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Challenges in developing ventilation and indoor air quality standards: The story of ASHRAE Standard 62

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ABSTRACT

Building ventilation has long been recognized for its role in occupant health, comfort and productivity, with some of the first recommendations on building ventilation rates published in the 19th century. These recommendations were subsequently transformed into more rigorous standards and guidance in the 20th century, with the first version of ASHRAE Standard 62 published in 1973. Since that time, ventilation standards have been issued in several countries around the world and have dealt with an increasingly complex and challenging range of issues as research on indoor air quality and the state of knowledge of building performance have progressed. This paper reviews and discusses some of the issues that have been addressed in the development of ventilation standards in recent years, using the development of ASHRAE Standard 62 as context, including: the scientific bases for ventilation requirements, perceived indoor air quality, contaminant sources from occupants and the building, outdoor air quality, airborne contaminant limits, indoor carbon dioxide concentrations, environmental tobacco smoke, and performance-based design. Issues that are expected to be dealt with as Standard 62 and other standards are developed into the future are also reviewed.

1. Introduction

Indoor air quality (IAQ) goals in designing and operating buildings focus on providing healthful and comfortable indoor environments. These goals are pursued by providing outdoor air ventilation to dilute internally generated contaminants to levels that are not harmful to human health and that do not negatively impact occupant perceptions of the indoor environment. In addition, other measures address the reduction of indoor contaminant sources and the removal of contaminants that are released in occupied spaces through, for example, moisture management, filtration and local exhaust. Many of these ventilation and contaminant control measures are included in ventilation standards such as ANSI/ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.1, Ventilation for Acceptable Indoor Air Quality [1]. Given that many ventilation and IAQ standards are written in the form of minimum requirements, other resources such as guidance documents are also useful in supporting IAQ goals [2]. Ventilation recommendations and standards have a long history, as summarized in this paper, which has involved consideration of what constitutes good or acceptable IAQ, how much outdoor air is required to support IAQ goals, which indoor contaminants need to be addressed, and a range of other issues. This paper discusses several of the more significant issues involved in the development of ventilation and IAQ standards in recent decades using the development of ASHRAE Standard 62 to highlight these points. In addition, the paper addresses some of the more challenging issues that need to be dealt with in the future in Standard 62 and other standards.

1.1. Historical review of ventilation requirements

There have been several reviews of the development of ventilation requirements over the years [3–7]. These reviews typically start with the work of Lavoisier in the 18th century, in which he suggested that carbon dioxide (CO_2) buildup rather than oxygen depletion was responsible for “bad air” indoors. About one-hundred years later, Pettenkofer suggested that biological contaminants from human occupants were the problem and not CO_2. In the late 19th and early 20th century, Billings and his colleagues suggested ventilation rates of 15 L/s per person or higher based on hygienic concerns due to organic exhalations by occupants. These

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rates were adopted by many states in the U.S. and included in a model law developed by ASH&VE (American Society of Heating and Ventilating Engineers, ASHRAE's predecessor society). In response to questions regarding recommended ventilation rates, the New York State Ventilation Commission was formed in 1913 to study ventilation requirements in schools and other public buildings. Their report stated that the 15 L/s per person requirement was not justified and that 5 L/s to 7.5 L/s per person was adequate for classrooms. In the 1930s, Lehmberg, Yaglou and their colleagues conducted chamber experiments in which individuals judged body odor levels as a function of ventilation rates. This work showed that about 8 L/s per person controlled these odors to levels that weren't objectionable to persons entering the space from clean air environments.

While this historical body of work to understand building ventilation requirements is quite impressive, these recommendations didn't constitute a ventilation standard. That started to change in 1946 when the American Standards Association issued a standard that required lighting and ventilation in all habitable rooms through the use of windows [8]. That standard did not contain ventilation requirements, but it did contain an appendix (not part of the actual standard) with recommended ventilation rates when mechanical ventilation was employed in addition to the required windows. Those rates were 2.5 L/s m^2 in offices and 7.6 L/s m^2 in public buildings including schools, which translate to 50 L/s per person in offices and 22 L/s in classrooms based on the default occupancy densities in ASHRAE Standard 62.1-2013. The next phase in the development of ventilation and IAQ standards began with the publication of ASHRAE Standard 62-73, Standards for Natural and Mechanical Ventilation [9].

1.2. ASHRAE Standard 62

ASHRAE Standard 62, and its subsequent incarnations as Standard 62.1 (covering commercial, institutional and high-rise residential) and Standard 62.2 (low-rise residential), has served as one of the most prominent ventilation standards since it was first published in 1973 [9]. That first version of the standard contained “minimum and recommended air quantities for the preservation of the occupants' health, safety, and well-being.” (Note that the standard doesn't define the goals and criteria behind the minimum and recommended ventilation requirements.) The bulk of the standard is in the form of a table with these ventilation rates for 271 individual space types. The large number of space types and the ability to arrive at ventilation rates for each space type is quite impressive, but the justification for the individual values was not documented. Ventilation rates for office spaces have historically been of interest, and the 1973 standard had a minimum requirement of 7.5 L/s per person and a recommendation for 7.5 L/s–12.5 L/s per person. Classrooms had a minimum requirement of 5 L/s per person and a recommendation for 5 L/s–7.5 L/s per person.

A number of other countries, primarily in Europe, issued ventilation and IAQ requirements starting in the 1980s and 1990s [10,11]. Most of these documents were standards and building regulations, but others were less formal guidance documents. The European Committee for Standardization (CEN) issued a standard for ventilation of non-residential buildings in 2007 [12], which is discussed later in this paper.

This first version of Standard 62 raised a number of issues which remained a challenge for subsequent versions and other standards for years to come: the roles of health and comfort, the use of standards in building codes and regulations, required ventilation rates, outdoor air quality and filtration, specific contaminants of interest, contaminant concentration limits, and performance approaches. These issues are discussed in this paper in the context of the development of ventilation and IAQ standards, focusing on ASHRAE Standard 62.

2. Issues in the development of ventilation and IAQ standards

This section reviews several issues that have been particularly challenging in the development of ventilation and IAQ standards using the development of ASHRAE Standard 62 to provide context, but other standards and documents are referred to as well.

2.1. Roles of health and comfort

As noted above, the first version of Standard 62 included the goal of preserving “occupants' health, safety and well-being” in its purpose statement. While subsequent versions of the standard clearly state that they were intended to address health, some individuals felt that the standard should only be about comfort and that ASHRAE, as an engineering society, should not consider health. These questions resulted in much discussion by the Standard 62 committee, as well as others in ASHRAE, primarily during the revision of Standard 62-1989. The ensuing controversy led to two ASHRAE presidential ad hoc committees tasked with addressing the role of health in ASHRAE standards and other activities, as well as a membership petition in 1999 that called to restrict all ASHRAE IAQ and ventilation standards to make no claims regarding “health, comfort or occupant acceptability [13].” In 2008, the ASHRAE Board of Directors posed several additional questions to the society membership to help clarify the intent in approving the 1999 membership petition, including a question as to whether ASHRAE standards should “… strive to provide health, comfort and/or occupant acceptability …” This particular question was approved by more than 80% of those ASHRAE members voting.

As a result of these discussions, the Board of Directors concluded that it was indeed appropriate for ASHRAE to consider health effects in developing standards as well as in its other activities [14,15], as it had been for decades, based in part on the statement in the society bylaws that ASHRAE exists to advance “the arts and sciences of heating, refrigerating, air conditioning and ventilating … for the benefit of the general public [16].” Ultimately, the ASHRAE Board of Directors approved a rule stating that IAQ and ventilation standards “shall not make any claims or guarantees that compliance will provide health, comfort or occupant acceptability, but shall strive for those objectives …” and that “ASHRAE standards shall consider health impacts where appropriate [17].” These actions helped to [illegible]e the controversy regarding the role of health in Standard 62 [illegible] ASHRAE standards in general.

This debate may be somewhat perplexing outside of the U.S. and ASHRAE, where the health impacts of indoor air and their importance are much less controversial. To that point, the WHO issued a report in 2000 declaring the human right to healthy indoor air [18]. Also, the European Committee for Standardization, or CEN, Standard EN 13779 “Ventilation for non-residential buildings - Performance requirements for ventilation and room-conditioning systems” makes it clear that its goals include both occupant comfort and health [12].

2.2. Adoption by building codes and regulations

ASHRAE Standard 62-73 was written as more of a technical statement on what constitutes acceptable ventilation and IAQ than as a clear set of requirements for use in designing and constructing buildings. While the ventilation rates are described as requirements, the inclusion of both minimum and recommended ventilation rates makes it unclear how the designer was expected to comply. Similarly, the standard contains many other requirements for which it would be very difficult to determine if compliance were achieved. For example, Section 4.2 states that "Outdoor air inlets shall be located to minimize or eliminate possible contamination." The idea behind this requirement is clear, i.e., locate inlets so as not to bring outdoor contaminants into the building, but the wording is extremely vague and it is not at all clear how one would comply or how the requirement would be enforced.

Over time it became evident that the impact of the standard would increase if the standard was adopted or referenced by building codes and other regulations. Such adoption was unlikely given the unclear and in some cases unenforceable requirements. Therefore, in 1997, the ASHRAE Board of Directors directed the Standard 62 committee to convert the document into a "code-intended" standard, writing it in mandatory, enforceable language. This change also meant that much useful information could not be included in the standard itself. That content, which included explanatory text and examples, had to be moved to either informative appendices that are not part of the actual standard or to user's manuals that were written as companion documents to the standard [19,20]. Examples of information that could not be included in Standard 62 are an explanation of the basis of the ventilation rate requirements and calculations of outdoor air intake requirements for multizone systems, all of which are contained in the user's manual. In the case of Standard 62.2, which covers low-rise residential buildings, ASHRAE developed a companion guideline containing a range of information to support good IAQ that in some cases go beyond the minimum requirements in the standard [21]. In order to provide similar guidance for buildings covered by Standard 62.1, ASHRAE partnered with several organizations to develop an IAQ guide covering design, construction and commissioning [2]. This document serves as a comprehensive IAQ resource, going far beyond minimum requirements. CEN Standard 13779 was not constrained by the code-intended goal, and therefore contains a wide range of informative material. In fact, its informative annexes, including one titled "Guidelines for Good Practice," are longer than the mandatory portions of the document.

The 1981 version of Standard 62 added a number of requirements related to ventilation systems and equipment. Many of these requirements were directed towards reducing contaminant source strengths, thereby supporting the expectation that the minimum ventilation requirements in the standard would be sufficient to provide acceptable IAQ. Most of these system and equipment requirements were difficult to enforce, but addressed a range of important topics including location of air intakes to avoid contamination, acceptable duct materials and construction, and capturing indoor contaminants as close to the source as practicable. In order to convert the standard into code-intended language, all of these requirements had to be rewritten. For example, the requirement to avoid entrainment of outdoor contaminants, was replaced by a table of minimum distances from outdoor air intakes to various outdoor sources such as cooling towers and loading docks. Similarly, requirements to deliver ventilation air to occupants were replaced by air change and system efficiency factors used to calculate outdoor air intake rates.

2.3. Ventilation rate requirements

Ventilation rate requirements for different space types have been revisited in subsequent versions of Standard 62 since it was originally published in 1973, as well as in other standards. The determination of these values has always been challenging based on limited research results to support specific values, pressures by some to lower rates based on energy considerations, and pressures by others to raise them based on IAQ benefits.

The 1981 version of ASHRAE Standard 62 replaced the minimum and recommended ventilation requirements with values for non-smoking and smoking spaces, with the latter being larger by roughly a factor of 2–5, depending on the space type [22]. The outdoor air requirements for office spaces were 10 L/s per person with smoking and 2.5 L/s per person without smoking, a factor of three lower than the minimum requirement in the 1973 standard. For classrooms, the outdoor air requirements were 2.5 L/s per person without smoking and 5 L/s per person with smoking, both significantly lower than the 1973 requirements. The decreased ventilation requirements in the 1981 standard were motivated in part by desires to reduce energy consumption in buildings.

ASHRAE 62-1989 eliminated the distinction between smoking and non-smoking spaces, requiring 10 L/s per person of outdoor air in offices and 8 L/s per person in classrooms. Those values stayed the same in the 1999 and 2001 versions of the standard [23,24]. The 2004 standard (designated as Standard 62.1, covering commercial, institutional and high-rise residential buildings) changed the form of the ventilation requirements to include both an outdoor air requirement per person and an outdoor air requirement per unit floor area [25]. These two requirements were multiplied by the number of occupants in the space and the floor area, respectively, and the two products were added together to determine the outdoor air requirement for the space. Using the default occupant densities in the standard, the office space ventilation requirement is 8.5 L/s per person. For classrooms covering ages 5 through 8 years, the minimum outdoor air requirement under the default occupancy is 7.5 L/s per person. In lecture halls with fixed seats, with a much higher occupant density, the outdoor air requirement is 4.0 L/s per person. These outdoor air requirements did not change in the latest version of the standard, 62.1-2013.

In 2004, Standard 62 was split into two standards, 62.1 covering commercial, institutional and high-rise residential buildings and 62.2 covering low-rise residential. The residential ventilation requirements in Standard 62-73 had a minimum ventilation requirement in general living areas including bedrooms of 2.5 L/s per person and a recommended range from 3.5 L/s to 10 L/s per person, with higher rates in kitchens, baths and toilet rooms. The 1981 standard required 5 L/s per room of outdoor air in general living areas. In 1989, the standard required an air change rate of 0.35 h^{-1} in living areas, but no less than 7.5 L/s per person, which remained in the standard through the 2004 version. The first version of Standard 62.2, Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings, was published in 2003 [26] and contained an outdoor air requirement of 3.5 L/s times the number of bedrooms plus one, with an additional 0.05 L/s per m^2 of conditioned space. That requirement remained in the standard through the 2010 version; the 2013 standard changed the additional requirement to 0.15 L/s per m^2.

Other international ventilation standards included a wide range of ventilation requirements in office spaces, from 3 L/s per person to about 10 L/s per person [10]. For classrooms, the requirements had a similar range of values, with most of them close to 8 L/s per person. Many countries used requirements for dwellings that are similar to those specified in Standard 62.2, though some used a lower value of about 4 L/s per person while others used a higher value of about 0.5 h^{-1}.

In 2007 CEN published Standard 13779 [12]. That standard doesn't set ventilation requirements but rather defines a framework for developing national standards, which employs four classes of IAQ from low to high. In an informative annex, outdoor air rates per person are presented for both smoking and non-smoking areas. The default value for the lowest class of IAQ is 5 L/s per person, increasing to 20 L/s per person for the highest class. The rates for smoking spaces are twice those for non-smoking.

In discussing these ventilation requirements and determining the values for inclusion in these standards, the responsible committees have considered available research results, past experience in designing and operating ventilation systems and, of course, various political and organizational factors. Summaries of the technical justifications are contained in the user's manual for Standard 62.1 and elsewhere [8,27]. As discussed in these references, these rates are based in part on the ventilation required to control odors from human bioeffluents, studied in the 1930s by Yaglou and colleagues as noted earlier. This research resulted in a recommended ventilation rate of 7.5 L/s–9 L/s per person to achieve a roughly 80% level of odor acceptability as judged by individuals entering the room from relatively clean air. Similar work was conducted in the 1980s and 1990s in North American, Japan and Europe, yielding similar results to those obtained by Yaglou. Starting with a minimum ventilation rate of 7.5 L/s per person to control body odor, ASHRAE Standard 62-1989 included an additional 2.5 L/s per person to control other contaminants, such as building materials and furnishings, but no specific technical justification for this increase was described [28].

This 10 L/s per person value is consistent with the recommended ventilation rate for office spaces in Standard 62-73, as well as the minimum requirement in the standard from 1989 to the present, but calls into question the minimum requirement of 2.5 L/s per person in the 1981 standard for non-smoking spaces. A lower ventilation rate can achieve acceptable levels of body odor perception for occupants who have been in the space long enough to adapt to those odors, but there is no explanation of that being the basis for the lower rates in the 1981 standard. For office buildings, research has shown that ventilation rates above 10 L/s per person are associated with lower rates of sick building syndrome (SBS) symptoms [29]. Another study focused on the impact of ventilation on worker performance, showing statistically significant improvements in performance for ventilation rates up to 15 L/s [30]. A subsequent study concluded that even higher rates, about 25 L/s per person, are associated with reduced SBS symptoms in offices [31], however no standards have yet adopted minimum rates close to that value. That same study cited evidence from Nordic homes suggesting that air change rates above 0.5 h^{-1} are associated with reduced symptoms of asthma and allergies. Such studies of associations between health outcomes and ventilation rates are challenging, resulting in only limited data for judging the health impacts of specific ventilation rates. In particular, while providing high quality environments in school classrooms is of great interest, data associating ventilation rates with health outcomes and student learning are extremely limited and not yet adequate to support specific ventilation rate requirements in standards [32].

The studies cited above suggest the benefits of higher ventilation rates in terms of reducing occupant health symptoms and increasing productivity, which are recognized in the USGBC LEED rating system by awarding an extra point for providing ventilation rates 30% above the minimum requirements in ASHRAE Standard 62.1 [33,34]. At the same time, some individuals have questioned whether the 10 L/s per person rate is higher than needed citing energy concerns and experience in designing buildings. From the author's experience on the 62.1 committee, some designers claimed they had designed buildings with less than 10 L/s per person without any increase in occupant complaints. However, no evidence supporting these claims was ever presented in the form of surveys of occupant satisfaction or measured ventilation rates or contaminant levels.

The following sections describe several issues that arose in the development of the ventilation requirements in Standard 62, specifically perceived air quality and combining ventilation requirements to control sources associated with people and sources associated with the building.

2.3.1. *Perceived air quality*

While ventilation standards were initially based on occupant dissatisfaction with human body odor, this focus had serious limitations. Other contaminants and sources clearly impact the acceptability of indoor spaces to occupants, as well as having important health impacts. In 1998, Fanger developed an approach to quantify perceived IAQ based on the level of occupant dissatisfaction caused by odors and airborne irritants from people, materials, smoking and other contaminant sources [35]. This approach defined two new quantities, the olf, which quantifies contaminant source strengths in terms of their impact on perceived air quality; and, the decipol, the perceived air quality in a space with a contaminant source strength of one olf and a ventilation rate of 10 L/s. Researchers subsequently quantified olfs emitted per unit floor area in different building types and from tobacco smoking in recognition of the importance of sources beyond human metabolism [27].

While the shift from considering only human body odor to considering perceived IAQ impacts from a range of sources was an important advance, the concept has limitations. Perceived IAQ does not account for important differences between contaminants and their unique health and comfort impacts, particularly imperceptible contaminants such as carbon monoxide (CO), and contaminants that have health impacts at concentrations below their odor and irritation thresholds. Nevertheless, perceived IAQ was used to support ventilation requirements for non-occupant sources in ASHRAE Standard 62 and CEN 13779. While these requirements only address sensory perception and oversimplify the complexities of contaminant emissions and differences between similar buildings, they constituted a significant change by explicitly acknowledging non-occupant sources.

2.3.2. *Addition of people and building rates*

A major focus in the revision of Standard 62-1989 was to update the ventilation requirements. These revisions were motivated by several factors: the existing material was written in non-mandatory language; new research results and practical experience were available; acknowledgement of the need to move beyond just bioeffluent control to consider other sources; and, a belief that the ventilation rates in densely occupied spaces were higher than necessary, and lower than advisable in sparsely occupied spaces. As a result, a new methodology for determining ventilation requirements was developed and first included in the 2004 standard. This approach, also used in the CEN 13779, specified two ventilation requirements for each space type, one per person and one per unit floor area. These requirements were multiplied by the number of occupants and the floor area, respectively, and the results added together to determine the outdoor air requirement of the space. The per person ventilation requirements were selected to control contaminant sources associated with the number of occupants, including but not limited to body odor, and the floor area requirements were based on contaminant sources associated with the size of the space, such as materials and furnishings. The basis for the rates themselves are described in some detail in reference [19].

In developing these changes to the Ventilation Rate Procedure, several issues were discussed extensively by the Standard 62 committee. First, given that the standard was being written for adoption by building codes, which aim for minimum levels of performance, the committee decided that the ventilation rates should be based on adapted occupants rather than individuals entering the space after exposure to clean air. Research has shown that after some time interval, building occupants adapt or become less sensitive to some odors, particularly body odor [36,37], such that 2.5 L/s per person can control body odor to acceptable levels. However, as noted in these same references, occupants do not become adapted to all contaminants over time and may even become more sensitive. The minimum approach to these ventilation rates also led to the floor area rates being based on “low-polluting” buildings [38,39], rather than on more typical levels of emissions associated with building materials and furnishings. Both of these decisions were made based on the fact that the standard is providing minimum requirements. Designers can of course exceed these requirements, for example by ventilating for visitors rather than adapted occupants, which may be desirable in retail buildings for example.

The other contentious issue in revising the Ventilation Rate Procedure was the addition of the people and building ventilation rates. The concept of additivity had been demonstrated in both laboratory and field settings [40–42]. In these studies, the authors measured the level of perceived IAQ from humans and different types of building materials and furnishings alone and in combination. They then compared the total source strength when the sources were combined with the sum of the source strengths of the individual sources. In general, the agreement was good, though not perfect. During the committee debate, some participants questioned the appropriateness of the additivity approach but the committee decided to use it. In part that decision was based on its value as a calculation method to deal with the two types of sources, those that depend primarily on the number of people and those that depend primarily on building floor area. This construct avoided the need to make assumptions about occupant density, which was important since occupant density can vary over a wide range within a single occupancy category. It also reduced the concerns about over- and under-ventilation of densely and lightly occupied spaces, respectively.

2.4. Outdoor air quality and filtration

It is well recognized that for ventilation to have a positive impact on IAQ, the air brought into the building must be relatively free of contaminants generated indoors as well as key outdoor air contaminants. This was recognized in Standard 62-73, and outdoor air quality has continued to be addressed as Standard 62 and other standards have evolved. In cases where the outdoor air quality is not acceptable for ventilating a building, particle filtration and gaseous air cleaning are recognized as the only solutions. However, requiring these strategies in standards presents challenges.

ASHRAE standard 62-73 defined acceptable air quality for ventilating buildings based on U.S. federal criteria promulgated in 1975 for several outdoor contaminants, plus odor as judged by a panel of 10 untrained subjects. Ventilation air was also considered unacceptable if the concentration of any contaminant exceeded one tenth of the threshold limit value (TLV) issued by the American Conference of Governmental Industrial Hygienists [43]. If the outdoor air did not meet these requirements, filtration or other air treatment was required to meet these criteria. However, the standard provides no detail on such filtration or air treatment equipment, such as required contaminant removal efficiencies. In addition to the EPA NAAQS (National Ambient Air Quality Standard) requirements for outdoor contaminant levels, Standard 62-1981 contained a table of limits for 28 additional compounds derived from “current practices in various states, provinces and other countries [22].” The requirement for outdoor air filtration or air cleaning when these criteria were not met remained as non-specific as it was in the 1973 standard. Similarly, Standard 62-1989 and 62-2001 did not contain specific requirements on how to deal with poor outdoor air quality. In fact, those documents said that air cleaning equipment “should” be used when the outdoor levels exceed the stated limits, which was definitely not mandatory language suitable for adoption by building codes.

Standard 62.1-2004 addressed outdoor air quality in much improved code language, requiring an assessment of outdoor air quality and nearby contaminant sources in all buildings, with the results of that assessment being reviewed with building owners or their representatives. It required particle filtration using MERV 6 or higher if the PM10 (particulate matter with a maximum diameter of 10 μm), levels exceeded the national standard and ozone filters of 40% efficiency or higher if ambient ozone levels were too high. The committee discussed other outdoor contaminants that are commonly at high concentrations, such as CO, but the lack of either practical air cleaning equipment or rating methods resulted in those contaminants not being addressed. Later versions of the standard refined the requirements under conditions of elevated outdoor particulate and ozone levels, but those substances are still the only two ambient contaminants explicitly covered in 62.1-2013.

2.5. Contaminant limits

As discussed later in the context of performance standards, indoor contaminant concentration limits could convert IAQ design to an engineering problem of achieving those limits through a combination of source control, air treatment and ventilation. However, the determination of concentration limits and their inclusion in ventilation and IAQ standards has always been a challenge given the limited information on health effects of different contaminants and contaminant mixtures in the concentration ranges of interest and for different human populations.

In the U.S., the Occupational Safety and Health Administration (OSHA) is a federal agency tasked with protecting worker safety and sets limits for many contaminants in industrial workplaces in the form of PELs (permissible exposure limits) [44]. On the non-governmental side, the American Council of Governmental Industrial Hygienists (ACGIH) issues TLVs (threshold limit values) for contaminant exposure in the industrial workplace [43]. These values, and similar limits in other countries, are based on protecting healthy, adult workers from health effects from exposures over eight-hour workdays. They are not applicable to non-industrial environments, e.g., offices, schools and residences, or to the general population including children, the elderly and those with pre-existing health conditions. It is also worth noting that while the U.S. EPA regulates outdoor contaminant levels, it does not have the authority to regulate indoor air. Both the OSHA PELs and ACGIH TLVs are usually well above odor thresholds, levels associated with sensory irritation, and levels associated with health effects to general populations [2]. Appendix B of ASHRAE 62.1-2013 explains the limits of using workplace concentration limits in non-industrial environments and for general populations [1]. That non-mandatory section of the standard also summarizes indoor contaminant values published by governmental and private sector organizations. A 2001 review of ventilation and IAQ standards lists a number of contaminant limits for outdoor and indoor air, for both industrial and non-industrial environments, but only the outdoor and industrial limits are from standards or regulations [10].

As noted above, ASHRAE 62-73 contained contaminant limits for air used for ventilation based on available outdoor air limits as well as one-tenth of the ACGIH TLV values. This one-tenth factor was not justified based on any specific exposure assessment or expected health outcomes, but nevertheless came to be viewed by some as having more technical justification than merited and was used in some IAQ programs as described in reference [2]. The 1981 standard included a longer list of outdoor air contaminant limits and required that for any other contaminants thought to be of concern, the outdoor air concentration should be limited to 1/10 of the OSHA levels. An appendix to the standard explained the use of this ratio based primarily on differences between industrial and general populations, but did not provide any specific technical justification.

ASHRAE Standard 62-1981 also introduced the Indoor Air Quality Procedure, the alternative, performance-based design approach, which is discussed below. As part of this procedure, the 1981 standard included a table entitled Selected Guidelines for Air Contaminants of Indoor Origin, which lists 20 compounds or classes of compounds but contained limits for only five of them: CO_2, chlordane, formaldehyde (HCHO), ozone and radon. All of the limits are referenced to a U.S. or other national government reference with the exception of CO_2. The CO_2 limit of 4500 mg/m^3 is discussed in an appendix, which notes (without reference) that 0.5% CO_2 is a good limit based on concerns about headaches and loss of judgment. A safety factor of two is used to account for variations in individual activity, diet and health, thus leading to the limit of 0.25% (equivalent to 4500 mg/m^3).

The 1989 version of Standard 62 also included the EPA ambient air quality standards for defining acceptable ventilation air and contained an appendix with a table of contaminant limits from air quality standards and guidelines, predominantly outdoor and industrial limits but also some guidance values for nonindustrial environments [45]. This appendix questioned the use of 1/10 of the TLVs for non-industrial environments, noting in particular that it won't protect “individuals who are extremely sensitive to an irritant.” The 1989 standard also contained a table of concentration limits for four contaminants (CO_2, chlordane, ozone and radon) for use with the IAQ Procedure. The CO_2 limit in the 1989 standard is 1800 mg/m^3, which is 60% lower than the value in the 1981 standard, but no explanation is provided for this reduction. The use and interpretation of CO_2 limits are discussed in the next section of this paper.

Subsequent versions of Standard 62 in 1999 and 2001 did not treat contaminant levels much differently than the 1989 standard, though the 1999 version removed CO_2 from the table of indoor contaminant limits. That table was removed entirely from the 2004 version of the standard, with all discussions of contaminants limits contained in informative appendices of the standard. The treatment of contaminant concentration limits has not changed significantly since the 2004 version of the standard.

As interest increased in the area of sustainable or “green” high-performance buildings, contaminants limits were included in programs and standards in a limited manner. Both the U.S. Green Building Council LEED rating system [33] and ASHRAE/USGBC/IES Standard 189.1 [46], Standard for the Design of High-Performance Green Buildings, include contaminant limits as an alternative to conducting a building flush out after construction but before occupancy. In the case of LEED, an extra point is obtained if a pre-occupancy flush out is conducted, or alternatively, if measured contaminant levels are within limits contained in a table. Standard 189.1 requires either a flushout or contaminant measurements that verify concentrations are within limits in its table. The table in LEED 2009 [34] included HCHO, PM10, TVOCs (total volatile organic compounds), 4-phyenycyclohexene (4-PCH) and CO. The more recent LEED v4 table contains the same limits for HCHO, PM10, TVOC and CO, but removes 4-PCH and adds PM2.5 (particulate matter with a maximum diameter of 2.5 μm) and individual VOCs based on the target chemicals in the California Department of Public Health (CDPH) Standard Method v1.1 [47]. The CDPH document is a standard for testing and evaluating VOC emissions from building materials in chambers and contains a list of maximum allowable concentrations for target VOCs that are equal to one-half of the Chronic Reference Exposure Levels (CRELs) issued by the California Office of Environmental Health Hazard Assessment (OEHHA). As stated in CDPH v1.1, these “CRELs are inhalation concentrations to which the general population, including sensitive individuals, may be exposed for long periods (10 years or more) without the likelihood of serious adverse systemic effects (excluding cancer).” The table in Standard 189.1 includes maximum concentrations for CO, ozone, PM2.5, PM10 and about 30 individual VOCs, but does not contain a limit for TVOC. The individual VOC limits are twice those in CDPH v1.1, which means they are the same as the OEHHA CRELs.

A detailed analysis of residential contaminant exposures by Logue et al. [48] highlights the fact that the OSHA PELs are much higher (several orders of magnitude in some cases) than several other non-regulatory exposure limits issued by the state of California and the U.S. EPA. That effort identified nine contaminants considered to be priority hazards based on available concentration data and the fraction of residences impacted, including HCHO and PM2.5.

Internationally, CEN Standard 13779 contains example guideline values for outdoor air pollutants in an informative annex but does not address indoor contaminant limits. The World Health Organization (WHO) issued guidelines for several indoor air pollutants in 2010. That report includes a review of the health effects and guideline concentrations for the following indoor air contaminants: benzene, CO, HCHO, naphthalene, nitrogen dioxide, polycyclic aromatic hydrocarbons especially benzo[*a*]pyrene (B[*a*]P), radon, trichloroethylene and tetrachloroethylene. Data for several other contaminants were noted as being insufficient to support concentration guidelines.

2.5.1. Carbondioxide

As noted in discussing the history of ventilation requirements, indoor CO_2 concentrations have had a prominent place in discussions of ventilation and IAQ since the 18th century. While indoor CO_2 concentrations are rarely close to any health guidelines (the ACGIH TLV is 9000 mg/m^3 over a 40-h work week and 54 000 mg/m^3 for a 15 min exposure), much confusion has resulted regarding CO_2 levels in ventilation and IAQ standards. As noted above, ASHRAE Standard 62-1981 contained an indoor CO_2 limit of 4500 mg/m^3 for use when applying the performance approach to complying with the standard, i.e., the IAQ Procedure. That limit was changed without explanation to 1800 mg/m^3 in 1989. CEN standard 13779 does not contain an indoor CO_2 limit, but an informative annex provides default CO_2 concentrations for its four classes of IAQ. The highest IAQ class is associated with concentrations about 700 mg/m^3 or less above outdoors, and the lowest class 1800 mg/m^3 or less above outdoors.

The 1800 mg/m^3 (roughly equivalent to 1000 ppm$_v$) value became a de facto standard in many applications without a sound understanding of its basis [49]. This reference notes the existence of anecdotal discussions associating CO_2 concentrations in this range with occupant symptoms such as stuffiness and discomfort, along with the fact that peer-reviewed studies do not support these associations with the CO_2 itself. While several studies have shown associations of elevated CO_2 levels with symptoms, absenteeism and other effects [50–52], these associations are likely due to lower ventilation rates elevating the concentrations of other more important contaminants in addition to CO_2.

The relevance of CO_2 concentrations to ventilation and IAQ standards is based on two factors: their relation to indoor levels of bioeffluents and associated odors, and their relation to ventilation rates per person. As discussed above, the control of body odor provides a basis for ventilation requirements on the order of 7.5 L/s per person. Several studies of bioeffluent odor perception in chambers showed correlations of dissatisfaction with these odors and both ventilation rate per person and CO_2 level. As discussed elsewhere [49,53], the ventilation rate per person and the indoor CO_2 level are related based on a single-zone mass balance of CO_2. In a chamber or building with a uniform CO_2 concentration, those two quantities are related under steady-state conditions based on the CO_2 generation rate per person, assuming that the generation rate, ventilation rate and outdoor CO_2 concentration are all constant. This relationship has been discussed in Standard 62 since 1981, in which the steady-state equation is presented as follows: the outdoor air ventilation rate per person equals the CO_2 generation rate per person divided by the difference between the indoor and outdoor CO_2 concentrations. Based on a ventilation rate of 7.5 L/s per person and a CO_2 generation rate of 0.3 L/min, the indoor CO_2 concentration will be about 1300 mg/m^3 above outdoors. Using slightly different values of the generation rate and outdoor concentration, one arrives at the CO_2 concentration value of 1800 mg/m^3. The CO_2 limits in ventilation standards are related to recommended ventilation rates for body odor control under idealized, steady-state conditions, not to the health or comfort impacts of the CO_2.

While indoor CO_2 concentrations are typically well below values of interest based on health concerns, recent research has shown evidence of impacts on human performance. A chamber study of individuals completing computer-based tests showed statistically significant decreases in decision-making performance at CO_2 concentrations as low as 1800 mg/m^3 [54]. These experiments were carefully designed to expose the subjects to elevated CO_2 but not to other contaminants. This work has not yet impacted ventilation and IAQ standards, but if the findings are repeated in other studies, it may support changes in the future.

2.5.2. Environmental tobacco smoke

Indoor smoking and environmental tobacco smoke (ETS) exposure have been contentious issues in the development of ventilation and IAQ standards. Some of the controversy started with ASHRAE Standard 62-1981, which contained separate ventilation requirements for smoking and non-smoking spaces. The justification for those distinct rates is not documented, but they were replaced in 1989 by a single set ventilation rate requirements, which the standard stated were chosen to account for "a moderate amount of smoking." As noted earlier, CEN Standard 13779 includes both smoking and non-smoking ventilation rates in an informative annex, though the publication of this standard in 2007 occurred after many of the events described below.

The ventilation requirements for smoking spaces in ASHRAE Standard 62 through 1989 were intended largely to control the associated odor and irritation. Things changed when the U.S. EPA classified ETS as a known human carcinogen in 1993 [55]. Given the purpose of Standard 62 to "minimize the potential for adverse health effects," the carcinogenicity of ETS became an issue. The standard was being revised when EPA issued this classification and there was much discussion of how the revised standard should deal with ETS. An Emergency Interim Standards Action (EISA) was submitted to ASHRAE in 1997 to remove the phrase regarding a moderate amount of smoking based on the carcinogenicity of ETS [56]. An EISA allows the ASHRAE President to correct an error to a standard if that error would "constitute undue risk to health or safety of the public or users of the standard or guideline." In 1998, the ASHRAE President at the time declined to act on this EISA, and the committee discussions of ETS continued.

When Standard 62 was republished in 1999, the statement that the ventilation rates accommodate a moderate amount of smoking was removed. The approval of that change was subsequently appealed to ASHRAE as well as ANSI (American National Standard Institute) and those appeals were denied. The table of ventilation requirements in Standard 62.1-2004 included a note that it "applies to no-smoking areas." A separate requirement stated that "smoking areas shall have more ventilation and/or air cleaning than comparable no-smoking areas" but that the amount of additional ventilation "cannot be determined until cognizant authorities determine the concentration of smoke that achieves an acceptable level of risk." In addition, the 2004 standard prohibited recirculation of air from smoking areas to non-smoking areas. The requirement for additional ventilation and air cleaning was deleted from the standard in 2009, such that the table of ventilation requirements applied to only ETS-free areas. Standard 62.1-2010 included additional requirements to limit the movement of air from ETS areas to ETS-free areas in the form of engineering controls such as partitions and pressure relationships.

Since that time there has been much less controversy related to smoking in Standard 62. The ASHRAE Board of Directors approved a policy that "ASHRAE standards and guidelines that address ventilation or indoor air quality in their purpose shall not prescribe ventilation rates in smoking spaces or claim to provide acceptable indoor air quality [17]." LEED 3.0 had the option of either prohibiting smoking in all spaces or restricting it to designated smoking areas which are isolated from the rest of the building, as well as prohibiting outdoor smoking within 7.5 m of building entrances, outdoor air intakes and operable windows [34]. LEED v4 removed the option for designated smoking areas except in residential applications, where smoking is still prohibited in common areas and compartmentalization is required between dwelling units to "prevent excessive leakage between units [33]." ASHRAE/USGBC/IES Standard 189.1 does not allow smoking inside buildings, requires signage to that effect at building entrances and restricts any outdoor smoking areas to be at least 7.5 m from entrances, intakes and windows [46].

2.6. Performance approach

One of the most significant changes included in ASHRAE Standard 62-1981 was the addition of the IAQ Procedure, an alternative, performance-based design approach in which one controls contaminant concentrations rather than complying with a table of prescriptive ventilation rates in the more familiar Ventilation Rate Procedure. The IAQ Procedure was developed to encourage innovative building and system design as well as technology development. It also allows a designer to meet higher performance goals for IAQ than the minimum requirements in the Ventilation Rate Procedure. However, there are significant challenges in using the IAQ Procedure, specifically identifying the contaminants on which to base the design, specifying acceptable concentrations and source strengths for those contaminants, and establishing an approach for evaluating IAQ from a subjective perspective, i.e., odor and perception.

The IAQ Procedure in the 1981 standard contained short discussions of different types of contaminants and the use of subjective evaluations for contaminants that can't be assessed objectively, but there are no actual requirements. The IAQ Procedure in the 1989 standard contains more detail (including tables of contaminant concentration limits as discussed previously) and a description of how to adjust the outdoor ventilation rate when using air cleaning, but the actual requirements are minimal. As the 62 committee converted Standard 62-1989 to code-intended language, this section was rewritten in the form of mandatory, enforceable requirements.

The IAQ Procedure in the 2004 version of Standard 62.1 was written in code language and consists of much more rigorous requirements: define contaminants on which the design will be based and the indoor and outdoor sources of each, identify the emission rate for each source, define target concentration limits for each contaminant, and select criteria for perceived IAQ in terms of the percentage of building occupants or visitors expressing satisfaction. Four acceptable design approaches are then described: mass balance analysis; approaches that have proved successful in similar buildings; validation by contaminant monitoring and subjective evaluations by occupants in completed buildings; and combinations of one of the previous three approaches for specific contaminants and the Ventilation Rate Procedure for general IAQ control. The IAQ Procedure has been revised further in subsequent versions of Standard 62.1, becoming more demanding along the way. For example, Standard 62.1-2010 requires the use of mass balance analysis and subjective evaluation in all cases.

The IAQ Procedure has been criticized as requiring data on source strengths and contaminant limits that isn't yet available. Also, some have raised the possibility that there could be contaminants that are not anticipated in the design and that result in unhealthy IAQ conditions. That possibility certainly exists, but while use of the Ventilation Rate Procedure achieves compliance with the standard regardless of the contaminants that may be present, IAQ problems could still exist if there are unanticipated or unusual contaminants. The scope of the standard acknowledges that compliance with the standard may not result in acceptable IAQ for a variety of reasons, such as the diversity of sources and contaminants. Therefore, the problem of non-design contaminants can be problematic for both the IAQ and Ventilation Rate Procedures.

Discussions of the IAQ Procedure also question how often it is really applied and whether designs are in compliance with the standard. Most of the published applications relate to the use of air cleaning technology to reduce outdoor air intake rates below those required by the Ventilation Rate Procedure [2,57,58]. Low ventilation rates are attractive in terms of reduced energy consumption and system costs, which is one key motivation for performance approaches. Interest in lower ventilation rates motivated a study in three big-box retail stores in which the IAQ Procedure was employed to evaluate whether the use of outdoor air intake rates below those based on the Ventilation Rate Procedure could control the levels of several contaminants and maintain occupant satisfaction [59]. Based on consideration of CO, HCHO and TVOC, the ventilation rates required to maintain these contaminants below the specified limits were about one-quarter of those based on the Ventilation Rate Procedure. As noted in that paper, the ventilation rate determined using the IAQ Procedure is highly dependent on the contaminant limits employed. For example, if the California OEHHA HCHO limit of 9 $\mu g/m^3$ is specified [60], the IAQ Procedure results in a ventilation requirement that is three times higher than the Ventilation Rate Procedure.

It is worth nothing both LEED and Standard 189.1 require use of the Ventilation Rate Procedure to determine minimum ventilation requirements [33,46]. LEED has an alternative compliance path based on the IAQ Procedure available for pilot testing, but it would benefit from further development [61].

3. Future development of ventilation standards

While ventilation and IAQ standards have progressed since the ASA standard in 1946, there are many areas where further improvement is needed. These areas include a more practical performance approach than the current IAQ Procedure, which better recognizes the differences between buildings, contaminant sources and design goals. However, an improved performance path will require more data on contaminants, contaminant mixtures, source strengths and IAQ control technologies such as gaseous air cleaning, as well as health-based contaminant limits that account for the variations among building occupants. It should be noted that the European Committee is developing health-based ventilation guidelines that should provide a more sound basis for future ventilation standards. The report of this effort has not yet been published but information is available in reference [62].

In addition, given that good building performance, including IAQ, depends on more than just building design, future standards will have more of an impact if they address operation and maintenance (O&M) of buildings and systems. While Standard 62.1-2013 has an O&M section, and Standard 189.1 has requirements for plans for operation, they could both be improved by moving beyond mostly system issues to more general building performance and source control issues (e.g. cleaning) and to existing buildings rather than focusing mostly on design. Finally, given the focus on high performance buildings, it will be important to provide high performance IAQ standards. Standard 189.1 is intended to meet high performance goals but its IAQ requirements are largely based on Standard 62.1, which is a minimum standard. More work is needed to define high performance IAQ and to develop standards that will support it [63].

4. Conclusions

The development of ventilation and IAQ standards has progressed significantly since the first ventilation standard was issued almost 50 years ago, but more work is needed to make the standards more successful in supporting better indoor environments in buildings. Many of these improvements will require additional research into the health effects of contaminants and contaminant mixtures, source strengths in buildings, the performance of IAQ control technologies and new design approaches. Ultimately, these standards need to recognize the differences between buildings and between occupants to support more flexible design approaches, while also meeting the needs of policymakers, regulators, building owners and designers who are striving to provide high-performance, sustainable buildings for the people who occupy them.

5. Disclaimer

Certain commercial programs and documents are identified in this paper in order to fully describe the concepts therein. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the programs and documents identified are necessarily the best available for the purpose.

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