Identifying and managing indoor-air problems

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Determining how to identify and manage indoor-air problems may appear straightforward. Instrumentation is nowadays capable of detecting pollutant concentrations at levels far below those considered to be a health hazard. Sophisticated, computer-controlled "smart" building systems are also available that enable parameters within large, multi-zone buildings to be set and maintained at required levels and that control other variables related to operating the buildings in response to outdoor climate. Buildings can also be designed so that indoor-air problems are prevented initially. Nevertheless, the frequency of media headlines on the consequences of indoor-air and indoor-environment problems indicates that much is still to be done in identifying and managing indoor-air deficiencies. This paper explores the causes behind indoor-air problems, particularly when measurements do not identify any problems and everything has been done properly. On the basis of the given illustrations, options for ensuring good air quality in complex and ever-changing indoor environments are discussed in this paper.

Key terms building system; health guideline; infection; occupational environment; submicrometer particle; ventilation.

Identifying indoor-air problems

It has been well known for centuries that certain natural processes, as well as human activities, can result in indoor-air pollution at levels dangerous to human health and life, particularly in occupational environments. Studies of the history of air pollution reveal that many attempts have been made to find ways to prevent identified indoor-air problems. For example, it has long been known that some underground mines have the potential for elevated carbon monoxide levels that create a risk of carbon monoxide poisoning. In the absence of carbon monoxide monitors in the early days of mining, caged canaries were hung in the mines. These small birds, particularly susceptible to carbon monoxide poisoning, were a good indicator of the presence of gases in the air. If the bird died, it was a signal for the miners to leave the mine.

Another example was the identification of the long-term effects that resulted from occupational exposures to asbestos. Recognition of the hazard goes back to Roman times, when the historian Pliny the Elder (AD 23–79), Roman officer and author of *Natural History,* and the geographer Strabo recommended that slaves from asbestos mines not be purchased because they "die young". They also suggested that miners use a respirator, made of transparent bladder skin, to protect themselves from asbestos dust (1). It is interesting to note, however, that it was not until 1971, when the first asbestos-exposure standard of the United States (US) Occupational Safety and Health Administration was issued, and not until 1973, when the US Environmental Protection Agency banned spray-on asbestos insulation, that asbestos was claimed to be an air pollution hazard.

Nowadays, we have much better methods for identifying problems with indoor-air quality and, in particular, for measuring a broad range of indoor-air pollutants, including volatile and semivolatile organic compounds, particulate matter, inorganic gases, inorganic trace elements and metals, mineral fibers, biological agents, radon, photochemical oxidants, and the like. We can also measure many indoor-air parameters of relevance to human health and well-being with high precision, such as temperature, relative humidity, airflow, air exchange rate, noise, or light. Modern methods for the management of indoor-air problems have been outlined in numerous national and international publications, with some examples including the World Health Organization's air-quality guidelines (2), Health Canada's exposure guidelines for residential indoor-air quality (3), the American National Standards Institute's and

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the American Society of Heating, Refrigerating and Air-Conditioning Engineers' standards 62.1 and 62.2 for ventilation and acceptable indoor-air quality (4, 5), European standards 13779 and 15251 for building design and ventilation performance (6, 7), the International Society of Indoor Air Quality and Climate's guidelines for biological indoor-air quality (8), the Finnish Society of Indoor Air Quality and Climate's classifications for indoor climate (9), and the Federation for European Heating and Air-Conditioning Association's guidelines for ventilation and hygiene (10).

Thus, considering the powerful tools available for detecting and managing indoor-air quality, can we be reassured that that the quality of indoor environments is acceptable, if all the measurements conducted indicate that this is the case? Unfortunately not always! Examples of problems with indoor-air pollution or building-related health problems follow.

Cancer cluster in the ABC television station in Brisbane

Between 1995 and 2005, 10 cases of breast cancer were identified in the ABC television studio at Toowong (11). These 10 cases represented 11 times the normal incidence rate. Indoor-air pollution was tested, as well as radio frequency emissions and electromagnetic radiation. No cause was found. However, as a preventive measure, the staff was relocated to new premises.

Health problems in houses in Germany

A high incidence of headache and dermal burn linked to wooden furniture was investigated by the Fraunhofer Institute for Wood Research in the late 1990s and early 2000s (Dr Tunga Salthammer, personal communication). Many measurements were conducted, initially without an explanation as to the cause being provided. In this case, a cause was eventually identified, when it was shown that exposure of the wooden furniture, which had been cured by ultraviolet light, to sunlight, resulted in a "postcuring" of volatile solvents, the result being secondary emissions and thus the deterioration of indoor-air quality.

Problems with indoor-air quality in Santa's Park in Rovaniemi, Finland

Early in 2007, Santa's Park in Rovaniemi, Finland, was closed after elevated levels of mold and bacteria were identified and then widely publicized by the local media. It was shown that the mineral wool from the sound insulation in the building had been exposed to leaking water, which provided grounds for microbiological growth. While no health effects of this occurrence were reported at the time, the cost of replacing the faulty system, in order to prevent the indoor-air quality from deteriorating was estimated to be EUR 700 000.

The preceding examples, and many other reported problems with indoor-air quality and related heath complaints, show that problems with indoor-air quality can exist even when everything has been done properly and appears to be working correctly, even if standard measurements do not identify them. There are several reasons, for example, (i) indoor environment systems are often too complex to foresee all potential interactions, (ii) humans are affected by concentrations lower than those prescribed by health guidelines or standards, and (iii) new sources of pollution can often be introduced.

Specific aspects of indoor-air problems

A further exploration of potential problems related to indoor-air quality has found the following three specific aspects to be of significant importance: (i) the impact of outdoor air on the indoor environment; (ii) indoor-air sources, and (iii) indoor spread of infection. The following discussion centers on exposures occurring in typical offices or workplaces. In other words, it does not include industrial environments in which specific processes take place or specific substances are manufactured or used. In such environments, the problems of risk associated with air pollution are likely to be recognized and adequately managed.

Impact of outdoor air on the indoor environment

Indoor-air pollution cannot be considered in isolation from outdoor-air pollution, as outdoor air penetrates indoors, bringing in many airborne pollutants present outside and providing a continuous indoor pollution background. Factors such as air exchange rate, penetration rate, filter efficiency, and deposition rate can modify these concentrations, and, as a result, indoor concentrations of pollutants that come from outside are usually lower than the concentrations outside. For example, for naturally ventilated buildings in the absence of any indoor sources, indoor air can still contain 50–100% of the particulate matter found outdoors. Two specific examples follow.

Air quality in surgical theaters. Measurements of particle concentrations in the surgical theaters of a hospital, surrounded by busy roads, showed that the levels were higher than what would be expected in such environments (12). Investigations were conducted to identify any additional sources of particulate matter, the initial hypothesis being that the sources were indoors. However, in-depth investigations showed that the indoor concentrations of particles were closely related to outdoor concentration levels.

Indoor-air problems in a radio station. Indoor particle number and concentrations of particulate matter with an aerodynamic diameter of <2.5 µm ($PM_{2.5}$) in a radio station, surrounded by busy roads, were investigated (13), and the results indicated that the indoor particle number and $PM_{2.5}$ concentrations were governed by the outdoor air and significantly affected by the location of air intake and the design of the heating, ventilating, and air conditioning (HVAC) system. While no health effects were investigated, the presence of a black powder deposit on indoor surfaces was reported, as well as the frequent failure of instrumentation within the building. As a mitigation measure, it was recommended that the air intakes for the building be relocated to a position that was shown to be less affected by outdoor pollution. By relocating the air intake of the HVAC, the outdoor particle number and $PM_{2.5}$ concentrations near the air intake were reduced by 35% and 55%, respectively. In addition, the penetration rate for particle number was reduced from 42% to 14%, and the overall filtration efficiency of the HVAC system increased from about 58% to 86%. For $PM_{2.5}$, the penetration rate after the upgrade was approximately 18%, and the overall filtration efficiency was about 82%.

These two examples illustrate that, under certain circumstances, (i) outdoor particles and air pollution were the main contributors to indoor particle levels (both in the hospital and in the radio station), and (ii) using a comprehensive approach, including the assessment of outdoor conditions and the characterization of ventilation and filtration parameters, satisfactory indoor-air quality could be achieved, even for indoor environments facing the challenge of poor outdoor air conditions.

Indoor-air sources

There have been many more studies investigating the contribution of indoor sources in residential environments than in occupational settings. A recent literature review conducted by Morawska & He (14) showed that most of the studies that have investigated individual sources concluded that the highest impact was from smoking, cooking, and general activities (such as vacuuming, dusting and sweeping, heating, walking, etc). This conclusion supports earlier findings from three major US studies on the impact of these sources and is summarized in a review by Wallace (15). However, in the same review, the author also concluded that a substantial portion of the indoor particles was due to unexplained indoor sources. It was estimated, through mass balance modeling, that the contribution from unidentified sources was in the range of 25% to 30% of the particle matter present in the indoor environment.

In the occupational environment, the sources are different. For example, smoking is becoming more frequently prohibited (in countries like Australia or Canada smoking is not permitted in any public places, including any type of occupational environment). Therefore, if cigarette smoke is removed as a potential indoor source, then what are the indoor pollution sources of significance in typical work environments, such as offices or schools? Below are two specific examples.

Printers in an office environment. A study (16) showed that office printers could be the main source of submicrometer particles in a large mechanically ventilated office building, where tobacco smoking was prohibited. Not all printers are submicrometer particle emitters; however, about 30% of the printers investigated were classified as high emitters. Ultrafine particles constituted about 98~99% of the total submicrometer particles emitted from the printers classified as medium and high emitters, based on the emissions of the submicrometer number of particles. However, the high standard deviation of the average emission rates estimated in this study also indicated that the particle emission process and the behavior of printers are complex and that they are still far from being completely understood. Many factors, such as printer model, printer age, cartridge model, and cartridge age may affect the particle emission process, and they require further study.

Formation of secondary particles indoors. Reactions of ozone with terpenes (d-limonene and α-pinene) lead to the formation and subsequent growth of nuclei mode particles. Terpenes are often present in detergents, cleaner's paints, fragrances (scented oil air freshener), floor polishes, and the like. Recent studies, conducted mainly in chambers and modified offices, showed that, when the conditions for the reaction were achieved, the formation of these particles occurred rapidly, resulting in an increase in indoor concentrations by one to two orders of magnitude over the background level (17, 18). While, so far, there have not been enough studies conducted in occupational environments, the studies conducted to date show that such processes are likely to occur in real environments, as the conditions of some of the studies were comparable with real conditions in many typical offices.

These two examples show that there are many possible sources of indoor pollutants in a typical work environment. The questions that can be asked include (i) are the two preceding examples the only indoor sources to cause surprise in terms of pollution emissions and (ii) how significant are the pollution levels generated by such sources? Obviously, the concentrations depend on many factors, the ventilation rate being the most important. However, in relation to the example of the office printers, workers who spend an average 8-hour day in a poorly ventilated office, with printers operating frequently, may be inhaling concentrations of particles well above those present in office buildings situated next to busy roads or similar to the levels when cigarette smoke is present.

Indoor spread of infection

Everyday, tens of millions of people worldwide suffer from various types of viral infections. Economic losses due to these viral infections are astronomic and include the costs of medical treatment for the infected people, lost income due to the inability to work, and decreased productivity on the part of those infected, yet continue to work. There are many pathways through which infection spreads, and among the most significant is airborne transport. Microorganisms can become airborne when aerosol droplets are generated and released during speech, coughing, sneezing, vomiting, or the atomization of feces during sewage removal and treatment. In addition to the physical properties of these droplets, physical characteristics of the indoor environment, such as temperature, humidity, and airflow characteristics, as well as the design and operation of building ventilation and filtration systems, are critically important in terms of their effect on the indoor spread of infection. Therefore, do we understand the mechanisms involved in the spread of infection, and can we quantify the droplet dynamics in the air under various indoor environment conditions? Unfortunately no, as this aspect of infection spread has attracted surprisingly little scientific interest (19). This example was dramatically illustrated during the recent epidemic of SARS (severe acute respiratory syndrome), in which it was not possible to pinpoint how the virus was spreading. As a result of extensive retrospective analysis, several hypotheses were presented about the mechanism of virus transport in this environment, although no direct evidence was produced (20).

In summary, the available evidence for the indoor spread of infection, while convincing, is only indirect, and there is a pressing need to develop a better understanding of the mechanisms involved. It is known that setting the key building parameters according to the current understanding of their optimal ranges would also result in lowering the potential for the spread of infection, although whether this is the limit of what can practically be achieved in the minimization of infection spread is not known. The provision of scientific knowledge on infection spread is important not only in relation to the spread of viruses like SARS or avian flu, which poses a new hazard, but also to the spread of many other widespread viral infections, like the common cold or flu.

Concluding remarks

How can indoor-air pollution be prevented? The most obvious steps in the prevention of indoor-air pollution include ensuring that (i) the design and operation of the building is according to the state of the art in relation to building application and conducted activities, (ii) building performance is according to the specifications in relation to pollutant concentrations and operating parameters, and (iii) steps i and ii are routinely monitored.

How can indoor-air problems be identified and managed? Even if the aforementioned preventive steps are taken, there is the potential for indoor-air problems to still occur, due to the various reasons outlined previously. In such cases, it is important to (i) be aware that there still could be problems, (ii) not ignore warnings or indications of problems, particularly if related to symptoms of human ill health, and (iii) be innovative and open to novel methods of investigation.

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