into the building. Structural elements between residential units should also be made airtight to reduce the risk of polluted air or smells spreading between them or into other zones. Good airtightness between foundations and the ground underneath help prevent radon from entering other parts of the building. Good airtightness also helps to reduce the transmission of airborne noise, for example, traffic noise.

An airtight building must have an efficient ventilation system to ensure that a good air quality level is always achieved, irrespective of the weather situation. The simplest way to do this is to install mechanical ventilation, i.e. a system with a fan. If so-called natural ventilation is used, this presumes that either the building is not airtight or that more or less extensive measures are taken to introduce air into the building so that a sufficient air change rate can be achieved. In old buildings with natural ventilation a large proportion of the air will enter the building via gaps and holes in the building envelope. If special sealing measures are taken in buildings like these, the air change rate will most probably be insufficient and, in unfortunate circumstances, give rise to moisture problems.

Energy management

Uncontrolled infiltration means that a building will have a larger air exchange rate than required. This will lead to unnecessarily high heat losses, as the infiltrating air will have to be heated to room temperature.

The magnitude of the infiltration not only depends on the size of the gaps and holes in the building envelope but also on the type of ventilation system used. In buildings with natural ventilation, or with balanced mechanical supply and extract ventilation, the infiltration and heat losses will increase linearly with the lack of airtightness. In locations exposed to wind, undesired infiltration might be significant and the extra heat

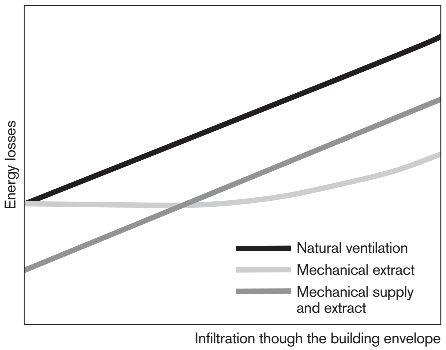

Figure 1. The diagram shows the principal relationships between energy losses and infiltration through the building envelope for different types of ventilation systems.

losses correspondingly high. A building with a mechanical supply and extract system should be built with a high level of airtightness to avoid unnecessary heat losses due to infiltration.

In buildings with mechanical extract ventilation only, the heat losses due to infiltration caused by poor airtightness will not be as large as in other cases. This is because the extract air fan will create a small underpressure in the building, which means that a proportion of the desired amount of supply air will enter the building via holes in the building envelope. The sizes of the air flows are governed by regulating the speed of the fan or by limiting the air flow in the extract air ducts. Up to a certain point a poor level of airtightness will have little effect on heat losses but in buildings with very inadequate levels the heat losses will be significant.

Figure 1 shows how infiltration can affect heat losses when different ventilation systems are used.

If the ventilation system has a heat exchanger to recover heat from the extract air, air infiltration will prevent full use of the heat recovery function. This is because the air that bypasses the ventilation system cannot

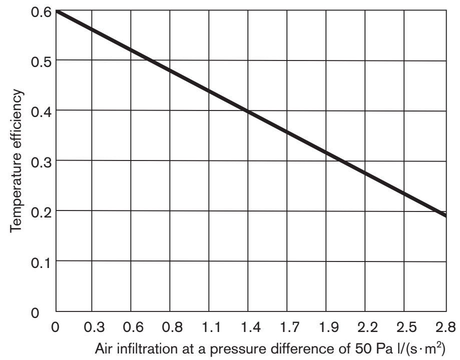

Figure 2. The diagram shows how the efficiency of a heat recovery unit with a plate heat exchanger is reduced as the infiltration through the building envelope increases (partly from Irving, 1994).

be heated by the heat exchanger. Buildings that have to fulfil very high energy efficiency requirements might not be able to do so because of unwanted infiltration. An example of how the heat recovery efficiency is reduced as leakages increase is shown in Figure 2.

Thermal comfort
It is quite often impossible to foresee where leakages, or infiltration, will occur. It will depend on how well the planning work has been managed and how well the construction work has been carried out. Typical risk zones in structures are the junctions between different building components and poorly made penetrations through the airtight layer, for example, for power points or holes for cables and ducting. The effects of infiltrating outdoor air in winter on how thermal comfort is perceived depend on whether the air enters the building via occupied rooms. The greatest discomfort is experienced when cold air enters a room at floor level next to external walls or if someone is subject to concentrated infiltration close to their place of work or in a reading room. Annoying draughts like these often result in requests to raise the air temperature in the room.

When cold air infiltrates into a building the surfaces of the walls and floors become colder and these cold surfaces, in turn, contribute to the radiant heat exchange between the occupants and the surfaces. The operative temperature in a room will then fall. Cold surfaces also become soiled more quickly, which means that they will have to be repainted at shorter intervals.

Ventilation becomes sub-standard in leaky buildings
In an airtight building, the ventilation rate is determined solely by the ventilation system. This means that it must be designed so that it can provide the correct air flows and the desired air quality in all parts of the building. On the other hand, in a leaky building, the combined effects of the outdoor climate and the ventilation system will determine how well the building will be ventilated and how the air will be distributed in the building.

In buildings with natural ventilation some of the outdoor air is introduced via air intakes, but it is also presumed that some air will infiltrate through gaps and holes to provide the necessary air change rate. It is almost impossible to foresee where infiltration will take place, though risks are greatest where there are many complex structural junctions. This can, in turn, mean that there will be more infiltration points in some parts of a building than in other parts. Consequently, certain weather situations might create undesirably large air exchange rates in some parts of a building and insufficient rates in others. The driving forces behind the air flows are the temperature differences across the building envelope and the effects of the wind. Air flows through gaps and holes cannot be regulated but are determined by the prevailing weather, which means that these air flows can vary in an uncontrollable way.

In a building with a mechanical extract air system it is assumed that most of the supply air is introduced into the building via correctly designed and suitably located outdoor air intakes. If the building is not airtight, the air will find its way in via unknown routes and there is a risk that the air exchange rates in some rooms will be too high due to infiltration while they could be too low in others because they are airtight. All balancing and commissioning work is carried out based on measurements of air flows through the extract air terminal devices. Unfortunately, these measurements provide no information about how the air entered the room. This can result in buildings having a correct average air change rate at the same time as there are great variations in the flows in individual rooms.

In buildings with mechanical supply and extract systems the system must ensure that all rooms have sufficient air flows. The system should be balanced so that the amount of extract air is somewhat larger than the required amount of supply air, so that a small under-pressure can be created in the building. This will help to avoid moisture problems. Gaps and holes can, on the other hand, cause disturbances in the form of undesir-

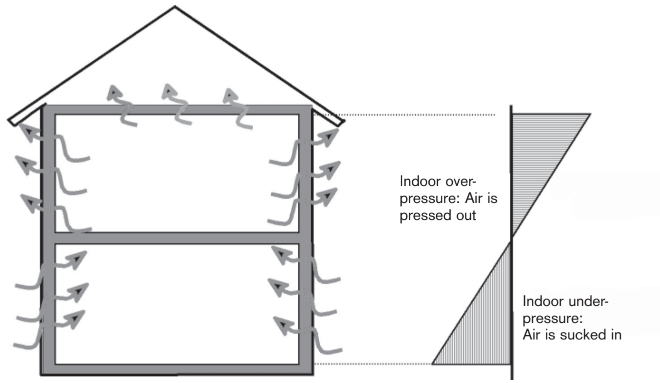

FIGURE 3. The wintertime pressure distribution in a building without mechanical ventilation and not subject to wind. Gaps and holes in the building envelope are assumed to be evenly distributed. Under-pressures are normal at floor level and corresponding over-pressures at roof level.

ably high air flows when it is cold and windy, making it is difficult to balance the system properly. Infiltration of outdoor air can lead to draughts and this can be perceived as poor comfort. Effective, efficient and controllable ventilation can only be achieved if the building is airtight.

Moisture protection
Air leakage can lead to moisture damage as a result of moisture convection. When warm moist indoor air meets a cold surface the moisture will either condense or create limited zones with very high relative humidities.

The wintertime pressure distribution in a building is often similar to that shown in Figure 3. Under-pressures at floor level are quite common and this means that cold air can enter via gaps and holes at the junctions between floors and external walls. There is a risk of cold floors but there will be no moisture problems within the structure or fabric of the building. Very low floor temperatures in winter can be lowered even more by thermal bridges at floor/wall junctions. In unfavourable conditions the drop in temperature might be so great that surface condensation occurs. This risk is increased if the local air change rate is low and if there is excess moisture in the room.

At roof level there is often a small over-pressure, which means that air from the building can leak into the loft space via gaps and holes. Leakages like these often cause serious moisture damage. This damage is often local and cannot be remedied by increasing the ventilation in the loft. The most effective measure is to make sure that leakage cannot take place at all, i.e. by making the building as airtight as possible. From a moisture point of view, the upper parts of a building are the most important to keep airtight.

Mechanical extract ventilation in an airtight, low-rise building could result in the building being subject to a small under-pressure for most of the year. This means that air will infiltrate via small gaps and holes as well as via the supply air terminal devices. The risk of air leaking out through the gaps and holes is small and the risk of moisture problems caused by moisture convection will be less. It is, however, almost impossible to maintain a permanent under-pressure indoors and any gaps and holes must be kept as small as possible. It is equally difficult to maintain a permanent under-pressure in a high-rise building.

Propagation of pollutants and sound
To prevent radon or odours caused by mould or rotting material that

forms part of or has been left in the foundations from finding their way into a building, it is important to ensure that slab foundations or suspended floors above voids are completely airtight.

The spread of odours and gases between dwelling units can be reduced if each unit or fire cell is airtight. It will also be more difficult for particles in the outdoor air to find their way into a building if the building envelope is airtight. The transmission of noise, for example from traffic, will also more difficult if the envelope is airtight. The same applies to noise between dwelling units. A fire cell must be airtight to reduce the risk of gases and smoke spreading if there is a fire.

AIRTIGHTNESS: GENERAL PRINCIPLES

Good airtightness can be achieved in a number of different ways:

- By placing plastic sheeting immediately behind the internal cladding, for example, gypsum plasterboard, or between the insulation layers.
- By using airtight gypsum wallboard.
- By using solid materials such as bricks or concrete.

No matter which technique is used, a well-thought out strategy will be required to achieve complete airtightness in a whole building. Airtightness must be ensured at all junctions, around and in windows and doors, and at all penetrations for building services. To achieve a good result, all the detail solutions must be considered very carefully, not only in the planning stage but also with respect to how they can be completed on site. It must also be taken into account that a number of different contractors will have to be informed about the airtightness requirements if they are to be fully met. Well-sealed junctions between external walls and floors, external walls and internal walls, external walls and windows, and penetrations for ducts and building services are often critical to good airtightness. These zones require great precision when planning, choosing materials and designing details. Having to pay attention to special details often means that other parts of a building are also more carefully built, which leads to better buildings in all respects. Different building systems will mean that airtightness issues will have to be dealt with in different ways. An important principle to adopt to ensure good airtightness is to make sure that there is a consistent strategy with respect to the function of the measures taken to ensure airtightness and how the sealing work is to be performed and checked.

In buildings constructed using lightweight building techniques, plastic sheeting is normally used to achieve the required airtightness. The sheeting is placed on the warm side of the thermal insulation or sometimes at a suitable depth within it. In the latter case it is possible to install wiring and power points without making holes in the sheeting. It will also offer better protection against damage caused by picture hooks or lighting fixtures. At junctions between different building elements the solutions must be designed so that there are generous overlaps between the different sheets and so that the work can be carried in a professional way, as even small holes can lead to considerable leaks. When buildings are constructed completely on site overlapping is relatively easy to arrange but it still requires a systematic approach both at the planning and construction stages. Sections of plastic sheeting should overlap well with the sections being pressed tightly together, preferably using wooden battens or stiff boards.

When prefabricated wall and floor elements are used great demands are placed on the solutions employed for junctions and penetrations. Junctions between different elements must be designed very carefully. It can be difficult to handle the extra lengths of plastic sheeting that will be used as overlaps and prevent them from being damaged during transportation and when the building element is put into place. The use of jointing mastic and sealing strips of approved quality will increase airtightness. Experience shows that it can be quite difficult to find acceptable methods for achieving good airtightness in buildings made of prefabricated elements. On the other hand, the quality of factory-made elements is high and they display good airtightness properties.

Airtightness in lightweight constructions can be achieved by using other materials than plastic sheeting. Different types of building boards are often sufficiently airtight. The joints between the boards, however, form weak points and these can be sealed by using special jointing tape. Jointing mastic can also be used but the materials must be carefully chosen with regard to durability and emissions. The use of jointing mastic might be necessary at junctions between floors and ceilings, and around windows. If there is a risk of movements in a joint, it must be designed so that the jointing mastic can withstand these movements without impairing its airtightness.

Solid elements, such as walls and floors of concrete or lightweight concrete, and walls of plastered brickwork, are normally sufficiently airtight as long as they are free from cracks. An advantage of elements like these is that electrical installations can be embedded in them without their airtightness being affected. Penetrations and joints must be carefully designed to ensure good airtightness and special attention paid to junctions between building elements. If large elements are used, tolerances and movements can be relatively large and this means that the junctions must be able to accommodate these movements if they are to remain airtight. It is therefore important that junctions are correctly designed and the correct sealing and thermal insulation materials are used. If movements up to 5 mm can be expected, the junction must be at least 20 mm wide for the jointing mastic to retain its function. If a junction is too narrow, the mastic will only be able to accommodate very small movements.

ACHIEVING GOOD AIRTIGHTNESS

This section gives examples of solutions that can be used to achieve good airtightness.

When plastic sheeting is used to ensure airtightness there are different ways in which it can be joined. On flat walls, joins can be made by overlapping but measures will also have to be taken to make sure that they are airtight. The simplest way to do this is to press the sheeting together using a wooden batten or building board and fixing it to a stud. If there is the slightest doubt that the stud is not perfectly straight or that nailing/screwing will not be sufficient, the sheeting can be welded or heat sealed, or a special jointing mastic can be applied between the sheets before they are pressed together. A practical method that can be applied when sealing horizontal surfaces is to use a U-shaped metal jointing strip. The plastic sheeting is placed over the strip and a plastic tube is used to press the sheeting into the strip, thus holding it in place and ensuring that the join is airtight, see Figure 4.

FIGURE 4. An example of how an airtight join between two sheets of plastic can be achieved by placing the overlapping areas over a U-shaped metal jointing strip and pressing the sheets together using plastic tubing.

Junctions between external walls and floors must be designed out so that the airtight layer in the wall fully connects to the sealant. An example of this design solution used at the junction of an external timber wall element and an intermediate concrete floor is shown in Figure 5. The vapour barrier ensures airtightness in the wall element. A sealing strip of EPDM rubber is placed on the upper side of the floor and, when the strip is subject to a load, provides a continuous seal against the plastic sheeting in the wall. Underneath the floor, jointing mastic is used to provide a seal against the plastic sheeting in the wall. The elastic jointing mastic can accommodate movements between the wall and floor while remaining airtight.

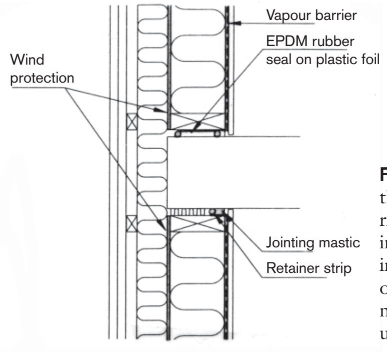

FIGURE 5. Vertical section through the junction of an external prefabricated timber wall element and an intermediate concrete floor. A sealing strip of EPDM rubber is placed on the upper side, and jointing mastic and a retainer strip are used underneath the concrete floor.

Fixing plastic sheeting to window frames is an especially difficult detail, see Figures 6 and 7.

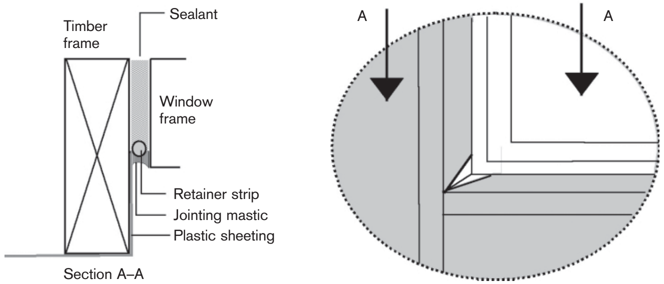

FIGURE 6. The left-hand drawing shows a section through a timber frame and a window frame. The plastic sheeting from the wall is folded into the reveal and sealed in place using jointing mastic between the two frames. The right-hand drawing shows how the plastic sheeting has been cut in one of the corners so that it can be folded into the reveal. This leaves a small area unprotected. To prevent any air leakage, extra strips of plastic sheeting are glued into the corners. [Mattsson and Sandberg, 2005]

Special attention is required when the plastic sheeting in a wall is not in the same plane as that of the sealing between the window frame and the wall. As seen in Figure 6, it is not sufficient to fold the sheeting into the reveal, as it will not be sealed in the corners. An extra strip of plastic film will be required here.

It is easier to achieve good airtightness if the plastic film in the wall is allowed to extend over the window frame and then pressed against it using a batten, see Figure 7. To ensure an even higher degree of airtightness a special sealing strip of EPDM rubber can be placed between the plastic sheeting and the window frame, both of which are then pressed together by the batten. There is also another advantage of positioning the window in the wall in this way: the extra thermal losses due to the thermal bridge in the join will be small.

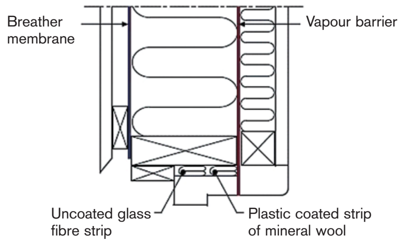

FIGURE 7. A vertical section through an external timber frame wall in which the plastic sheeting/vapour barrier has been placed within the wall. In this example the window frame has been positioned so that the plastic sheeting can be extended over the window frame and secured using as special sealing batten. The plastic sheeting between the window frame and the wall are then in the same plane which means that difficult corner solutions can be avoided.

Penetrations for wires, pipes and ducts always increase the risk of leakages and the number of penetrations through the air barrier must be limited as far as possible. Electric wiring can, for instance, be placed entirely on the room side of the plastic sheeting in external walls, if the design of the wall allows, see Figure 8. Special solutions will always be required to ensure airtightness where ducts penetrate airtight barriers.

In solid structures, the main details that have to be designed to ensure that airtightness, thermal insulation, and wind and rain protection requirements can be met are the junctions. Figure 9 shows a solution for a vertical junction between sandwich elements of concrete. The actual airtightness is achieved by using an internal jointing mastic and a retain-

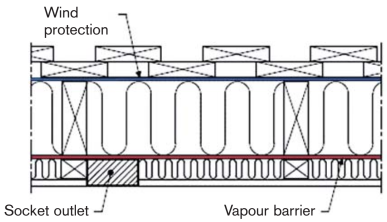

FIGURE 8. Horizontal section through a socket outlet in an external timber frame wall. The plastic sheeting in the wall is positioned within the structure of the wall, which makes it possible to locate wiring and socket outlets on the room side of the plastic sheeting. This means that the sheeting can be placed continuously and the airtightness requirements can be met. [Elmroth and Levin, 1983]

ing strip. Externally placed rain protection is in the form of a rubber strip with an air gap behind, which ensures that there is no pressure difference across the seal. Mineral wool is used for the thermal insulation in the junction. The junctions between external walls, internal walls and floors must be very carefully designed.

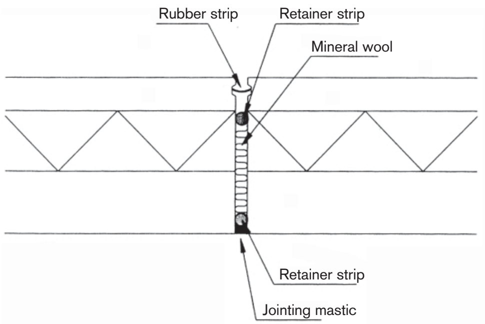

FIGURE 9. A vertical junction between two concrete elements. Jointing mastic is used for internal sealing. The junction is thermally insulated using mineral wool. There is an air gap behind the rubber rain protection strip.

MEASURING AIRTIGHTNESS

At the planning stage it is difficult to determine how airtight a building will be and to ensure how the requirements will be met. Consequently, airtightness has to be tested when the building is complete or nearing completion. A standardized method entails measuring the airtightness at a pressure difference of 50 Pa, the so-called pressure testing method according to SS-EN 13829. The method description assumes that the whole building will be tested and this can be a complicated task in large buildings. Instead, it might be more practical to test the airtightness in a single fire cell, which in a residential building would be an individual dwelling unit.

Before testing commences, the ventilation openings have to be well sealed. A pressure difference between the indoors and outdoors of 50 Pa is then created using a portable fan and this can be installed in the doorway to the unit. By subjecting the unit to a relatively large pressure difference, measurements can be made even if it is slightly windy outdoors. The amount of air required to achieve the pressure difference, the air permeability, is recorded and this is a measure of how much air can leaks from, or infiltrate into, the unit. When using this method to measure airtightness, air can, of course, leak from or into neighbouring units and stairwells and not only via the building envelope. Air leakage between units is usually small for a number of reasons, as mentioned previously. The measured air leakage and infiltration can be regarded as a good approximations of the airtightness of the building envelope and it should be possible to use the result to estimate the airtightness properties of the building as a whole. An air exchange rate that is determined in this way and that is lower than about one air change per hour at a 50 Pa pressure difference can be regarded as fulfilling reasonable demands for airtightness. However, a building can never be too airtight.

Airtightness testing using a pressure difference method will only provide quantitative data. What is also of great interest, however, is where leakage or infiltration takes place. A simple way of investigating this is to use smoke to detect points where leakages are suspected. An even better way is to combine pressure testing and thermography.

Modern infrared cameras are lightweight and easy to handle and are primarily used to detect surface temperature differences. If the dwelling unit is subject to an under-pressure relative to the outdoors, outdoor air will infiltrate through gaps and holes. If this air is a few degrees colder than the room air, the point of entry will be easily detected by the camera. With the help of an experienced camera operator and a few simple calculations it will be possible to estimate the magnitude of the infiltration. Some infrared cameras have computerized help functions to determine the temperature of the surfaces. It is recommended to carry out all types of airtightness tests at an early stage as possible, especially in large developments or when new production methods are introduced, so that airtightness solutions can be continually improved.

QUALITY ASSURANCE

A client must formulate quantitative requirements when stipulating the airtightness of a building. The fulfilment of the requirements must then be verified by testing. When planning a building there must be a well-thought out strategy that clearly sets out how airtightness is to be ensured. Specifications and technical solutions should be very clearly shown on the construction drawings so that solutions will not have to be invented on site. This means that the design engineers must be well acquainted with the production process so that a correct airtightness strategy can be adopted. It is hardly feasible to provide drawings of all the different building details and this is why clear principles for creating solutions are a necessity. When prefabricated building elements are used focus must be on designing good sealing solutions. When on-site methods are used airtightness can be achieved, for example, by letting the air barriers attached to each element overlap generously. Every junction is a potential leakage point. The more corners and junctions, the more attention must be paid to ensure that the building as a whole is airtight.

Penetrations for ducts and services installations always create leakage risks. This is why the different contractors on site must make sure that no extra holes are made and that existing holes are systematically sealed. Plans for locating pipes, ducts and wiring must be carefully drawn up to minimize the number of penetrations and to facilitate the work to make them airtight. Electrical wiring should, as far as possible, be installed in internal walls.

Regular checks should be made on the building site to ensure that stipulated solutions are used. Temporary solutions using tape or unspecified jointing mastics should not be accepted. It must be remembered that it is not possible to determine the airtightness of a building by carrying out a single inspection. As early as possible in the building process airtightness testing of a fire unit/dwelling unit should be carried out to get an idea of whether the technique chosen has provided the desired results. If the pressure testing method is combined with thermography, leaks can be detected and the necessary changes made to the chosen design solutions. Tests should be repeated continually.

Good results can be achieved, if all those engaged in a project are made aware of the requirements for good airtightness. Open cooperation between the different contractors is therefore very important.

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13. PEOPLE AND BUILDINGS – BOTH NEED LIGHT

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Claiming that 'to see we need light' is perhaps now regarded as somewhat self-evident: we are also aware that light is both useful and a necessity. However, it is not only needed to see by – light also plays an indispensable role in our very existence. 'No life without light' is a phrase in which the word light can now be replaced by radiation and energy, as forms of life have been found to exist in the absence of visible light but in the presence of other energy sources, such as UV, ultraviolet, radiation and IR, infrared, radiation.

We, as Homo Sapiens, have developed over millions of years in a daylight environment in which the variations of light intensity have controlled our existence and evolution.

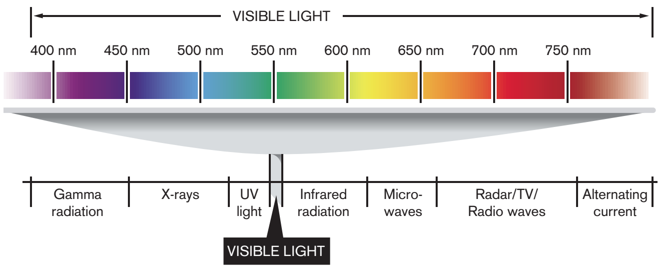

FIGURE 1. The electromagnetic spectrum.

This is not only true with regard to our eyesight, the result of the function and sensitivity of our eyes adapting to the daylight radiation spectrum over millions of years, but also to other biological functions of our bodies. Our biological clocks, i.e. our sleep-wake cycles, are controlled by variations of light. The body's capability to absorb vitamin D, its metabolism and its immune defence are also controlled by light and possibly by other, so far unestablished, factors.

What is light? In the eighteenth century, Dr. Samuel Johnson noted that 'we all know what light is; but it is not easy to tell what it is'. Today, the recognized explanation says that perceptible light is visually experienced electromagnetic radiation, see Figure 1. It is important to include the distinction 'visually experienced', as man in his natural environment is subject to radiation from the whole of the electromagnetic spectrum. The part of the sun's radiation spectrum that reaches Earth comprises about 50 % light radiation, about 45 % IR radiation and about 5 % UV radiation. These figures also indicate the relative proportions of the energy contents of these different types of radiation.

We experience different types of solar radiation in different ways. IR radiation is absorbed by the skin, where cells or receptors register it as heat. When the heat sensation becomes too great, our brain transmits signals to regulate our body temperature by opening pores in the skin and creating a sweat, resulting in a reduction of the sensation. As far as we know, human beings do not have any receptors with which we can experience UV radiation. On the other hand, the effect of an excessive dose of UV radiation can be detected – our skin turns red and we might experience a burning sensation and nausea. Light radiation is absorbed

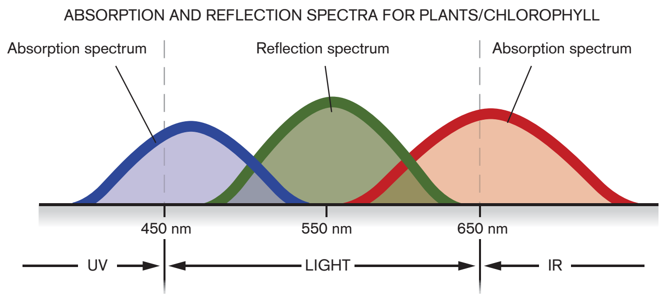

FIGURE 2. A diagram showing the absorption and reflection spectra for chlorophyll. Radiation in the blue and red parts of the light spectrum are absorbed by plants, while the radiation in the middle of the spectrum, the green area, is reflected. Artificial lighting for plants should therefore emit both short and long wave light radiation, i.e. both blue and red light.

less by the skin than both IR and UV radiation. All our light-sensitive cells or receptors are situated in our eyes and these react in different ways, depending on whether they have a biological or visual function.

Human beings, however, are not alone in experiencing and making use of radiation for their existence. All forms of life depend, in some way, on the radiation spectrum. Plants need light for photosynthesis, a process by which the carbon dioxide in the air, light energy and water create cells and release oxygen. On the other hand, not all parts of the spectrum can be used or absorbed by plants, primarily only the blue and red parts. The green part of the light spectrum is not used, but is reflected by chlorophyll, the substance in plants responsible for photosynthesis, see Figure 2. Consequently, we perceive plants as being green and, in the autumn, when the chlorophyll has disappeared, leaves turn brown and straw turns yellow.

As we have evolved in an environment dominated by vegetation, our eyes are most sensitive to light in the green part of the spectrum. Sensitivity then rapidly decreases towards both ends of the light spectrum, where light is seen as blue or red.

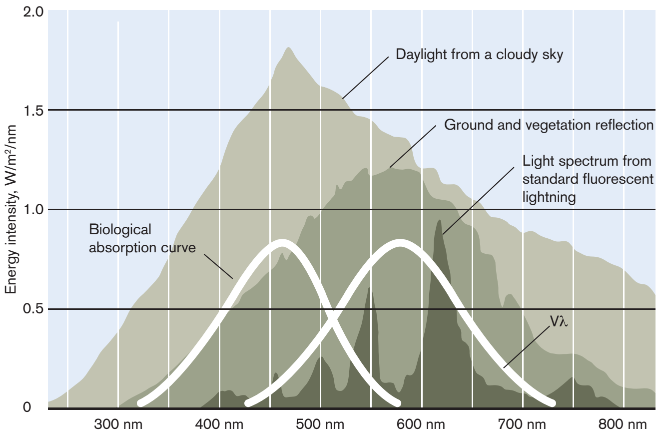

Figure 3. The diagram shows different types of light spectra and absorption spectra for biological and visual receptors. The so-called Vλ curve, showing the visual sensitivity of the eye, correlates well with the curve for light reflected from vegetation. The biological absorption curve correlates well with the diffuse solar radiation spectrum, daylight from a cloudy sky, with a maximum around 460 nm, where the energy content of the diffuse radiation spectrum is greatest.

The biological effects of light radiation on human beings have only been more fully understood thanks to progress made in research over the past ten years or so. For instance, regarding the effect of light on the body's ability to absorb vitamin D and how this process works. Another example is the effect of light on our immune defence system. How light affects our biological clock has also been explained. What was unknown until a few years ago was that our eyes have two different light-sensitive receptor systems – one for visual processes and one for biological processes. The biological receptor system that controls glandular activity, i.e. hormone production, is most sensitive to blue light, as seen in blue skies. Sensitivity is reduced dramatically when it is subject to light with longer wavelengths and the system is practically insensitive to green, yellow and red light, see Figure 3. When blue light from the sky or light with similar wavelengths is incident on or stimulates the biological receptors a signal is sent to the glands in the body, primarily to the pineal gland, so that the production of cortisol increases and the production of melatonin, the so-called sleep hormone, is inhibited. When blue light ceases to stimulate the biological receptors, the production of cortisol is stopped and melatonin is produced instead, and we become sleepy.

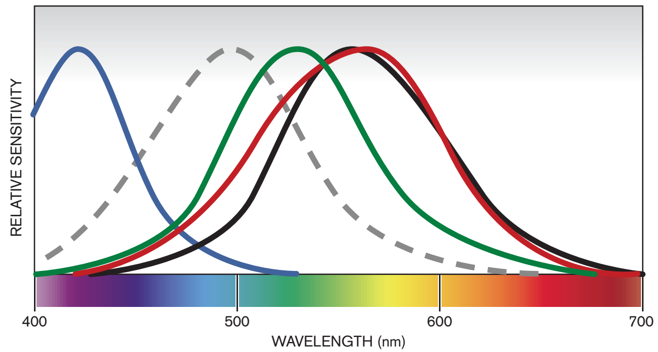

Figure 4. Schematic absorption curves (light sensitivity curves) for the visually active receptors. The blue, green and red curves represent the cones that provide us with an experience of colour and detail vision in daylight conditions. The black curve, the so-called λ curve, represents the sum sensitivities of light stimuli of the cones. The grey dashed line represents the rods, which are much more light sensitive than the cones, but which do not contribute to experiencing colour. The rods function at low intensities of illumination, such as at dawn and dusk, and at night.

The human body assumes a state of rest as nerve signals become slower and reaction times are reduced. These changes normally take place as part of the natural biological twenty-four-hour clock. However, if the light from a blue sky or similar blue light is not experienced, glandular production of melatonin will not cease and the body will remain in a state of rest for longer periods than those dictated by its natural daily rhythm. In winter, blue light is not visible in the northern and southern parts of the globe and this means that daily rhythms for people living in these regions will be disturbed. This results in an uninterrupted production of melatonin and a weakened immune defence. The effect on the body is like trying to drive a car with the handbrake on and the wrong oil in the engine. Many people become depressed, to different degrees, during these periods.

Similar reactions also occur among people not living in these northerly and southerly regions, i.e. people who spend most of their working hours indoors, in premises with little or no access to daylight. Before the biological receptor was discovered, it was thought that artificial electric light would be a sufficient substitute for daylight.

In the wake of these more recent discoveries, it has been shown that both lighting levels and light quality, i.e. the spectral distribution of light, are insufficient from a biological and health point of view. As mentioned in the introduction to this chapter, we evolved in a daylight environment in which the radiation intensity outdoors was, and is, far greater than that indoors. Outdoors, the intensity of illumination during the day varies between 500 lux on an overcast day and 100 000 lux on a clear sunny summer day. Indoors, the intensity of illumination is usually between 200 lux and 500 lux. Compared to the conditions outdoors this like very weak twilight. As nearly all light sources available today have been developed to meet our visual requirements, the radiation spectrum is mainly biased towards wavelengths where the visual light-sensitive receptors have maximum absorption, i.e. in the 500 to 700 nm range, see Figure 4. The biologically active receptors have their absorption spectrum in the 430 to 500 nm range. However, the use of artificial sources, such as fluorescent lighting or other discharge lamps, to create a level of light radiation within the wavelength ranges that are acceptable from a biological point of view would be very energy-demanding and would also create excessively large amounts of heat.

The conclusion that can be drawn from these new findings is that the amounts of daylight in buildings must be increased considerably. This will mean designing buildings differently, as those built today at best only provide sufficient levels of daylight a few metres in from the facade of the building. An architectural paradigmatic shift is needed, if buildings are to provide good healthy environments in which daylight can function both biologically and visually, while at the same time replacing electrically created light during daylight hours. The problem that has to be solved is how to introduce a sufficient amount of daylight into buildings without having a heating effect that will call for a cooling solution – or how to develop and use energy-efficient light sources that display spectra that are effective both visually and biologically.

Light sources like these are available, for example, in the microwave plasma lamp. On the other hand, this solution is difficult to install in modern buildings and has therefore not been used to any great extent. Another example of a source of light that could be developed along these lines is the LED or light emitting diode. However, it must not be forgotten that genuine daylight also has another effect on the indoor climate: namely, its aseptic effect. This was previously made use of in schools and hospitals to reduce the spread of bacteria and viruses, something that seems to have been completely forgotten today.

A well known example of these powers was observed by the English nurse Florence Nightingale during the Crimean War in 1864. She discovered that the wounds of the soldiers who could not be cared for indoors, and who were forced to lie outdoors, healed much quicker than those who were treated indoors. She concluded that daylight was instrumental in fighting harmful bacteria. This led to hospitals and schools being opened up to admit health-bringing daylight. As a further consequence, the designs of residential and office buildings were influenced by these findings, primarily seen in the functionalistic building styles that dominated the first half of the twentieth century.

It was previously mentioned that light levels indoors are generally too low from a biological point of view. Unfortunately, the same observation can also be made about them regarding our visual system. The maximum sensitivities of the eye were originally developed at outdoor daylight levels, generally 10 to 200 times greater than levels indoors. Light levels, however, are not the only factors that matter, the spectral distribution is important too. Daylight has an even and continuous spectrum as opposed to the spectra of light sources normally used indoors. To understand why this is a problem, a short explanation of the function of the eye and the visual process is necessary, see Figure 5.

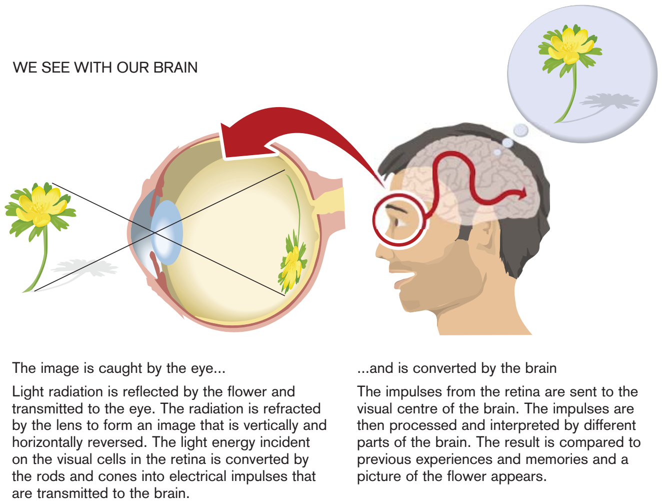

Figure 5. The illustration shows a somewhat simplified picture of the visual experience, the act of seeing.

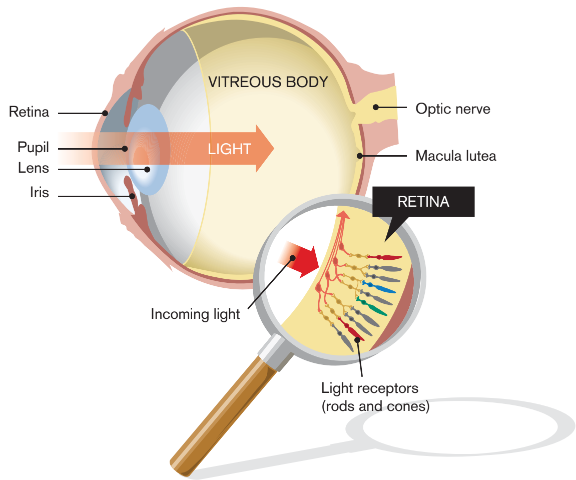

Figure 6. The structure of the eye and a detailed section of the retina.

The eye can be described as a camera in which the act of seeing corresponds to images being projected onto a film, the retina, where an electro-chemical process converts light energy into nerve signals to the brain, where they are processed and interpreted. The visual process, however, is not quite that simple. The optical system in the eye is far more complicated than that in a camera. The sensitivity of the retina and its ability to adapt to different levels of light greatly exceed the properties of the most advanced electronic cameras, see Figure 6.

The eye can adapt to light conditions that vary by a factor of up to 100 000. To span this enormous range, the retina is equipped with receptors that have different sensitivities to light, with a distinction being made between scotopic and photopic adaptation. Scotopic adaptation means that the eye adapts to dawn/dusk and night vision, i.e. low levels of light. The extremely light-sensitive receptors that come into play for these conditions are called rods. A special feature of these receptors is that they register low-level light radiation, but not from which part of the spectrum it originates. This results in everything being seen as grey at low light levels – at night, all cats are grey. At higher levels of light, daylight, the somewhat less light-sensitive receptors, called cones, are brought into play. The eye is then said to be photoptically adapted.

There are three types of cones, each with different absorption spectra. They each register light radiation from different parts of the spectrum and have individual maximum sensitivities for red, green and blue light, see Figure 4. In other words, this means that the cones form the basis for colour vision. Strange as it may seem, if each of the three different types of cones were subject to light with wavelengths within the blue, green and red parts of the spectrum, this would create the sensation of white light. By varying the radiation intensity of these combined colours, the sensation of new colours can also be created. This technique is used in colour TVs as well as in fluorescent lights and other light sources to create the impression of light of different colours. Our retinas cannot detect that light from artificial sources has an uneven spectrum. Nor are we aware of the effects of this, namely, that the colours are not always experienced correctly (metamerism), that visual acuity and contrast sensitivity are affected and that we can experience after-image effects that affect our detail vision. Natural daylight has an even spectrum and therefore provides a better balance between the registration, by the different cones, of both the direct and reflected light radiation that meets the eye. This means that visual impressions such as shape, colour, movement and contrast etc are roughly sorted out as soon as they reach the retina. As the eye twitches with small, rapid movements, fixing an image for a few microseconds before its next movement, a so-called saccadic movement, its field of vision is recorded in steps on the retina. Each time the image is fixed, the receptors in the retina send different streams of signals, containing information about the observed environment, to the brain. This complex information is then processed by the brain to raise our level of awareness of our surroundings.

The greatest amount of work performed by our brains is to reject all the information that the brain regards as unnecessary or already known. This is accomplished according to a complicated reference pattern, individually built up during our lifetime. It is estimated that if the brain receives about 100 megabytes of information per second, we only actually become aware of about 30 to 40 bytes. The greatest load on the brain is the work performed to reject visual information and this uses about 90 to 95% of its capacity. The remaining capacity is used to process information from other senses and other bodily functions.

The way in which the retina and brain process the information received can be regarded as a genetically developed program. It was developed for our survival in the natural and dangerous environments in

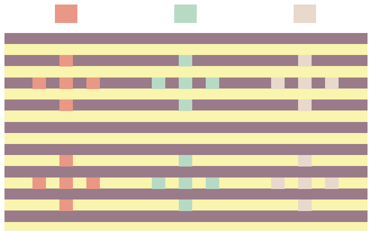

Figure 7. The vertical pairs of coloured squares between the horizontal lines are indentical but are perceived as being different. The phenomenon is called chromatic induction or metamerism. Its underlying causes are still not fully understood.

Figure 8. What do these black blobs represent?

A man cutting grass.

which our forefathers lived and which were left only a few thousand years ago.

Modern environments are characterized by features with long straight lines, right angles, symmetrical patterns – such as glazed facades – and saturated colours, which hardly exist at all in nature. In addition, objects are often lit by a number of different light sources, creating contrasts and shadows, also nonexistent in nature. The conditions under which we now see things have been radically changed. The effects that they have on our daily visual interpretation of our artificial environment must not be underestimated. Thinking that we can see something does not necessarily mean that that we actually see it. Figures 7 to 12 show us how visual information can be interpreted or misinterpreted.

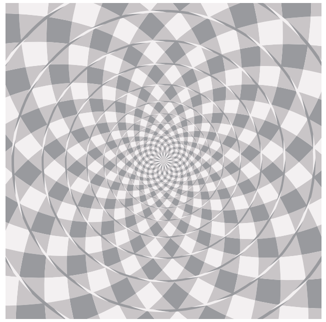

Figure 9. Is this a spiral or a number of circles?

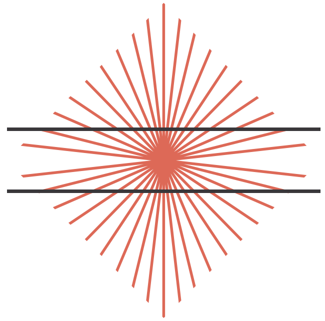

Figure 10. Are these horizontal lines parallel?

The ability of the eye and the brain to discern the essential part of the visual information in our surrounding environment is sometimes subject to extremely difficult challenges by artificial environments.

Over the past ten years or so we have increased our understanding of what vision is all about and it is now possible for us to design visual environments so the conditions under which we observe our surroundings can be greatly improved.

This new knowledge will almost certainly mean that present standards and recommendations regarding lighting will be radically changed in many respects.

In the future, more emphasis will most probably be placed on the spectra from different sources of light and these will become more im-

Figure 11.

Figure 12.

Look at the centre of the left-hand picture for 30 seconds and then look at the right-hand picture – what happens to the black-and-white picture?

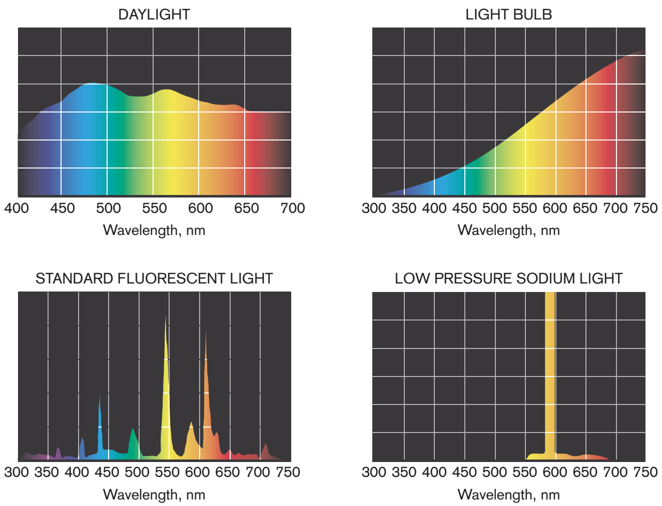

Figure 13. The colour spectra emitted by different sources of light vary considerably. For most visual purposes, the best results are obtained if the colour spectrum of the light source corresponds, as far as possible, to that of daylight. Research has shown that health and performance increase in environments with high quality light. [U.S. Department of Energy. Vision 2020. March 2000.]

portant when assessing the quality of the light and its source – not only with respect to biological effects but also to visual functions. Demands for glare-free environments and how light is distributed in them will also be given more emphasis. This will be done partly to eliminate various after-image effects and partly to improve visual acuity and contrast sensitivity. Where older generations are concerned, these demands are more essential for safe vision than increasing lighting intensities.

A completely different aspect, that has nothing to do with the visual experience, but, nevertheless, one which is essential for the survival of man, is the use of energy: A large proportion of the energy that we use, and considerably more than most people realize, is used to create light.

Lighting, for example, uses nearly 20% of the global production of electrical energy. This is more than all the electrical energy used in the EU, see Figure 14.

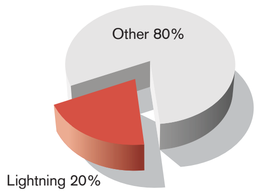

Figure 14. The proportion of electrical energy produced for lighting in a global perspective. [Light's Labour's Lost, OECD/IEA, 2006]

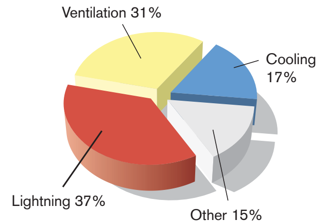

Figure 15. The proportions of electrical energy, according to usage, used in office buildings in Sweden [Stil 1/Energimyndigheten].

Lighting also generates heat. In the Nordic countries this can sometimes be regarded as a contribution towards heating needs, but in most cases it actually contributes to the need for cooling! This means that lighting demands indirectly affect the energy use of other building services, such as cooling and ventilation.

Lighting is thus one of the greatest factors behind the production of greenhouse gases. It gives rise to three times as much greenhouse gases than all global air traffic. [OECD/IEA, Light's Labour's Lost, 2006]

A large proportion of this energy is used when outdated low-efficiency light sources convert electrical energy into light radiation. And these energy-consuming light sources do not even provide a satisfactory visual light spectrum.

This means that when new standards and recommendations are produced the amount of energy used by lighting will be emphasized even more than today. One of the factors that will be stressed is the greater use of daylight as an alternative to electrical lighting. This is not only for health reasons, as mentioned previously, but also for energy use reasons.

Daylight on a cloudy day will provide more than twice the amount of light for every watt of heat load that the most efficient electrical light source in a building can provide. An increased but more intelligent and efficient use of daylight in modern buildings would also indirectly reduce the energy needs for cooling and ventilation.

These multiple arguments for increasing the availability of daylight in buildings – for health and energy purposes – provide even more reasons why changes must be made in the design of buildings. They also emphasize why it is not only important to develop new energy-efficient light sources but also new lighting solutions, so that demands for biologically and visually satisfactory environments, as well as demands for lower energy uses than today, can be met.

The technology required is both known and available and, to a certain extent, solutions have been tested and provided good results. What remains to be done is to introduce and implement these new solutions and products on a broad front, so that ideal indoor environments can become a reality in future buildings.

Eyes and light: facts and figures

The eye

Number of rods	5 million, used for colour vision	
Number of cones	100 million, used for night vision	
"The third receptor"	Used to control our biorhythm	
Number of nerve paths from the retina	1 to 2 million	
Typical lighting levels	Clear sunshine	60 000 to 100 000 lux
	Cloudy summer day	20 000 lux
	Misty winter day	10 000 lux
	Cloudy winter day	3 000 lux
	Office, indoors	300 to 500 lux
	Clear moonlight	1.0 lux
	Starlight without moonlight	0.25 lux

Luminous flux is the measure of the perceived power of light. The unit of luminous flux is the lumen, lm.

Illuminance is the amount of light incident on a surface. Illuminance is measured in lux, where 1 lux = 1 lumen per square metre, 1 lm/m^2.

Luminous intensity is a measure of the power emitted by a light source in a particular direction. The unit of luminous intensity is the candela, cd.

Luminance is the amount of light from a light source or illuminated area that reaches our eyes. Luminance is measured in candelas per square metre, cd/m^2.

Luminous efficacy is the ratio of luminous flux to the total electrical power input to the source. Luminous efficacy is expressed in lumens per watt, lm/W.

Typical values of luminous efficacy:
Light bulbs, about 10 lm/W
Halogen lamps, about 20 lm/W
Compact fluorescent light strips, 50 to70 lm/W
Fluorescent lights*, 95 to 100 lm/W
LEDs, white light, 70 to 80 lm/W (Nov 2007)**

* with electronic high-frequency controls
** LEDs in laboratory tests, at present 130 lm/W

Present recommendations in Sweden state that the maximum installed lighting power requirement should not to exceed 2 W/100 lux per square metre floor area.

Example: In a 10 m^2 office with an illuminance requirement of 500 lux, the installed lighting power should not exceed 100 W or 10 W/m^2.

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COMMENT

Every employer regards increased productivity and fewer days lost through sickness as highly desirable factors, as they result in increased profitability. As the indoor environment has an important effect on performance, efficiency, well-being and health, tenants are already demanding improved indoor climates and environments. Property owners who have understood and accepted these needs find it easier to rent out their buildings and can also demand higher rents than owners who have not understood or accepted the connections.

EPILOGUE

The *Swegon Air Academy* hopes that this book will, to some extent, contribute towards an increased understanding of how a good indoor climate can help to make a building comfortable, efficient and profitable. We also hope that this book will increase understanding between the different players in the building industry and pave the way for an even better dialogue between property owners, architects, builders, consultants and installation contractors.

The chapters that discuss the present energy situation and how we ourselves affect the outdoor climate will, hopefully, cause us to reflect on these issues and stimulate active engagement. We can hardly prevent climate changes but we can join together to try and reduce them.

We would like to take this opportunity to thank all those who have made this book possible. In addition to all the contributing authors, we would like to thank Dr. Per-Erik Nilsson and his colleagues at CIT Energy Management for their valuable advice and especially Dr. Lars E. Ekberg, both for contributing three chapters and for his careful scrutiny of the other author's contributions.

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numerous ideas and suggestions, as well as a good dose of encouragement when I was almost ready to give up.

With your help and that of the authors, the result has not been a dry textbook but a timeless publication with a soul of its own. You don't have to read it from cover to cover in one go: read it as you please - just pick out a suitable chapter and satisfy your curiosity!

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The *Swegon Air Academy* is a forum for objective and company-neutral sharing of knowledge and experiences related to air handling and indoor climate issues.

One of our primary goals is to explain complex relationships in an intelligible way, so that those who are interested in a subject can understand it at a deeper level.

Via seminars, newspaper articles and literature, the *Swegon Air Academy* contributes to a greater awareness of the importance of indoor air quality for health and well-being, to an increased understanding of the energy issue and to a higher level of involvement in matters concerning the outdoor environment.

The *Swegon Air Academy* provides information and educational activities all over Europe and co-operates with well-known experts in relevant fields.

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