International Energy Agency

Demand Controlled Ventilating System

State of the Art Review

Energy Conservation in Buildings and Community Systems Programme

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Preface

International Energy Agency

The International Energy Agency (IEA) was established in 1974 within the framework of the Organization for Economic Co-operation and Development (OECD) to implement an International Energy Programme.

As one element of the International Energy Programme, the participants undertake co-operative activities in energy research, development and demonstration. A number of new and improved energy technologies which have the potential of making significant contributions to our energy needs have been identified for collaborative efforts. The IEA Committee on Energy Research and Development (CRD), assisted by a small secretariat staff, co-ordinates the energy research, development and demonstration programme.

Energy Conservation in Buildings and Community Systems

The IEA sponsors research and development in a number of areas related to energy. In the area of energy conservation in buildings, the IEA is sponsoring various exercises to more accurately predict the energy use of buildings, including:

- comparison of existing computer programs
- building monitoring
- comparison of calculation methods, ventilation and air quality
- studies of occupancy

Sixteen countries and the Commission of European Countries (CEC) have elected to participate in this area and have designated contracting parties to the Implementing Agreement that covers collaborative research in this area. Participation was not restricted solely to governments, but a number of private organizations, universities and laboratories were selected as contracting parties. This brought a much broader range of expertise to projects in various areas of technology. The IEA recognizes the importance of associating industry with government-sponsored energy research and development, and every effort is made to encourage this trend.

The Executive Committee

Overall control of the R&D programme Energy Conservation in Buildings and Community Systems is maintained by an Executive Committee, which not only monitors existing projects but identifies new areas where collaborative effort may be beneficial. The Executive Committee ensures that all projects fit into a predetermined strategy without unnecessary overlap or duplication, but with effective liaison and communication. The Executive Committee has initiated the following projects to date:

1 Load Energy Determination of Buildings •

2 Ekistics & Advanced Community Energy Systems •

3 Energy Conservation in Residential Buildings *

4 Glasgow Commercial Building Monitoring *

5 Air Infiltration and Ventilation Centre

6 Energy Systems & Design of Communities *

7 Local Government Energy Planning •

8 Inhabitant Behaviour with regard to Ventilation *

9 Minimum Ventilation Rates •

10 Building HVAC Systems Simulation •

11 Energy Auditing •

12 Windows and Fenestration •

13 Energy Management in Hospitals

14 Condensation

15 Energy Efficiency in Schools

16 BEMS 1 - User Interfaces & System Integration

17 BEMS 2 - Evaluation & Emulation Techniques

18 Demand Controlled Ventilating Systems

19 Low Slope Roof Systems

20 Air Flow Patterns

21 Thermal Modelling of Buildings

22 Design of Energy Efficient Communities & Urban Planning

(* denotes completed projects)

Annex 18 Demand Controlled Ventilating Systems

The subject of indoor and outdoor air quality has generated a great deal of attention in many countries. Areas of concern include outgassing of building materials as well as occupant-generated pollutants such as carbon dioxide, moisture and odours.

Progress has also been made towards addressing issues relating to the air tightness of the building envelope. Indoor air quality studies indicate that better control of supply flow rates as well as the air distribution pattern within buildings are necessary. One method of maintaining good indoor air quality without extensive energy consumption is to control the ventilation rate according to the needs and demands of the occupants, or to preserve the building envelope. This is accomplished through the use of demand controlled ventilating (DCV) systems.

The specific objective of Annex 18 is to develop guidelines for demand controlled ventilating systems based on state of the art analyses, case studies on ventilation effectiveness, and proposed ventilation rates for different users in domestic, office, and school buildings.

To fulfil this objective, the work was divided into the following subtasks:

Subtask A	Review of existing technology
Subtask B1	Long term testing of the performance of sensors in laboratory and field
B2	Trials in unoccupied test buildings or test rooms
B3	Field trials in occupied buildings
Subtask C	Preparation of a source book on design and operation of demand controlled ventilating systems

The activities of Annex 18 are a follow-up to the work undertaken by Annex 9 to establish minimum ventilation rates for buildings.

Annex 18 - Participants

The participants will undertake a co-ordinated effort, involving the sharing of activities within the Subtasks. Each participant will deliver a product of its own to provide support to all Subtasks. The participating countries are:

Belgium	
Canada	leader of Subtask B3
Denmark	
Federal Republic of Germany	leader of Subtask A
Finland	
Italy	leader of Subtask B2
The Netherlands	
Norway	
Sweden	operating agent leader of Subtasks B1 and C
Switzerland	

1 Introduction

The work undertaken in Subtask A provides an assessment of existing technologies and current knowledge about DCV systems.

With regard to the specific goals of Annex 18 and the ongoing research work, a demand controlled ventilating (DCV) system is defined in the following way:

A DCV system is a ventilation system in which the air flow rate is governed by airborne contaminants.

- **An automatic DCV system is one in which the air flow rate is governed by an automatic control device.**
- **A manual DCV system is one in which the air flow rate can be governed by the user (a human being acts as an indicator).**

A DCV system can therefore consist of a time clock control, and/or a presence control, and/or a sensor control, where the latter is activated by suitable gases such as carbon dioxide, humidity or hydrocarbons to keep air quality at a desired level.

The following example demonstrates the potential of DCV systems. The calculations were done using a simplified model which is described in Appendix C, together with the basic hypotheses adopted.

The model is able to determine CO_2 concentration and air change rates (shown in Appendix C) for a number of different ventilation strategies. Table 1.1, summarizing the essential characteristics of the different systems, shows that DCV systems are able to maintain acceptable CO_2 concentration levels while requiring a minimum amount of fresh air. Conversely, other systems are either unable to maintain acceptable indoor air quality (IAQ) or they require an excessive amount of fresh air.

Table: 1.1: *Average and maximum CO_2 concentrations and average daily air change rates for different ventilation strategies.*

	average CO_2 concentration during occupation [ppm]	maximum CO_2 concentration [ppm]	average daily air change rate [h^{-1}]
STRATEGY A (constant air change rate)			
n = 0.1 h^{-1}	6500	9660	0.1
n = 2 h^{-1}	1280	1860	2.0
STRATEGY B (windows open)			
n = 0.1 h^{-1}	2250	5790	1.13
n = 2 h^{-1}	1200	1860	2.83
STRATEGY C (mech. ventil.)			
n = 3 h^{-1}	1020	1390	1.19
n = 5 h^{-1}	790	1000	1.92
STRATEGY D (DCV)			
1400 ppm	1370	1400	0.64
1000 ppm	980	1000	1.05

A DCV system provides a good compromise between energy conservation and indoor air quality.

Before effective DCV systems for various applications can be developed, the following questions must be answered:

- What types of pollutants or indicators can be controlled?
- What are acceptable levels for these contaminants with regard to existing codes and regulations?
- What is the current state of the art of DCV systems and sensors?
- What research, testing and monitoring are needed to determine the usefulness of these systems?

This document reviews contaminant levels in buildings, standards, the sensor market and DCV research in IEA countries. Conclusions and recommendations for further research are given.

The following countries, through their representatives, took part in the preparation of this document: (For complete addresses see Appendix E)

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Switzerland
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The work for Subtask A started in November, 1987.

The following abbreviations are used in this report:

ACR	Air change rate
AIC	Acceptable indoor concentration
AIVC	Air infiltration and ventilation centre
CEC	Commission of European Countries
CIBS	Chartered Institution of Building Services Engineers
DCV	Demand controlled ventilation
DD	Degree days
IAQ	Indoor air quality
IEA	International Energy Agency
MAC	Maximum allowable concentration at the work space
ME	Maximum environmental value
RH	Relative humidity
RSP	Respirable suspended particles
TLV	Threshold limit values
VAV	Variable air volume
VOC	Volatile organic compounds
WHO	World Health Organization

2 Contaminant Levels in Various Building Types

The majority of information concerns CO_2-levels, especially in schools. The maximum levels reported are between 3,000 and 5,000 ppm. A Belgian study concludes that 50% of measured levels are higher than 1,500 ppm. In a German school with mechanical ventilation, maximum measured levels were between 800 and 1100 ppm. An auditorium in Switzerland shows the following relationship between the ventilation rate and CO_2-levels:

16 m^3/h per person:	CO_2 levels 1,400 ppm
30 m^3/h per person:	CO_2 levels 1,000 ppm

Some results suggest that the air change rates used were too high from an energy conservation point of view, resulting in average CO_2 concentrations of about 800 ppm.

In Finnish bedrooms, measured CO_2-levels vary from 500 to 3,700 ppm, with an average value of 1,400 ppm. These results were independent of the ventilation system design. The relationship between odour and CO_2 concentration is well established. /31/

There is little information available about average or peak concentrations of CO_2 and odour levels in occupied spaces.

Levels of hydrocarbon concentration were normally measured at less than 1,000 $\mu g/m^3$. In new buildings, higher concentrations of up to 10,000 $\mu g/m^3$ can be found.

In Italian houses, Volatile Organic Compounds (VOC) concentration of 3,250 $\mu g/m^3$ has been measured. In the same houses, the average value of Respirable Suspended Particles (RSP) was 81 $\mu g/m^3$, compared with the outdoor air concentration of 63 $\mu g/m^3$.
In one study of Dutch houses with occupants who smoke, the RSP-24 hour Threshold Limit Value (TLV) of 140 $\mu g/m^3$ was exceeded.

Formaldehyde levels are not a problem if the right building materials are chosen in combination with the correct Air Change Rate (ACR).

Comparatively more information exists about humidity levels in occupied spaces. Over the past 10 years many European countries have reported a large number of cases in which damage has been caused by excessive relative humidity within rooms. This damage is caused by poor ventilation, thermal bridges and/or high moisture emissions.

The field of moisture damage, physical phenomena, mould growth and occupant behaviour etc., is subject to research work currently being done in IEA Annex 14, Condensation and Energy. Research shows that many of the cases reported occurred in rooms with natural ventilation.

Mould problems can be avoided or at least alleviated by the use of exhaust, balanced or even DCV systems.

A review of papers relating to measured contaminant concentrations in occupied spaces can be found in Appendix A.

3 Review of International Standards for Indoor Air Quality

There are many irritating or harmful contaminants in the indoor environment. Tables 3.2 through 3.6 refer to some of these. More detailed information is provided in /25/.

All participating countries with the exception of Denmark took part in this review. United States and World Health Organization (WHO) standards are included, along with other sources. Three different concentration levels are listed:

- MAC: Maximum Allowable Concentration at the work space for an eight hour period (occupational health criteria)
- ME value: Maximum Environmental value
- AIC: Acceptable Indoor Concentration

The MAC values given here represent threshold concentration levels in an industrial environment and do not apply to long exposure in the indoor environment.

There is some question as to which threshold levels can be applied when assessing the indoor air of living rooms, offices, schools, theatres etc. The German Federal Minister of Labour and Social Affairs recently addressed this question as it pertains to offices /32/. An excerpt from his remarks follows:

> "Established MAC values apply to a limited, usually eight hour exposure at the working space. They are generally chosen in such a way as to ensure that the health of employees is not affected, and that no irritation is caused. MAC values apply to healthy working persons, and are used as a basis for assessing the work space. In special cases the list of MAC values must be expanded to include other factors.
>
> The MAC working group does not propose threshold limits for indoor rooms. A proven, scientific connection between both values cannot be established at this time, according to the MAC commission, because criteria for indoor air threshold values differ substantially from criteria for MAC values (e.g. consideration of elderly or sick persons, children, assumption of 24 hour exposure, etc.)
>
> * * *
>
> Concerning the indoor air quality in offices...the air should be almost the quality of outdoor air, and contaminant concentrations should be below MAC values."

To explain the meaning of ME-values, we cite an excerpt from /9/:

> "ME values refer to concentrations of at locations away from the source. They refer to what people perceive at a specific location, where the origin or the source is not as important as what people perceive.
> These values, if adhered to, protect man and his environment to the best of our present knowledge as derived on the basis of relevant criteria."

ME values in Tables 3.2 to 3.6 are included for information only. They do not represent guide values for DCV systems.

The following definition for AIC value is taken from /25/:

> "In order to characterize the health effects of pollutants, we introduce the concept of acceptable indoor concentration (AIC) for each of the various gases considered. For concentrations below the AIC the negative health effects are either negligible or, if no threshold is known, are at least tolerable."

These limits are only meant for discussion, since it is not the task of the Annex to set limits.

3.1 Water Vapour

Thermal Comfort:

For optimum comfort, the upper limit of absolute humidity should be 11.5 g water/kg dry air. Relative humidity of 65% should never be exceeded, according to the German standard. /24/. There is currently no proven knowledge about the lower limit. It is recommended that the relative humidity should be kept above 30% independent of the temperature, although occasional drops to 20% are justifiable. If there is a likelihood of electrostatic discharge on the floor covering, the minimum humidity level must be determined. If this is not possible, the relative humidity should be kept around 50%

Fig. 3.1 shows the ASHRAE /26/ comfort zone.

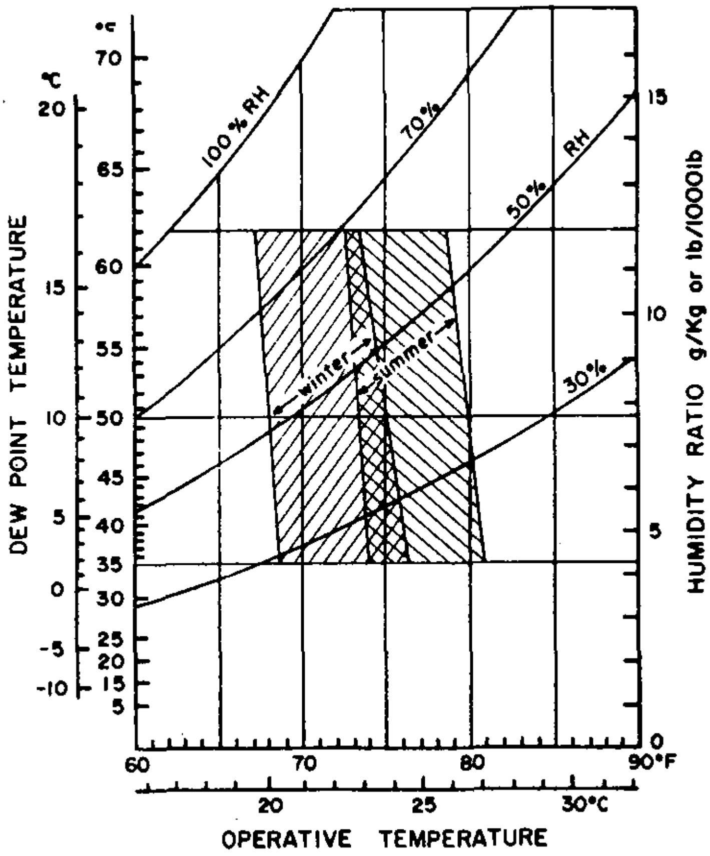

Figure: 3.1: ***Acceptable ranges of operative temperature and humidity for persons clothed in typical summer and winter clothing, at light, mainly sedentary, activity (≤ 1.2 met) /26/.***

In 1972, a German working group /27/ established guidelines for temperature and humidity values depending on the usage of the room. They distinguish between living rooms, bedrooms, bathrooms, working kitchens, and lived-in kitchens.

Table 3.1 summarizes relative humidity and temperature ranges for different rooms.

Table: 3.1: ***Standard values for temperatures and relative humidity /27/.***

room	temperature range [°C]	rel. humidity range [%]	x max [g/kg]
living rooms	18 - 23	35 - 65	11.5
bedrooms	15 - 20	40 - 70	10.0
bathrooms	20 - 26	40 - 80	14.7
working kitchens	15 - 28	55 - 80	13.0
lived-in kitchens	18 - 24	30 - 65	12.0

Hygienic Requirements

The new ASHRAE 62-89 standard "Ventilation for Acceptable Indoor Air Quality" /20/ states:

> "High humidities can support the growth of pathogenic or allergenic organisms. Examples include certain species of fungi, associated mycotoxins, and dust mites. This growth is enhanced by the presence of materials with high cellulose and low nitrogen content such as fibre-board, dust, lint, skin particles, and dander. Areas of concern include bathrooms and bedrooms. Therefore, bathrooms shall conform to the ventilation rates in Table 2.3 (not given here). Relative humidity in habitable spaces preferably should be maintained between 30% and 60% relative humidity to minimize growth of allergenic or pathogenic organisms."

To operate a humidity controlled ventilating system, the threshold value of the relative humidity in the room must be determined in order to avoid problems with mould growth. A joint research project, IEA Annex 14, Condensation and Energy is currently looking at the question of humidity and mould growth. /33, 39/ More details and design parameters are available at the end of Annex 14, probably by the end of 1990.

3.2 Carbon Dioxide - CO_2

Table 3.2 shows threshold values for carbon dioxide in buildings in various countries. MAC values are the same in all countries, and there are no ME values established yet. To determine AIC values, it is necessary to differentiate between carbon dioxide produced by metabolism (used as an indicator of odours caused by humans) and CO_2 produced by other processes (e.g. fermentation in a brewery). It is necessary to determine whether CO_2 itself is a problem or whether it is being used as an indicator for human generated odours and a measure for the ventilation rate. The maximum desirable levels are between 800 and 1,500 ppm. Canada, the U.S. and Finland are the only countries that differentiate between CO_2 as a product of metabolism and as a product of other processes and that have established threshold values for both areas.

The carbon dioxide concentration of the atmosphere is 320 to 350 ppm. This value is increasing slightly from year to year due to the combustion of fossil fuels.

CO_2 concentrations increase in industrial areas. Average values are usually below 400 ppm measured over half hour time periods. Half hour mean maximum levels can increase to 500 ppm in Germany, according to the statistical reports of the State Department of Baden-Württemberg /29/. Peak values of up to 800 ppm have been measured in industrial areas, according to some publications, although official statistical reports do not confirm these values. Conditions must have been very unusual to result in these readings.

From the data it would seem that under normal atmospheric conditions, variations of CO_2 concentration in the environment are not normally greater than 150 ppm. If CO_2 is used as an indicator of ventilation rate per person and, as a result, human-produced odours, its increase in relation to the ambient level is important. If the ambient level changes significantly, (may be between 320 and 800 ppm absolute) one could not fix one absolute CO_2 threshold value for the indoor environment, such as 1,000 ppm, as a measure of ventilation rate only. It could be fixed from 1,000 to 1,450 ppm. However, since CO_2 levels in the ambient air do not vary greatly, then it is reasonable to set one absolute value.

It should be mentioned here that there are many publications in which authors argue that if the maximum CO_2 concentration is set to 800 ppm and the outdoor air already has 800 ppm or more, ventilation does not make sense. This argument is only valid in a certain sense. Up til now there is no evidence that CO_2 is harmful, annoying, or irritating at concentrations below 1000 ppm. Even if the outdoor concentration is 800 ppm it is only partly true to say the outdoor air quality is poor. Because for ventilation purposes CO_2 is only used as an indicator for body odour and only the difference between indoor and outdoor level is decisive and a measure of indoor air quality.

The true part of the argument is, that it is often true that outdoor air with a high CO_2 concentration is heavily polluted with other harmful contaminants (CO, NO_x, $C_nH_m$etc.) and therefore of poor quality.

Toxicity of CO_2:

A concentration of less than 50,000 ppm CO_2 is non-toxic to humans. Physiological effects are observed at levels above 10,000 ppm. Above 40,000 ppm subjects complained about headache /28/.

Table: 3.2: *Threshold levels for carbon dioxide CO_2 in different countries.*

Concentration Level Country	MAC ppm	Peak limit ppm	Ref.	ME-value ppm	Ref.	AIC ppm (absolute)	Ref.	Remarks 1 ppm = 1.806 mg/m³ (at 1 bar, 293 K)
Canada	5000 -	-	21	-		3500 1000	22 20	CO_2 level not used as indicator for body odour Produced by metabolism
Germany	5000	2 x MAC	8	-		1000 1500 max.	24 24	Pettenkofer-value used to establish necessary AIC-air flow rates
Finland	5000	5000 (15 min)	1	-		2500	35	AIC: of which 1500 ppm is produced by metabolism If the outdoor air flows are controlled based on the carbon dioxide content of the indoor air, a maximum set point of 800 ppm may be used
Italy	-	-		-		1500	2	
The Netherlands	5000	15000 short time	40 41	-		1000-1500	42	
Norway	5000	MAC + 25% (15 min)	3	-		-		
Sweden	5000	10000	4	-		-		supply air 1/10 of MAC /5/
Switzerland	5000	-	6	-		1000-1500	30	proposed according /30/
U.K.	5000	15000 (10 min)	17	-		-		
U.S.A.	5000	-	21	-		1000	20	
Columbus Space station	-	-	-	-		4000	19	

MAC = Maximum Allowable Concentration at the work space 8 h/d
ME-value = Maximum Environmental Value
AIC = Acceptable Indoor Concentration

3.3 Carbon Monoxide - CO

The natural base level of CO is 0.044 - 0.087 ppm. Rural areas have 0.175 - 0.435 ppm, industrial areas 0.87 - 1.75 ppm and downtown levels with heavy traffic can reach 40 ppm /29/.

Typical CO sources in dwellings or other occupied spaces are tobacco smoke and exhaust gas from open fireplaces.

Table 3.3 lists threshold values for carbon monoxide in various countries. MAC values in the countries range from 30 to 50 ppm. ME values are only reported from Germany and Switzerland. Germany's AIC values for CO reflect the increase of CO due to smoking, which was a result of the first working phase of IEA Annex 9, Minimum Ventilation Rates /7/. Here, CO served as an indicator of irritation caused by tobacco smoke. The AIC values of Canada, Sweden and the U.S.A. are 11 or 12 ppm, and reflect the exposure to CO as a combustion product.

Variations of CO in the outdoor environment can be significant. Using a CO sensor to control the supply air of a ventilation system based on the presence of smokers in a room does not seem like a promising strategy for the following reasons:

1. As the ambient CO level varies in urban areas, two sensors would be required, one placed indoors and one outdoors to detect the increase of 1 or 2 ppm caused by smoking.

2. There is no sensor on the market able to selectively measure CO in a range between 0-20 ppm with an accuracy of 0.5 ppm.

3. If CO sources other than smoking are present, excessive ventilation rates might be demanded.

Given the current technology, it would appear to be impractical to use CO as an indicator that smoke is present.

Table: 3.3: Maximum Concentration level for carbon monoxide (CO) in buildings in different countries.

Concentration Level Country	MAC ppm	Peak limit ppm	Ref.	ME-value ppm	Ref.	AIC ppm	Ref.	Remarks 1 ppm = 1.149 mg/m³ (at 1 bar, 293 K)
Canada	50	400 (15 min)	21	-		9	20.22	
Germany	30	2 x MAC (30 min) average	8	43 (1/2 h) 8 (24 h) 8 (1 year)	9	1-2 9 living rooms 18 kitchen (3 h)	7 27 27	
Finland	30	75 (15 min)	1	-		8.7 daily av. 26 hourly av.	35	
Italy	30	-	2	-		-		
The Netherlands	25	120 (15 min)	40	-		35 (1 h) 8.7 (8 h)	43	
Norway	35	+50% (15 min)	3	-		-		
Sweden	35	100	4	-		12	10	supply air 1/10 of MAC /5/
Switzerland	30	-	6	7 (24 h) average	16 37	-	-	ME-value: this value ought to be exceeded only once a year
U.K.	50	400 (10 min)	17	-		-		
U.S.A	50	400 (15 min)	20			9	20	
WHO		87 (15 min) 53 (30 min) 26 (1 hour) 9 (8 hours)	10	-		-		Guideline value; based on effects other than cancer or odour/annoyance
Airplanes	50	-	18	-		-		

MAC = Maximum Allowable Concentration at the work space 8 h/d
ME-value = Maximum Environmental Value
AIC = Acceptable Indoor Concentration

3.4 Nitrogen Dioxide - NO_2

Nitrogen dioxide is emitted mainly from hot water heaters in kitchens and bathrooms. Measurements show that NO_2 concentration in poorly ventilated rooms can be several times higher than ME values /7/.

Maximum concentration levels are listed in Table 3.4. The participants of Annex 18 agreed not to investigate the use of combustion byproducts for the purpose of controlling ventilation systems.

Table: 3.4: *Maximum concentration level for nitrogen dioxide (NO_2) in buildings in different countries.*

Concentration Level Country	MAC ppm	Peak limit ppm	Ref.	ME-value ppm	Ref.	AIC ppm	Ref.	Remarks 1 ppm = 1.888 mg/m^3 (at 1 bar, 293 K)
Canada	3	5 (15 min)	21	-		0.3 0.052	20 22	offices homes
Germany	5	2xMAC (5 min average)	8	0.1 (1/2 h) 0.05(24 h)	9	-	35	
Finland	3	6 (15 min)	1	-		0.08 daily av. 0.16 hourly av.	35	
Italy	-	-		-				
The Netherlands	2	-	40	-		0.16 (1 h) 0.08 (24 h)	43 43	
Norway	-	-		-		-		
Sweden	2	5, 15 min	4	-		0.2 0.15	12 10	supply air 1/10 of MAC, max. value for 24 h /5/
Switzerland	3	-	6	0.04 (24h) a) 0.05 b) 0.015 c)	16 + 37	d)		a) 24 h mean value ought to be exceeded only once a year b) 95 % of 1/2 h mean values of a year ≤ 0.05 ppm c) annual arithmetic mean d) there are no building regulations for kitchens with gas-powered furnaces
U.K.	3	5 (10 min)	17	-		-		
U.S.A	3	5 (15 min)	21	-		0.3	20	offices
WHO				0.16	10	0.21 1 hour 0.08 24 hour		AIC: Guideline value, based on effects other than cancer or odour/annoyance

MAC = Maximum Allowable Concentration at the work space 8 h/d

ME-value = Maximum Environmental Value

AIC = Acceptable Indoor Concentration

3.5 Formaldehyde - HCHO

Formaldehyde is emitted mainly from particle board and various insulation materials. In contaminated rooms HCHO levels can reach 1 ppm /30/.

The formaldehyde threshold levels are listed in Table 3.5. MAC values are between 0.5 and 2 ppm. AIC values are between 0.01 and 0.26 ppm.

Keeping formaldehyde concentrations low is best accomplished by controlling the sources, not by excessive ventilation. Besides, formaldehyde is difficult to measure and no sensors are available. Therefore formaldehyde is no key contaminant in the sense of Annex 18 and Table 3.5 serves for information only.

Table: 3.5: ***Maximum concentration level for formaldehyde (HCHO) in buildings in different countries.***

Concentration Level	MAC	Peak limit	Ref.	ME-value	Ref.	AIC	Ref.	Remarks
Country	ppm	ppm		ppm		ppm		1 ppm = 1.231 mg/m³ (at 1 bar, 293 K)
Canada	1	2 (15 min)	21	-		0.1 0.1	20 22	
Germany	1	2xMAC, 5 min average	8	-		0.1	14	
Finland	-	1 (15 min)	1	-		0.12 0.24	11	AIC: for new buildings for existing buildings
Italy	-	-		-		-		
The Netherlands	1	2 (15 min)	40	-		0.1(0,5h)	43	
Norway	1	+100% (15 min)	3	-		-		
Sweden	0.5	1 (15 min)	4	-		0.1 0.01-0.05	5,10 12	supply air 1/10 of MAC, safety factor 10 AIC-safety factor for avoiding annoyance: 10 /5/
Switzerland	1.0	-	6	-		0.2	13	
U.K.	2	2 (10 min)	17	-		-		
U.S.A	1	2 (15 min)	21	-		0.1	20	
WHO		-		-		0.1 0.08	10 10	AIC: Guideline value based on effects other than cancer or odour/annoyance

MAC = Maximum Allowable Concentration at the work space 8 h/d

ME-value = Maximum Environmental Value

AIC = Acceptable Indoor Concentration

3.6 Hydro Carbons ΣC_mH_n

Hydrocarbon threshold values are listed in Table 3.6. This is for information only in the sense of Annex 18. Further information is provided in /25/.

Table: 3.6: Maximum concentration level for hydro carbons (ΣC_mH_n) in different countries.

Concentration Level Country	MAC ppm	Peak limit ppm	Ref.	ME-value ppm	Ref.	AIC ppm	Ref.	Remarks
Canada	-	-		-		-		
Germany	-	-		0.05	15	-		
Finland	-	-		-		-		
Italy	-	-		-		-		
The Netherlands	-	-		-		-		
Norway	-	-		-		-		
Sweden	-	-		-		0.16	12	supply air 1/10 of MAC, max. value for 3 h /5/
Switzerland	-	-		-		-		
U.K.	-	-		-		-		
U.S.A	-	-		-		-		

MAC = Maximum Allowable Concentration at work space 8 h/d

ME-value = Maximum Environmental Value

AIC = Acceptable Indoor Concentration

4 Sensors

4.1 Function Principle of Sensors

4.1.1 Humidity Sensors

A general description of methods for measuring atmospheric humidity is given in /34/. The most common principles of sensors for DCV systems are discussed here.

Hair and Polyethylene-Strip Hygrometer

A hair hygrometer changes its length for about 2 % for a humidity change from 0 to 100 % relative humidity. Other hygroscopic materials such as silk, cotton and synthetic materials are also in use. There are some disadvantages to this type of sensor, including its need for recalibration and the fact that it must be placed in humid air to maintain elasticity. Hysteresis is between 2-5 %. The length change of the sensor strip often works on a potentiometer to give the required analogue electric output signal.

Capacitive Hygrometer

This uses a humidity sensitive folio which is placed between two electrodes. A change in relative humidity will cause a capacity change. Additional electronics (other than the sensor) are needed to get an analogue output signal in ohm, ampere or volt. Linearization and temperature compensation are often necessary. Capacitive humidity sensors vary in price, depending on their accuracy and response time, but overall are they fairly inexpensive. Unfortunately, they are sensitive to contaminated air (dust, organics).

Conductance-Film Hygrometers

An electrode is placed on a plastic ground plate and covered with a hygroscopic layer, where the conductivity changes with humidity. The result is a change of the electric current. This type of sensor is supposed to be highly accurate and have a short response time, with no need for recalibration or maintenance.

Lithium Chloride Sensors

This type of sensor uses thermodynamic equilibrium between humid air and a salt solution. The lithium chloride solution absorbs water from the air until the total pressure of the solution is the same as the partial pressure of water vapour in the air. Accuracy is between 1-3 %. The measuring element consists of a thermocouple enclosed in a glass-fibre sleeve soaked in LiCl solution. The sleeve contains a bifilar thread connected to a power source. Assuming that the LiCl solution is unsaturated, the electrical current gradually heats it so that the equilibrium vapour pressure rises. If it rises above that of the predominant vapour pressure in the air, water will evaporate from the solution, so that it first becomes saturated and then crystallizes, reducing the amount of liquid solution.

This leads to a rise in resistance and a fall in current, bringing the rise in temperature to a halt. When equilibrium is reached the temperature of the solution and therefore of the sensor provides a direct measurement of the predominant vapour pressure /34/.

4.1.2 Carbon Dioxide Sensors

All sensors designed to selectively measure CO_2 in the air use infrared (IR) absorption. At this time, there are only two types of CO_2 sensors available:

- photoacoustic
- photometric

Photoacoustic CO_2 Sensor

This sensor consists of a light source, an infrared filter, a cell, and a microphone. A filter in front of the light source ensures that only the wavelengths corresponding to the absorption spectrum of CO_2 can enter the cell along with the room air. In the cell the CO_2 molecules absorb the infrared light as a function of their concentration. The absorbed energy increases the vibration energy of the molecules, leading to more pulses between molecules. The generated acoustic field is measured by a microphone and transformed electronically to a CO_2 count. Although extensive long term experience does not yet exist, it is recommended that the calibration should be checked every 18 months.

Photometric CO_2 Sensor

In this sensor, infrared light is emitted by a cell, reflected by mirrors to create a long path, and received by a special detector. Transmission of some wavelengths is affected by CO_2 concentration. The analogue output from the photodetector is generally converted by a microprocessor to readable CO_2 levels.

Cross sensitivities of CO_2 sensors are fairly small. Accuracy is between 10 and 100 ppm, and response times are about three minutes.

4.1.3 Mixed Gas Sensors

To control air quality in buildings, two types of sensors are used:

- homogenous metal oxide semi-conductor
- catalytic gas

Homogenous Metal Oxide Sensor

This type of sensor consists of pure metal oxide compounds (n-type: SnO_2, ZnO, ZiO_2, Fe_2O_3; p-type: CuO, NiO, CoO) where the total conductivity changes due to the reaction of gases with oxygen on the surface. The n-type sensors react on combustible (non-oxidized) gases like CO, H_mC_n and alcohols. Most human-generated odours belong to this group and are detectable. The sensors are heated up to 100-500°C.

The structure of the semi-conductor layer can be threefold: polycrystalline, thin-layer techniques, and monocrystalline.

Polycrystalline sensors are based on SnO_2. While this type of sensor has the advantage of being easy to produce and almost universally applicable, it has the disadvantage of a slow response time, high cross sensitivities to air humidity and long term drift.

Using thin-layer technology, response times are in the range of several minutes with a fairly high influence of humidity. The advantage of thin layer technology is high sensitivity to simple gases like H_2S, CO, NO_2, CH_4 and C_2H_5OH. Cross sensitivities can avoided by changing the sensor working temperature, but reproducibility and long term stability are not yet satisfactory.

Most mono-crystalline sensors are in the developmental stage. Preliminary results indicate good and reproducible quantitative properties. The only disadvantage is the high cost involved.

Catalytic Gas Sensors

Catalytic gas sensors are based on the determination of the amount of heat which is emitted due to an exothermic reaction of the non-oxidized gas at a catalytic acting metal surface.

A representative of this sensor type consists of a heating wire embedded in a sintered body, which is covered by a thin catalytic layer. The sensor is heated to 550°C. The reaction with the gas results in an increase of temperature and therefore in an increase of the resistance of the heating wire. The change of resistance which depends on the gas concentration is measured.

Tables 4.1-4.5 show the results of a sensor market analysis. Only the main features of the sensors or of the whole measuring device (sensor + additional electronics) are listed. Further information can be obtained from the appropriate companies, whose addresses are listed in Appendix D.

4.1.4 Discussion

How well sensors work in practice and how well they are suited to control the specific contaminant will be investigated in the Sensor Test Program as part of IEA Annex 18, Subtask B1. Various companies have done sensor evaluations with the hopes of incorporating these sensors into new instruments. Unfortunately, these results have not been published and valuable information is not available.

4.2 Sensor Market Today

A survey of available IAQ sensors was performed during January and April 1988 and extended until December 1988. Specifications in the following lists are based on manufacturers' data only. Further information is given in Appendix B2 and B3 of the final report of IEA Annex 18.

Table 4.1 gives specifications of sensors that measure relative humidity. By themselves, these sensors cannot be used to directly control a fan or a damper. Additional electronics are necessary so that the sensor gives a defined linear output signal in ohms, volts or amperes.

Table 4.2 gives specifications of complete instruments for measuring relative humidity, i.e. a sensor integrated with additional electronic circuitry which can then be used for control purposes. It should be mentioned that many manufacturers do not develop sensors on their own but buy the naked sensor and add their own electronics for linearization, display and other features. From this it is obvious that complete measuring devices from different companies can differ in their properties, reliability, maintenance and cost, even though they use the same sensor element. This is particularly true of the so-called IAQ-sensors based on non-oxidized gas detection (see below).

Table 4.3 lists companies that produce complete sensing devices for carbon dioxide CO_2. Many of these devices are fairly new, and are not always readily available.

Table 4.4 lists companies that produce sensors and complete sensing devices for carbon monoxide CO. Complete sensing devices are usually not designed for IAQ control in a non-industrial setting, but rather to give alarm when a critical or hazardous level of CO is reached. These devices do not seem to be sensitive enough to control tobacco smoke. They operate on a CO level that is too high for that purpose.

Table 4.5 includes companies, mainly German and Swiss, that produce complete sensing devices for odour detection. Most manufacturers use the Japanese Figaro sensor. These sensors are also distributed under the name Tagushi.

The following is an example of how companies have developed an air quality sensor:

Going back to the original Figaro specification of the sensor, TGS 812, one reads "high sensitivity against poison gas (CO, NH_3, SO_2 etc.) and organic soluble vapours. Little sensitivity against methane". There is no reference to body odours.

In this example, the company used this sensor and developed the electronic circuitry (i.e. the right heater voltage and amplification of output signal) in such a way that there is a sensitivity to body odour.

This seems to be the general approach used by many companies, since to the best of our knowledge no special odour sensor element is currently available. Obviously, complete sensing devices from different companies can have very different properties and capabilities, even when they have the same sensor element. Moreover, the sensor elements themselves vary on a broad scale. These are the main reasons for the large tolerances of odour sensing devices.

The prices in Table 4.1 to Table 4.5 are of January-March 1988. The currency at that time was:

1 US $ = 1.7 DM
1 US $ = 1.42 SFr
1 US $ = 1200 Ital. Lire

All prices are net and do not include sales tax.

Appendix D gives addresses of all companies contacted and/or mentioned in this sensor survey.

Attention: all data in tables 4.1 to 4.5 are based on product information forms or personal telephone contact. The author is not liable for mistakes or improper content in the tables. No responsibility can be accepted for the use of data presented in this publication. It is recommended that the reader order the latest information on a specific product directly from the appropriate company.

Table: 4.1: *Sensors only for Measuring relative humidity.*

No.	Company/Sensor Type/Remarks	Kind of Sensor	Range % r.H.	Accuracy % r.H.	Long Term Stability/ Calibration/General Remarks	Stability/Drift Cross Sensitivity	Output	Size	Price US $
1.	Valvo/ 2322 691 9001/ sensor only	capacitive	10-90	± 2	-/not necessary	0.1% r.H./K	additional electronics necessary	16x23x17mm	15 1 item 7 1000 items 3.5 5000 items
2.	Murata/HOS 103 sensor only	resistance change	60-100	-	the sensor seems to be used only for dew point detection (video recorders)	-	ohm, no linear output signal, constant below 60% r.H.	7x6x1mm	1.2 1 item 0.6 1000 items
3.	Murata/HOS 201 sensor only	resistance change	50-100	-	-	-	ohm	φ16x10 mm	7.5 1 item 3.7 1000 items
4.	Coreci/CCH/	capacitive	0-98	<±1 at 5<φ<90%	-/-/water droplets cause wrong output signals for short times	-/-/-	oscillatory circuit necessary	6x6x1.5mm	100
5.	Rotronic/ DMS-100/ hygrolyt	electrolytic solution	0-95	± 1,5	good/6-12 months resistant against aggressive contaminants	good/0.1 % r.H.	Impedance change add. electronics necessary	10x5,5x 3.3 mm 0.5 g	180 (1989, 1 US$=1.90 DM)
6.	Rotronic/ C83/hygrometer	capacitive	0-100	± 1.0	good/6-12 months	<0.5%/<0.5 %	add. electronics necessary	20x6x0,2mm 0.02 g	110 (1989, 1 US$=1.90 DM)

Addresses are listed in Appendix D

Table: 4.2: *Complete sensing devices (sensor + electronic converter + analog output) for relative humidity.*

No.	Company/Sensor Type/Remarks	Kind of Sensor	Range % r.H.	accuracy % r.H.	Stability/Calibration/General Remarks	Output	Size/Weight	Price US $
1.	Coreci/CHRTAC humidity+temp.	CCH/capacitive	5-98	2 at $10<\theta<50°C$	stable/no/	4-20 mA for hum. + temp.	357x125x80mm 500 gr.	705
2.	Galltec/ FG120 Pt100/ humidity + temperature	polyester stripes, resistance	0-100	2.5 at $40<\varphi<100\%$ 3.5 at $10<\varphi<40\%$	-0.25% r.H./K/no calibration in clean air/-	in ohm	128x74x49mm 200 gr	290 1-9 items 260 10-19 items 165 20-50 items
3.	Rotronic/ YA100/hum. + temp.	capacitive hygrometer C83	0-100	<±1	±0.5% r.H. at θ=70K/6-12 months	0+1V hum. -0.5+1.5V temp.	195x25 mm 150 gr	630
4.	Ahlborn/F80	plastic stripe	0-100	±2.5	-/-/sensor can be cleaned with soap water, usually no maintenance	100-138.5 ohm	- 600 gr	255
5.	Driesen/ HMW 20 U	Humicap capacitive from Vaisala (SF)	0-100	<3	-/-/membrane filter for sensor protection	0-1 V 0-5 V 0-10 V 0-20 mA	-	340
6.	HY-Cal/ CT 828-A	-	0-100	±3	-/-/time const. 50 s; sensor washable	4-20 mA	110x70x40 mm	-
7.	Vaisala/ HMP 123b/ hum. + temp.	thin film	0-100	<2	-/-/-	0-20 mA	12x65 mm	550
8.	Landis & Gyr/ QFA 62.2	capacitive Valvo sensor	20-90	-	-/-/-	0-10 V	-	180
9.	Landis & Gyr/ QFA 62.1/ hum. + temp.	capacitive Valvo sensor	2-90	-	-/-/-	0-10 V	-	195

Addresses are listed in Appendix D

(Table: 4.2: Continued)
Complete sensing devices (sensor + electronic converter + analog output) for relative humidity.

No.	Company/Sensor Type/Remark	Kind of Sensor	Range % r.H.	Accuracy % r.H.	Stability/Calibration/General Remarks	Output	Size/Weight	Price US $
10.	Landis & Gyr/ QFM 61.1 abs. humidity	hygro- scopic stripe	0- 20g/kg	-	-/-/-	0-10 V	-	570
11.	Landis & Gyr/ QFM 61	Rotronic capacitive sensor	0-100	± 2	-/-/for higher requirements	0-10 V		1075
12.	Centra Burkle/ HKT 1/humidity + temperature	capacitive NTC (temp.)	10-90	≤ 3	max. 0.1 % r.H/K/-/-	0-10 V	283x965	305
13.	System Con- trols/ -/	TiO_2 con- ductance film	5-95	-	stable over years/not necessary/ no maintenance, life time > 10 years, suited for water/oil emulsions, self-cleaning	-	-	-
14.	Com air/BU 11/	Murata capacitive	-	-	-/-/switch point between 55-60 % r.H.	-	170x105-80mm	-
15.	Aereco	Hygroscopic stripe	40-75	-	-/-/sensor controls cross-section area of vent. duct, centr. + decentr. systems avail.	-	-	-
16.	AB Gemlaplast/ Fresh 99	-	Set- point 45 - 85%	-	-/-/passive system, no fan, a damper is controlled by a humidity sensor, for wall mounting	-	140x140x445	70
17.	AB Gemlaplast/ Fresh 2000	-	Set- point at 55 or 70%	-	-/-/humidity controlled fan with 88-95 m/h	-	140x140x140	100

Addresses are listed in Appendix D

Table: 4.3: Complete sensing devices for carbon dioxide (CO_2).

No.	Company/Sensor Type/Remarks	Kind of sensor	Range ppm.	Accuracy	Stability/Calibration/General Remarks	Output	Size/Weight	Price US $
1.	Sauter/ EGQ 10 F001/ CO2 selective	non-dispersive infrared absorpt.	0-2000 0-6000	± 100 ppm.	weak influence of hum. + temp./ 5 years/appr. available July'88	0-10 V 0-20 mA	120x120x60 mm 200 gr.	520
2.	Aritron/ AROX 425AB2E3	infrared, photo-acoustic	35-2000	-	+0.3% FS/°C +0.06% FS/% r.H. every 18 months	0-10 V	188x110x70 mm	720-1400 depending on country & retailer
3.	AF-Energi/ prototype/exp. with Lund University	infrared absorp.	0-2000		± 20 ppm short time < 200 ppm after 2 months	4-20 mA	-	330
4.	Horiba/APBA-250E/	non-dispersive infrared absorption	0-3000 0-10000	± 300 ppm ± 1000 ppm	-/every 3 months/well designed with display, suction pump and alarm output	4-20 mA non-linear	222x85x262 mm 2700 gr	1520 (1989) at this time 1 US$ = 1.90 DM
5.	Simrad Optronics	IR absorp. 2 chamber comparis.	0-10000	± 5 %	-/None/-	0-10 V 0-20 mA		
6.	Siemens/ M52080-A74-A11	photo-acoustic	0-2000 ppm	10 ppm reproducibility	100 ppm in 18 months /-/-/	0-20 mA	193x184x135 2 kg	1000 (1989) 1 US$ = 1.90 DM

Addresses are listed in Appendix D

Table: 4.4: *Sensors and complete sensing devices for carbon monoxide (CO) detection.*

No.	Company/Sensor Type/Remarks	Kind of Sensor	Range ppm.	Accuracy	Stability/Calibration/General Remarks	Output	Size/Weight	Price US $
1.	Unitronic/ TGS 712D	thin film produced by Figaro/ Japan	20-200	-	-/-/working temp. at 200°C	ohm	ϕ20x23mm	44 sensor only
2.	Unitronic/ TGS 711	thin film Figaro/ Japan	50-500	-	-/-	ohm	ϕ20x21mm	43 sensor only
3.	Unitronic/ TGS 203	thin film	50-1000	depends on sensitivity of circuit	temp. compensation included	ohm	-	130 a)
4.	Unitronic TGS 100 + TGS 800	Figaro sensor	1-100 or above	-	-/-/suited for CO, H_2, cigarette smoke, gasoline vapour, etc.	ohm	-	12 sensor only
5.	Unitronic TGS 812	thin film	-		-/-/used for smoke and alcohol detection	-	-	-
6.	Preussag /-/	Figaro sensor	0-45	-	-/-/	digital	-	100 sensor only 710 complete device
7.	Endrich/ NAP-11A/	Semi-conductor	50-	-	-/-/-/	ohm	ϕ17x25 mm	25

a) price includes the sensor, the temp. compensation and IC-unit (FIC 5401)

Addresses are listed in Appendix D

Table: 4.5: *Sensors and controlling devices for odour detection (mostly based on the amount of non-oxidized gases).*

No.	Company/Sensor Type/Remarks	Kind of Sensor	Stability/Calibration/General Remarks	Output	Size/Weight	Price US $
1.	Staefa/FRA-Q1/	semiconductor	sensitive to changes in air velocity/ no need/-	0-10 V	10x10x1 cm 50 gr	200
2a	Landis & Gyr/ QPA 61.1/ sensor only	semiconductor heated	-/-/-	0-2.5 mA	100x81x32mm 140 gr	140-240 (D)-(I)
2b	Landis & Gyr/ SER 61.1 complete controler unit	QPA 61.1	-/-/0-100% air quality adjuatable	0-10 V	-	220
3.	Staefa/FR-G4/ sensor RNG 92/controller	TGS 812 from Figaro semiconductor	sensitive to temp. /-/ signal increases with odours or tobacco smoke	0-20 V	80x80x22mm 185x133x51mm	120 sensor only 375 complete controller
4.	Centra/ CR-LQR1	semiconductor		0-10 V	166x75x34mm	212-380 (D)-(I)
5.	Sauter/EGQ1-F001/sensor ERQ1-F001/ sensor + controller	Figaro	<1%/°C; <0.3%/% r.H. /-/ manual set point switch at ERQ1 (external one possible), 30< <70% r.H.	0-10 V	70x70x50 mm 100 gr	175
6.	Unitronic/ F3801+F3103 from Figaro	semiconductor	-/no/microcomputer enables simulation close to human olfaction	0-20 mA 5 levels	70x50x20 mm 100x70x35 mm	not yet available device sold in Japan

Addresses are listed in Appendix D

4.3 Sensor Market in the Future

Chemical sensors have a huge development potential. With the increasing technical complexity of mechanical, electronic, electro-mechanical and chemical factories on one hand, and increasing concern about industrial and technical by-products' effect on the environment on the other, sensors are needed to control production processes as well as to warn of toxic substances and hazards. Sensors are a key technology to improve products and to strengthen the competitive position.

Chemical sensors must be sensitive, selective, stable and durable against chemical, mechanical, and thermal influences. The response time of the sensor is also important, along with the price. Nevertheless, a high development potential for chemical sensors is expected. (VDI-Nachrichten, Nr. v. 10. Feb. 1989, p. 23, in German.)

The Japanese company Figaro is producing a large variety of chemical sensors, and is one of the leading companies in the world. They produce SnO_2 sensors in large numbers. This type of sensor is used to detect non-oxidized gases like H_2, CO, H_2S, etc. and is also used as an indoor air quality sensor.

A further goal is the development of integrated multi-sensors. Sensors for temperature, humidity, pressure, oxygen, CO/CO_2 and NO_x, for example, are integrated on one substrate to a single sensor to check conditions in rooms and cars.

Thin film and thick layer technology and micromechanics may possibly reduce the cost as well as the size of sensors. Although the development potential is substantial, the immense investment costs must be considered. The production of most sensors is too small to support large development costs. Several studies in the U.S., Japan and West Germany (e.g. Mackintosh and Battelle) show that sensor applications are dominant in automobiles. In Japan, humidity sensors to be used in microwaves and videos, as well as sensors to detect combustible gases in households have the highest development potential.

A survey entitled "State of the Art and Perspectives of Chemical and Biochemical Sensors" of the Zenith GmbH, Mühlheim/Ruhr, W. Germany, cited in the "VDI-Nachrichten" of 19 Aug. 1988 concludes that chemical sensors, which would be produced with manufacturing methods of the microelectronic techniques, will govern the market in five years. This will decrease manufacturing costs by approximately 90 %.

5 Summary of Findings

Considerable research has gone into DCV systems over the past ten years. Table 5.1 (Contents of Reviewed Papers) lists the 31 papers examined and their content.

Appendix B includes the collection of reviews of DCV system measurements performed. Some of these reviews are included in AICV's bibliographic database, known as AIRBASE /36/. If so, this is indicated by an AICV reference number.

Section 6 of this document (CONCLUSIONS) summarizes the main points (results, facts, open questions) of the papers reviewed, and provides the basis for further research work of this project.

General remarks

Up until 1983 most papers on DCV systems stressed energy savings and pay-back times, but it is indoor air quality that is being emphasized in more recent papers.

Thirteen of the papers reviewed deal with demand control applications in public rooms such as lecture halls, theatres and schools, five deal with offices in particular, and three deal with dwellings. The remainder deal with DCV systems in general without specifying a particular application. The number of papers dealing with DCV systems in public rooms would suggest that this is the application that is expected to realize the greatest cost savings.

In public rooms, research focused primarily on CO_2 control (1982/b; 1985/b; 1986/a; 1986/c; 1989/a) as opposed to tobacco smoke control. To study CO_2 control in principal, researchers often used a standard CO_2 IR-analyzer. Paper 1985/a evaluates the controller type in detail.

Experiments with manual control of a ventilation system (1987/f) did not produce satisfactory results, nor did tests with occupancy or IR-presence sensors (1983/f, 1987/f).

Table: 5.1: *Contents of reviewed papers.*

contents of reviewed paper code of reviewed paper	building type			control strategy							savings		others		comments
	offices	halls, theatres, schools	dwellings	use of sensors	*air quality control	CO_2 control	smoke control	vapor control	temperature control	time clock or manual or presence control	energy	costs	sensor location	user acceptability	
1979/a		x				x					x	x			
1981/a				x		x					x		x		
1982/a		x				x					x	x		x	
1982/b						x			x				x		detailed calculat. techn.
1982/c		x		x		x			x		x	x			
1983/a	x			x		x				x	x	x		x	
1983/b		x				x						x			
1983/c				x		x									
1983/d			x	x				x			x	x			passive system
1983/e			x			x		x							
1983/f		x		x		x				x					
1984/a						x								x	
1984/b		x				x							x		
1984/c		x				x	x				x				
1985/a	x			x	x	x	x								P,PI,PID-contr. comparison
1985/b		x		x	x	x		x							
1985/c			x					x			x				passive system
1986/a	x	x		x		x			x		x	x		x	
1986/b		x				x					x	x			
1986/c		x		x		x			x	x				x	
1987/a			x					x							theoretical approach
1987/b	x			x		x							x		
1987/c	x				x	x									
1987/d				x	x	x					x				
1987/e		x		x	x	x	x								
1987/f		x				x				x					
1987/g	x	x		x	x	x	x								
1988/a		x		x		x							x		
1988/b						x			x						
1988/c			x	x		x		x							passive system
1989/a		x		x		x			x						

* air quality control means by use of a broad band sensor which reacts to non-oxidized gases

Representative contaminants

CO_2:

According to the literature (1983/e; 1983/f; 1984/c; 1985/a; 1985/b; 1987/e; 1987/f) there is no doubt that CO_2 is the best gas to use in a ventilation system when a building is occupied, and no other large pollution sources such as smokers are present. It is an excellent surrogate measure for ventilation rate per person. In all papers it is shown that the CO_2 concentration in a room could be simulated very well using the metabolic CO_2 emission of the person load.

Other papers deal with CO_2 versus temperature control. Paper 1985/b investigated an auditorium with combined temperature (dominant) and CO_2 control. Research showed that temperature control is dominant when the outdoor temperature is above 10°C, and when the temperature dropped, the CO_2 sensor (set point 1,200 ppm) calls first for more air.

Paper 1986/c confirms that CO_2 control alone can cause severe problems concerning thermal comfort, especially during the summer. Paper 1982/a reports that occupants feel warmer with CO_2 control, although air temperatures were unchanged. In papers 1983/a and 1986/a occupants did not mention any feelings of discomfort with either CO_2 control or constant flow.

Tobacco Smoke:

Smoking does not reflect the CO_2 concentration in a room. Paper 1984/c discusses an aerosol monitor for smoke control. Paper 1985/a suggests the use of the variation of particles and the concentration of combustible gases for smoke control, while paper 1985/c recommends the CO concentration. Although aerosols, particles, combustible gases, or CO may be used, none of these reacts reliably to occupancy load (1985/a). This means that in rooms where smoking is allowed and the number of occupants changes frequently, at least CO_2 and another tobacco smoke constituent must be monitored. Both concentration signals have to act in parallel on the controller, and the ventilation rate must be adjusted according to the measurement which calls for more air. The tobacco smoke surrogates mentioned do not have suitable sensors with respect to accuracy, reliability and cost (see chapter 3.3). Only the use of mixed-gas sensors (see chapter 4.1.3) promises a solution. (See further details in "Experience with Sensors" in Section 6 CONCLUSIONS.)

Water vapour:

Papers 1983/d and 1988/c investigate the possibility of using the level of relative humidity to control a ventilation system. A very poor relationship between the relative humidity and the occupant load in a room was discovered. This is due to the fact that moisture is absorbed and desorbed by the building fabric, furniture, carpets, etc., reducing the variations in relative humidity. As a result, relative humidity cannot be used as an indicator of occupancy.

Five papers in Table 5.1 discuss water vapour control as it applies to dwellings. Papers 1983/d, 1988/c, and 1985/c describe the performance of passive humidity-sensitive devices which were developed in France. Paper 1987/a discusses an advanced strategy for humidity control in which the set point is a function of indoor and outdoor temperature and the u-value of the exterior walls.

Odour:

Body odour is discussed in papers 1985/a,b,c and 1987/d,e,g. The most common area of study is the signal of a mixed gas sensor along with changing occupancy load and occupant activity. (See also "Experience with Sensors" in Section 6, CONCLUSIONS.) The signal from the odour sensor is usually not proportional to the occupancy load and the CO_2 concentration because odours, like water vapour, are adsorbed and desorbed on room surfaces. (1985/b, 1987/e).

Experience with Sensors

CO_2 sensors:

Seventeen papers discuss the application of various types of sensors. Most of those tested were CO_2 sensors. Certain papers (1985/b, 1986/c, 1987/d,e,g) describe research done by the companies that developed the sensors, while others (1983/a, 1983/f, 1985/a, 1985/c, 1986/a, 1988/a, 1989/a) report the findings of independent research institutions. The experiment in paper 1987/b failed due to the high drift of the CO_2 sensor tested. In paper 1988/a, the experiment failed when the CO_2 sensor could not be tested because of a short circuit. In all other papers, the CO_2 sensors appear to have performed well. It should be noted that experiments were often done only over a one week period, so long term experience of CO_2 sensors is not available.

Mixed Gas Sensors:

Papers 1985/a,b,c and 1987/d,e,g investigate mixed gas sensors for odour and tobacco smoke control, which are also known as air quality sensors. Test results so far indicate that they react well to tobacco smoke, but their reaction to odours is much weaker. The sensor signal is very unreliable for both odours and tobacco smoke. Unusual signals were encountered during testing, which could not be explained. Very little is known about this type of sensor at this point.

Relative Humidity Sensor:

Papers 1983/d, 1988/c and 1985/c examine the passive French type of sensor, which has the sensor element integrated into the control unit. In other common humidity sensors, the signal is transferred to a fan or a damper. None of the papers reviewed tested the performance of the latter type in dwellings, but since they have proven reliable in industrial applications and other air conditioned spaces, no further research is warranted. In fact, the price of these sensors may prohibit their use in dwellings and low-cost apartments. Technical details about humidity sensors and their application potential can be found in a recently published comprehensive German study /38/.

The passive ventilation controllers mentioned above were found to work exactly as described in the technical information forms published by the manufacturer.

Paper 1988/c states that the passive systems do not react against occupancy load and suggests that a CO_2 control would be more flexible, if affordable.

While this may be true, the goal of these systems is to prevent the humidity levels in rooms from getting too high in order to protect the building fabric. This can be achieved with these passive systems, but not through CO_2 control.

Sensor Location and Ventilation Efficiency

Many papers do not address problems with the location of a sensor because during testing the CO_2 sensor and the IR-analyzer were placed in the exhaust duct. Only researchers who took additional measurements in the room and in the occupied zone realized that concentration levels varied depending on the location (1982/b, 1984/b, 1987/b, 1988/a). The only cases reported are of very large rooms of more than 1,000 m². Here the distribution of air has to be studied carefully. None of the papers gives recommendations for the placement of sensors. Paper 1984/b discusses CO_2 control in a multi-level library hall with 6,400 m². The author suggests placing a CO_2 sensor on each floor, then choosing the highest reading for control.

Particular attention should be paid to the change of air flow pattern with occupancy load (1988/a), and the influence on the sensor signal.

The French system previously mentioned works as a centralized system in dwellings, with the room air exhausted in the bathroom and kitchen. The sensor element is situated beside the exhaust duct. The distribution of water vapour in a room is usually fairly uniform, so the air flow pattern is well mixed and no vapour distribution exists.

To create an effective and low cost system, a minimum number of humidity sensors should be installed, and a minimal level of technical sophistication should be applied to the controlling system. Since only limited information exists about the transfer of moisture from room to room, the best way to design a centralized system has not yet been determined.

Energy Savings

Most studies were performed to evaluate energy savings. With CO_2 control, savings are highest in rooms where occupancy variation is high and/or unpredictable.

Energy savings of between 8 % and 40 % are reported where energy consumption has been measured. When calculations were done by simulation or estimation, savings of 30 % to 60 % were reported. It seems that theoretical calculations always overestimate the potential savings. Paper 1988/b reports a 70 % reduction in running time, a 90 % reduction in energy consumption (including heat recovery) and a 20 % reduction in maintenance. In paper 1986/c it was even possible to reduce the running time from 10 hours per day to 22 minutes per day.

Paper 1981/a calculates an air flow reduction of 60% with CO_2 control. The author states that CO_2 control is more efficient than a heat recovery system.

Paper 1983/a specifies energy savings of 40 % with a CO_2 set point of 700 ppm, and a 10% saving with a set point of 650 ppm, compared to constant flow. However, a 30 % energy saving over constant flow can be realized with an adequate time control. In other words, time control seems to be a good--if not the best and most cost effective--control strategy when the occupancy load of a building over time is known. Reported pay-back times range from two to five years.

Conflicting information exists regarding the French humidity systems. Whereas paper 1983/d calculates energy savings between 50-60 %, paper 1985/c reports savings of 30 to 45 %. Paper 1988/c reports that this kind of system is not more efficient than a ventilation system with heat recovery.

6 Conclusions and Recommendations

6.1 Demand Controlled Ventilation: A Real Need

Airborne pollutants may affect the occupants of building and building fabric in different ways:

- **Health risks to occupants.** Exposure to airborne pollutants such as tobacco smoke, formaldehyde, combustion products, organic compounds, radon, humidity and moisture (mould and fungus) may result in an acute health response in the short term, and in more severe health risks the long term.

- **Irritation or discomfort.** Body odour, other odours and irritants, although not directly damaging to health, may give rise to minor physical irritation.

- **Damage to building fabric.** Internally generated pollution, especially water vapour, often leads to severe damage to the building fabric.

Many pollution sources originate in building materials, furnishings and decorations, as well as from activities and processes taking place within the building. Consequently, to achieve good indoor air quality the two most important strategies are source control and an adequate supply of outdoor air. At times it may be necessary to increase the rate of outdoor air supply, thus increasing the energy consumption for heating, cooling and distribution of the ventilation air. If, however, the ventilation system can be controlled so the supply air is constantly adjusted to the demand, significant energy savings may result, along with an improved quality of indoor air.

Strategy for demand controlled ventilating systems will depend on the type and function of the buildings in which they are located, and on the type of pollutant(s) present. In non-industrial buildings, demand for indoor air quality will depend mainly on occupancy load and human activities on the premises. Annex 18, therefore, focuses only on odours from occupants and building materials, tobacco smoke, carbon dioxide and humidity. Radon, combustion products, etc. will not be considered.

The findings of Subtask A are grouped in the following way:

- Control of Indoor Air Quality
- Sensors
- Demand Control Strategy
- Benefits

6.2 Control of Indoor Air Quality

The carbon dioxide concentration in a room is well established as an indicator of ventilation rate per person, and thus of indoor air quality, where odours emitted by non-smoking occupants are the major concern. This does not necessarily mean that odours in general can be regulated with CO_2 control, since odours can have many other sources, as described above.

Odour concentrations cannot be directly measured very easily because odour constituents vary from case to case. How well odour control (including tobacco smoke control) can be achieved will depend to a great extent on the performance of mixed gas sensors.

Humidity controlled ventilation is of primary importance in dwellings. The probability of mould growth varies from one room to another, depending on the moisture load, quality of insulation, ventilation rate, orientation of exterior walls, etc. /33/. No defined strategies exist to determine where humidity control or CO_2 control should be dominant. For example, many bedrooms have severe moisture problems. Normally, there is a significant increase in CO_2 concentration when the room is occupied, but only a slight increase in the relative humidity. The best way to approach this and other related problems has not yet been determined.

Cooking produces not only odours but also water vapour. While odours may bother occupants, excessive water vapour causes damage to the building fabric. In this case humidity control should be viewed as a primary goal.

Relative humidity and CO_2 levels by themselves are not always reliable indicators of overall air quality. Other factors such as tobacco smoke and odours may have to be monitored in buildings with DCV systems, to ensure that the resultant air quality is acceptable.

6.3 Sensors

Carbon Dioxide:

A variety of CO_2 sensors exists. Both old and new developments are on the market, and will be commercially distributed as of fall 1989. It appears that older developments have often been used in other applications than those pertaining to Annex 18, such as CO_2 control in greenhouses, breweries or other industrial areas. They are often used to ensure that the MAC value of 5,000 ppm will not be exceeded. Research into the long term performance of CO_2 sensors in the range between 400 and 2,000 ppm in different situations is needed.

Odours:

The term "mixed gas sensor" refers to any sensor which does not selectively measure one gas. These sensors are offered on the market under many names (CO-sensors, tobacco smoke control sensors, air quality sensors) which indicates their many applications.

Investigations show that signals from CO_2 and mixed gas sensors do not always correlate, although occupants were the only source. Mixed gas sensors often showed a strong sensitivity to tobacco smoke.

At this time, knowledge about the performance of mixed-gas sensors is very limited. Not only is there a lack of long term experience, but there are also questions about short term properties such as drift, stability, reproducibility, calibration etc.. There is a great need to accumulate more knowledge about these sensors.

Humidity:

There is a large variety of humidity sensors on the market, ranging in price, precision, measuring range and response time. In general, very inexpensive humidity sensors have not been used for ventilation control. A need exists for a design guideline for making a humidity sensor choice according to reliability, accuracy, maintenance and price.

Proper control of relative humidity is a complex issue. Theoretically, the desired set point should vary with indoor temperature, outdoor temperature, insulation and air leakage characteristics of the exterior walls. To date, there is no humidity control system which incorporates these requirements.

A humidity sensor test has been performed in Germany, from which valuable information can be extracted. However, additional information regarding the performance of humidity sensors in buildings is still required.

For each sensor type, performance requirements and existing properties have to be determined. A sensor test program is necessary to accumulate more knowledge. A final comparison of the test results and performance requirements will show which sensors are suited for demand control applications.

6.4 Demand Controlled Strategy

It is necessary to define the prerequisites, such as building envelope tightness, ventilation system maintenance and proper balancing, which must be met in order for the DCV system to be effective.

Depending on the use and design of the building and the ventilation system, sensor location and air flow patterns can greatly influence measured pollution levels. The influence of the number and location of sensors on DCV design and performance must be investigated, particularly with centralized systems.

DCV systems design must take other ventilation system functions into consideration, such as thermal comfort and control.

In larger buildings at certain times of the year, using large quantities of fresh air to control thermal loads can be a cost effective alternative. Under these conditions, thermal control will dominate over air quality control.

The potential benefits of DCV systems at different control reference levels can vary widely, depending on climate, building size and type, ventilation system design and occupancy patterns. The effect of the control set point on energy consumption should be investigated.

Cost will often be an obstacle to the widespread use of DCV systems. One possibility that should be investigated is whether manual, occupant or time clock control will deliver equivalent performance under field conditions, but at a lower initial cost.

DCV systems will often be added to existing buildings as a retrofit measure. Conditions under which retrofit DCV systems are practical should be defined.

A DCV system should be designed so that when the maximum predicted pollution emission rate takes place, the ventilation system will have a sufficient capacity to control indoor concentrations at desired levels.

6.5 Benefits

DCV system benefits will vary depending on climate, building type, ventilation system design and occupancy patterns.

Energy savings must be well defined, and must always be reported in relation to a defined reference system. Using this reference system, different control strategies can be examined to compare not only energy savings, but investment costs, pay back times etc.. It is also very important to report savings with regard to the achieved air quality.

7 References

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/24/ DIN 1946, part 2, Ventilation Techniques Health Requirements, January 1983

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/34/ N.N.: Study of methods for measuring atmospheric humidity, NOVEM, Nederlandse Maatschappij Voor Energie en Milieu b.v., P.O. Box 8242, NL-3503 RE Utrecht, Report No. M.87.235.1

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/45/ Werner, H. et al.: Fortschrittliche Systeme für Wohnungslüftung, Fraunhofer Institut für Bauphysik, P.O. Box 1180, D-8150 Holzkirchen 1, IBP-Bericht EB-21/1989, Teil B (in German)

Appendix A: Litterature Review of Contaminant Concentrations in Occupied Spaces

a) Feasibility of DCV systems in different buildings

Description:

The aim of the project was to monitor pollutants (CO_2, particles and combustible gases) in order to identify the most reliable indicator of air quality and to evaluate the feasibility of DCV systems. Thirteen buildings were monitored, including a department store, several office buildings, a theatre and a dining hall.

Results:

CO_2 appears as a reliable and accurate indicator where smoking is prohibited. Particles and combustible gases proved to be more reliable in situations in which smoking is allowed. In the department store a good correlation was always found among the three indicators, but in the dining hall, no correlation was found between CO_2 and the other indicators. In the theatre, only CO_2 provided reliable information about the occupancy level. Results were inconsistent in the offices, with good correlations being found some days and no correlation at all on others. As a conclusion, in buildings where smoking is prohibited the author recommends the use of a base ventilation such as 0.5 ACH, and peak ventilation depending on CO_2. In buildings where smoking is allowed, it is recommended that two indicators be measured (e.g. CO_2 for occupancy levels plus CO for cigarette smoke) and that the ventilation system be controlled according to the indicator calling for more air.

Reference:

Suomi, U.;
Control of the outdoor air intake by the use of contaminant monitoring. Proc. CLIMA 2000, Copenhagen, 25-30 August 1985, Vol. 4, Indoor climate [AIVC # 2108]

b) Measurement of organic compounds in 15 buildings in Italy

Description:

Fifteen buildings (detached houses and apartment houses) were studied, in the area of Varese (Northern Italy: about 2,400 DD (degree days), based on 19°C.)

The measurements were performed during the whole year, and the difference between indoor and outdoor temperatures ranged from 0 to 20°C.

The indoor and outdoor air were sampled locally, and then the concentration of respirable suspended particles (RSP) and of 35 organic compounds were measured at the laboratory.

The air change rate (ACH) was simultaneously measured during sampling time, using a tracer gas decay technique (SF_6).

Results:

A weak correlation was found between the number of air changes per hour and the temperature difference showing an increase of ACH with temperature difference.

No correlation at all was found between total volatile organic compounds (VOC) or RSP concentration and the number of ACH.

On the average, the VOC concentration indoors was about 10 times higher than the concentration outdoors (3,250 vs. 370 $\mu g/m^3$), while the average RSP value was only 30 % higher indoors than outdoors (81 vs. 63 $\mu g/m^3$).

Concentrations of formaldehyde remain well below the most conservative threshold limit value (120 $\mu g/m^3$), ranging between 8 and 52, with an average value of 27 $\mu g/m^3$. These results compare favourably with other reported values.

Reference:

De Bortoli et al.;
Measurements of Indoor Air Quality and comparison with ambient air - A study on 15 homes in northern Italy. EUR 9565 EN, 1985. Ispra (Italy) [AIVC # 2095]

c) Measurement of CO_2 level in a school (U.S.A)

Description:

This study focused on a new university building in Indiana, U.S.A. with IAQ complaints. The four-storey building had 5,600 m² floor area, and housed classrooms and offices. The ventilation system used is a VAV system which operates during the day from 06:00 to 23:00 and is turned off at night. The system operates on minimum 20% outdoor air supply and can be varied up to 100% for heating and cooling. The CO_2 level was monitored by a portable analyzer in both spring and autumn during eight-week periods. Once a week, each room was monitored five times on the same day.

Results:

Nine classrooms and two hallways were monitored. The highest CO_2 levels of 2,600 ppm were observed in fully occupied rooms. Levels up to 1,800 ppm were observed in hallways, but these levels were only observed during three weeks. The average CO_2 concentration was estimated to be 1,000 ppm. This conclusion is made from 660 observations.

The study indicates that a VAV system provides effective ventilation to highly occupied spaces.

Reference:

Godish T.; Rouch J.; McClure D.; Eliad L.; Seaver C.; Ventilation System Performance in a New Classroom Building Assessed by Measurements of Carbon Dioxide Levels Proceedings ASHRAE IAC '86, ISBN 0 910 110-40-4.

d) CO_2 levels in Portuguese school buildings

Description:

Ten schools located in the mildest climatic region of Portugal (900-1200 DD base 18°C). The CO_2 content was measured using a Dräger detector.

About 100 measurements were made by mid-mornings during the winter. Classroom windows were either partly open or completely closed.

In some cases, the CO_2 concentration was continuously monitored in order to assess the air change rates.

Results:

The air change rate was around 0.5 h^{-1} when the windows were closed, corresponding to 0.4 - 1.0 l/(s person). With open windows the air change rate was from 2 to 4 h^{-1}, corresponding to 1.6 - 10 l/(s person).

A statistical analysis of CO_2 levels, although not too significant due to the limited amount of data, shows that the typical allowable indoor concentration (AIC) value of CO_2 (1,000 ppm) is exceeded in 93 % of observations, and that a concentration of 5,000 ppm is exceeded in about 10% of observations. (See Figure A-1).

Reference:

Canha de Piedade A.; Rodrigues A.; Canau A.; Pereira J.; Air quality in Portuguese School Buildings: some results. Proc. III Int. Congress on Building Energy Management, Lausanne, September 1987.

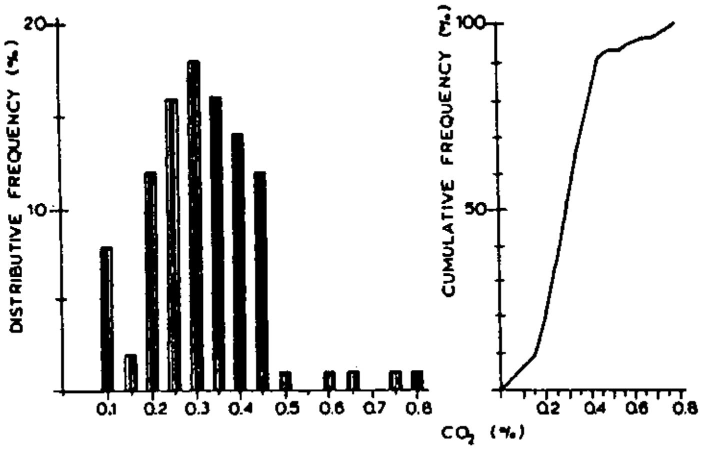

Figure: A-1: *Distributive and cumulative frequency function of CO_2 concentrations.*

e) Connection between body odour, CO_2 content of room air and air temperature in an auditorium of the Swiss Federal Institute of Technology, Zurich

Description:

The building studied was a mechanically ventilated auditorium with a room volume of 950 m^3 and seating capacity of 160. The ventilation system air inlet was located in the ceiling and the air outlet in the floor. Students were given a questionnaire at the end of each lecture concerning the auditorium's indoor climate and air quality. During the study, there were various numbers of occupants in the room, and the ventilation rates, CO_2 levels and air temperatures fluctuated. Room air was exhausted from the auditorium a few times during each lecture and offered to a test panel to judge the odour intensity in comparison to pyridine reference odours.

Results:

Variations were reported in the levels of CO_2 under different ventilation situations during two-hour lectures. After a 45 minute break, the CO_2 content of room air decreased. After about 80 minutes the CO_2 concentration stayed at the same level. With a ventilation rate of 16 m^3/hPers., the CO_2 concentration at the end of the two- hour lecture was about 1,400 ppm. A ventilation rate of 30 m^3/hPers. resulted in a concentration of about 1,000 ppm.

Results indicate that the test panel's judgments of odour intensity in comparison to pyridine reference odours seem to depend on the concentration of CO_2 in the room air. A good correlation could be found between the increased concentration of CO_2 and odour intensity of the room air. Only a weak correlation could be found between CO_2 concentration and increasing air temperatures. Conclusion: In rooms where smoking is not permitted, CO_2 content is a good indication of room air quality, and can be used to control the fresh air supply.

Reference:

Fecker, I.;
Frischluftbedarf und Regelung der Lüftung in klimatisierten Räumen, Diss. ETH Nr. 8361, Zürich 1987, Kapitel 7, p. 52-71, in German.

f) CO_2 levels in Finnish bedrooms

Description:

The Heating, Ventilation and Air Conditioning (HVAC) laboratory of the Helsinki University of Technology measured carbon dioxide concentrations in residential buildings during the heating season of 1987-88. Overnight CO_2 concentrations were recorded in 48 dwellings. The values in Table A-1 are steady-state concentrations measured in master bedrooms, and are therefore not necessarily maximum concentrations.

Results:

In dwellings with natural ventilation, the steady-state CO_2 concentration in master bedrooms varied from 500 to 2,800 ppm with an average of 1,400 ppm. In dwellings with mechanical exhaust the CO_2 concentration varied from 800 to 3,700 ppm, with an average of 1,350 ppm. In dwellings with balanced ventilation, the CO_2 concentration was between 800 and 2,900 ppm, with an average of 1,350 ppm (See Table A-1).

Reference:

Rönnberg, R.; Ruotsalainen, R.; Majanen, A.;
The performance of ventilation in residential buildings, Helsinki University of Technology, Laboratory of heating and ventilation, Report B23, Espoo 1989 (in Finnish).

Table: A-1: ***Steady-state CO_2 concentration in Finnish bedrooms for different ventilation and building types.***

CO_2-concentration ppm	Number of persons	Ventilation system	Building type
950 *	2	1	1
1 000	3	1	1
1 000	2	1	1
1 100	2	1	1
1 450	3	1	1
1 450	3	1	1
1 700	3	1	1
2 800 *	3	1	1
500	2	1	2
850	2	1	2
1 000	1	1	2
1 200	3	1	2
1 600	3	1	2
1 850	2	1	2
2 400 *	1	1	2
800	2	2	1
900	3	2	1
900	2	2	1
950	4	2	1
1 050	3	2	1
1 100	2	2	1
1 200	2	2	1
1 250	2	2	1
1 300	2	2	1
1 050	2	2	2
1 150	3	2	2
1 300	2	2	2
1 300	2	2	2
1 600	2	2	2
1 700	3	2	2
1 700	2	2	2
3 700 *	3	2	2
850	2	3	1
950	2	3	1
1 000	2	3	1
1 000	2	3	1
1 000	2	3	1
1 200	3	3	1
1 300	3	3	1
1 400 *	3	3	1
2 200 *	2	3	1
800	3	3	2
800	2	3	2
900	2	3	2
1 050	2	3	2
1 600	3	3	2
2 500 *	3	3	2
2 900 *	3	3	2

* = bedroom door closed

Ventilation system:
1 = natural ventilation
2 = mechanical exhaust
3 = balanced ventilation

Building type:
1 = dwelling
2 = flat

g) Comparisons of CO_2 concentrations in a school with natural and with mechanical ventilation (Germany)

Description:

CO_2 concentrations were measured in four classrooms as well as outdoors. Two of the classrooms had natural ventilation and two had mechanical ventilating systems.

Results:

Figure A-2 shows five minute mean values during a daily measuring time from 08:00 to 13:00, averaged over all school days in the heating season of 1985-86. CO_2 concentrations in the naturally ventilated rooms were significantly higher than in the rooms with the balanced ventilating systems. CO_2 levels decreased during the breaks after the 45-minute lectures. Figure A-3 shows the CO_2 concentration in a naturally ventilated room during a one-day period with extremely poor ventilation. The peak concentration at 14:00 is only slightly below the MAC value.

It is possible that CO_2 concentrations in the naturally ventilated rooms increase when the outdoor temperature is lower, because occupants do not open the windows as frequently as they do on moderate days. Figure A-4 shows the frequency function of CO_2 concentrations during lecture times in these four rooms. As Figure A-4 indicates, levels of 2,000 ppm were never reached in the two rooms with the balanced systems, whereas concentrations above 3,000 ppm were recorded in the naturally ventilated rooms.

Reference:

Efstratios Rigos; Wido Amonn;
Natürlich und mechanisch belüftete Klassenräume - Vergleich von Luftqualität und Energieverbrauch, KI 5/1988, p. 232-235, in German.

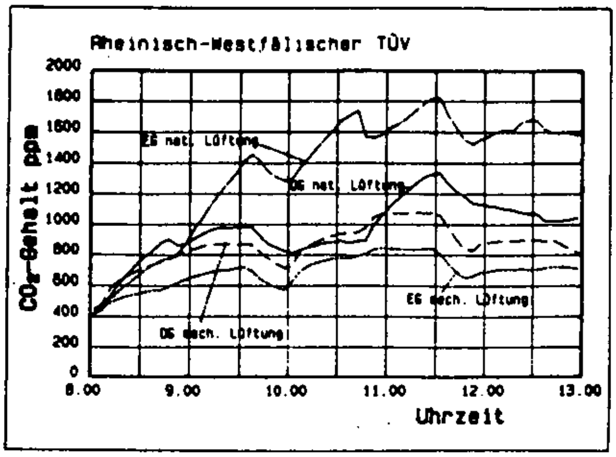

Figure: A-2: *CO_2 concentration vs. time averaged over all lecture days during the heating season.*

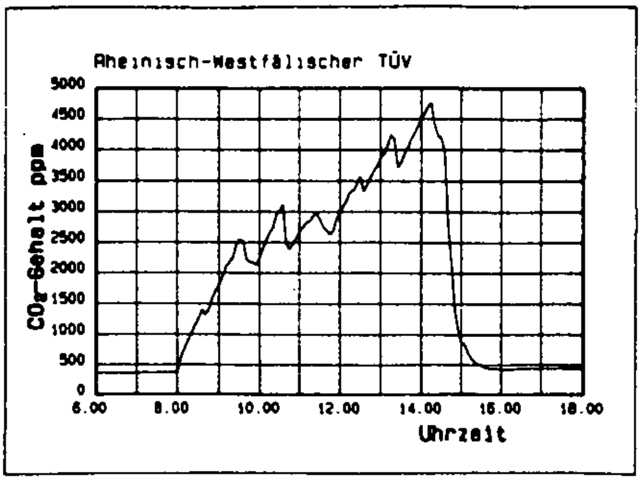

Figure: A-3: *CO_2 concentration vs. time during a day with extremely poor ventilation.*

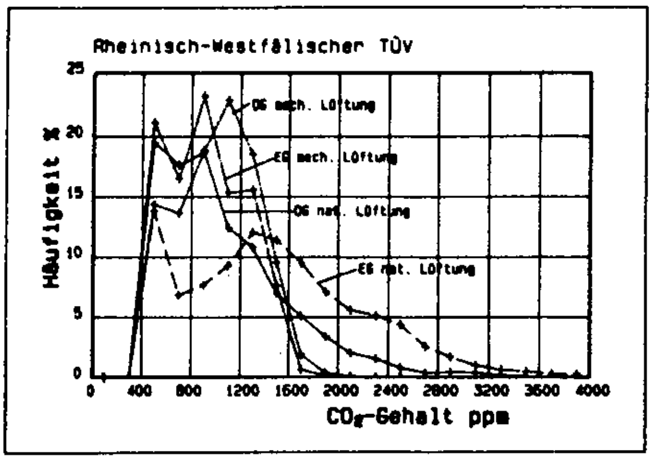

Figure: A-4: *Frequency function of CO_2 concentrations during the heating season 1985 / 1986.*

Translation:
EG nat. Lüftung = naturally ventilated room on ground floor
EG mech. Lüftung = mechanically ventilated room on ground floor
OG nat. Lüftung = naturally ventilated room on first floor
OG mech. Lüftung = mechanically ventilated room on first floor
Häufigkeit = frequency

h) CO_2 measurements in Belgian school buildings

Description:

A large measurement campaign was carried out in 260 classrooms during the 1987-1988 heating season. Only instantaneous values of CO_2 levels, temperature and air velocities were recorded.

A second campaign, limited to 25 classrooms, was carried out during the 1988-1989 heating season.

CO_2 and temperature levels were recorded continuously over a period of several weeks. A third campaign is planned for the heating season 1989-1990 to evaluate the effect of certain improvements.

Results:

Table A-2 and Figure A-5 summarize the results obtained during the first heating season. Concentrations of more than 1,500 ppm were measured in almost 50% of the cases.

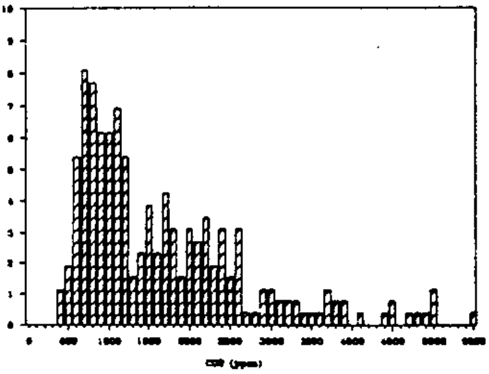

Figure: A-5: *Histogram of measured CO_2 levels in 260 classrooms.*

Table: A-2: *Number of CO_2 measurements in classrooms exceeding a certain limit [16].*

CO_2 (ppm)		⩾ 1000	⩾ 1200	⩾ 1500	⩾ 2000	⩾2500	⩾ 4000
Number	ABS	181	147	123	84	47	11
	%	70	57	47	32	19	4

Reference:

Wouters, P.; L'Heureux, D.; Voordecker, P.; Bossicard, R.; Ventilation and air quality in Belgian buildings: a state of the art, 9th AIVC Conference Gent, 1988

i) Summary of Measured CO_2 Concentrations

Table A-3 reports CO_2 levels from a number of studies of auditoria, gymnasia, schools, day nurseries and offices with various ventilating systems. The measured mean and maximum CO_2 levels vary substantially, indicating that some rooms have CO_2 values that are too high, while others seem to be over ventilated.

References to Table A-3:

1. Strindehag, O. Persson, P-G
Auditorium with demand controlled ventilation
Air Infiltration Review Vol. 10, No. 2, Feb. 1989, AIVC

2. Drangsholt, F.
Ventilation by demand
SINTEF Report No. STF15A88-038
October 1988, ISBN 82-595-5365-1

3. Anon.
Ventilation control by measurement of carbon dioxide levels in public entertainment buildings July 1986, [AIVC # 2599]

4. Hansen, L.
Monitoring of symptoms as a control of the effect of intervention in the sick building syndrome
Indoor Air '87, Berlin, Vol. 2, p. 459 - 463
ISBN 3-89254-034-9

5. Nguyen, V.H.; Martel J.G.
A field study in three office towers in Quebec, Canada
Indoor Air '87, Berlin, Vol. 2, p. 512 - 514
ISBN 3-89254-034-9

6. Brännström, J. et al.
Ventilation, air quality and annoyance in a large office building (in Swedish)
Report No. 9603-8501 from Statshälsan, 1985

7. Matsson, M.
Progress report from measurement in 19 day nurseries in a suburb of Stockholm, 1989, unpublished

8. Egedorf, M.
Ventilation in kindergartens (in Danish, Ventilationsbehov i bφrneinstitutioner)
Teknologisk Institut, Taastrup Dec. 1987
ISBN 87-7511-803-3, [AIVC # 2953]

References to Table A-3, cont'd

9. Andersson R.; Boman, C-A.; Sandberg, M.
Indoor climate problems in a kindergarten and how they were solved. Indoor Air '84, Stockholm, Vol. 3, p. 335-340 Swedish Council for Building Research Report D 18:1984
ISBN 91-540-4195-3

10. Potting, J. et al.
Health Complaints, CO_2 levels and indoor climate in Dutch schools. Indoor Air '87, Berlin, Vol. 2, p. 582-586
ISBN 3-89254-034-9.

Table: A-3: Measured CO_2 concentration levels in different types of buildings

Identification		Measured in country	BUILDING DESCRIPTION								Air rate exhaust h^{-1}	Sick bldg.	Stuffy air	absolute CO_2 conc.									COMMENTS
			Type of use	Ventilation system										measured in				conc. [ppm]			no of persons in the room	room volume m^3	
Reference				Natural	Exhaust	Supply Exhaust	Supply Exhaust +Return air	Supply +Exhaust +Humidified	Unknown	DCV System				single room	rooms	whole bldg	unknown	mean	max	min			
1.	Test room Fläkt	S	auditorium							X				X				800			51	390	VAV-system
2.	Drangsholt	N	gymnasium -"-			X	 X							X X					600 1000		0-30 0-30	1200 1400	
2.	Drangsholt	N	school school			 X	X							 X		X		 450	950 500		450 100	18000 8000	3 hours max conc.
3.	Cinema and Bingo Hall	GB	cinema			X												910			679	22500	
4.	7 Day Nurseries	DK	day nursery						X			X					X		2700	400			Problem: man-made mineral fiber
5.	3 offices in Quebec	CAN	office				X	X				(X)		X					1200	700			problems were found
6.	Garnisonen	S	office				X				after work 0,1	X			X			700	1000				At 800 ppm body odour was recognized
7.	19,Day Nurseries Max conc.	S	day nursery			X						X		X	X			1600	2600	350			Max conc. during
8.	8 Day Nurseries	DK	Day nursery	X	X	X											X		2100	800			Mean conc. during 12 h, peaks 5000 ppm measured
9.	1 Day Nursery 2) Malmö, before remedial action	S	day nursery			X					8	X		X				1300 1500	a) b)		18	54	Supply-exhaust devices at the ceiling
9.	1 Day Nursery 2) Malmö, after remedial action	S	day nursery			X					4			X				1400 1700	c) d)		18	54	Supply-exhaust devices floor-ceiling
10.	14 classrooms	NL	school						X				X	X					2500	1200			

1) The day nurseries are located in the ground floor of 4 storied bldgs.

2) The objective with this project was to reduce energy without sacrificing the IAQ.The supply air temp. was compaired to roomair temp and the difference was a) -2,1° C b) +5,6° C c) -1,2° C d) +4,1° C.

j) Indoor climate in Dutch dwellings, State of the Art

Results:

Figure A-6 shows the percentage of the Dutch dwellings in which the threshold limit values (TLV) of various contaminants exceeded those for a healthy indoor climate.

NO_2: The TLV of NO_2 for a healthy indoor climate were exceeded in approximately 90% of the dwellings. Levels could be considered seriously high in 23% of the cases. In dwellings, NO_2 is caused mainly by gas appliances such as hot water heaters and gas stoves which lack discharge facilities. Concentrations of up to 2,000 $\mu g/m^3$ occur with geysers, but the peak level of contamination caused by gas stoves is much less.

CO: A CO concentration of 8.7 ppm corresponds with the threshold value for healthy indoor climate. In 1985, 5.6% of dwellings studied exceeded this value. In 20% of the dwellings examined, using a geyser for 15 minutes led to average hourly concentrations of more than 50 ppm.

CO appears as a result of incomplete combustion. Outside dwellings, traffic is the most common source. The TLV for the mean of eight hours was exceeded in about 1% of the dwellings due to traffic. Indoors, a geyser without discharge is the main source. High concentration levels occur when appliances are not properly maintained.

Respirable dust:
The concentration of respirable dust in dwellings of non-smokers is about 30 mg/m^3. Each cigarette smoked causes an increase of the daily average of 2-5 mg/m^3.

One person smoking eight to 10 cigarettes a day is enough to exceed the average yearly threshold value of 40 mg/m^3. With one or more smokers present, the TLV of respirable dust was exceeded in about 60% of the dwellings studied.

Moisture:
Approximately 15% of the Dutch dwellings investigated had problems caused by excessive relative humidity.

Reference:

N.N.: Zorgen voor Morgen, RIVM, Rijksinstitut voor Volksgezondheid en Milieuhygiene, Nationale Milieu Verkenning, 1985-2100.

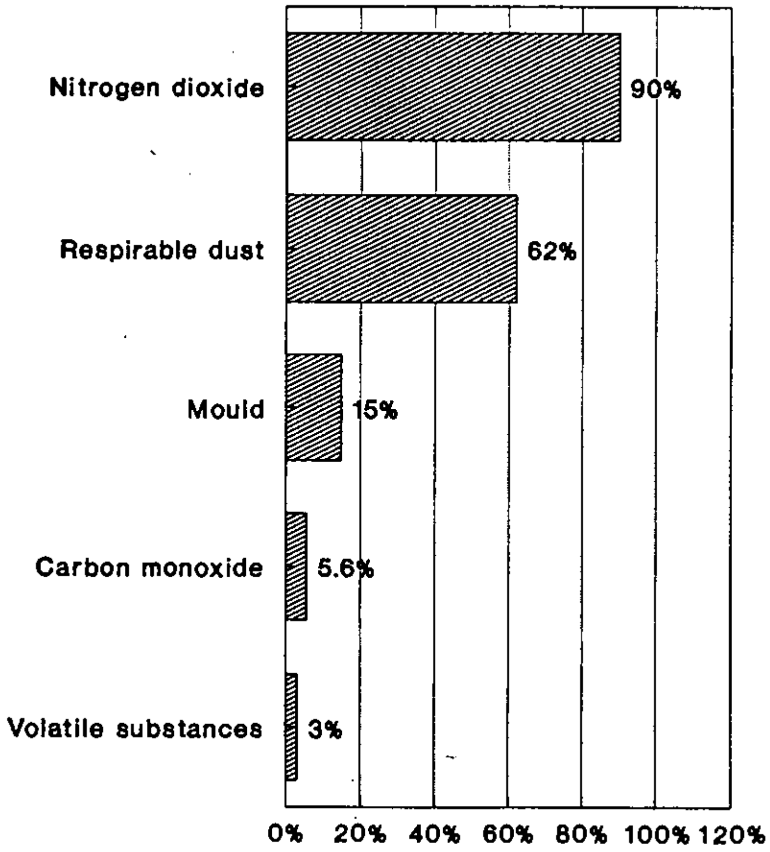

Figure: A-6: *Percentage of Dutch dwellings in which the threshold values for healthy indoor climate were exceeded.*

Appendix B: Litterature Review of Measuring Results and Knowledge about Demand Controlled Ventilating Systems

1979/a CO_2 Controlled Ventilation - American School

Description:

This 1979 paper is probably one of the first to address the problem of demand controlled ventilation (DCV). It examines the various contaminants produced indoors as possible indicators of the need of fresh outdoor air for the assessment of ventilation rates.

Existing heating, ventilation and air conditioning (HVAC) systems are also evaluated for possible conversion into DCV systems.

Finally, the paper estimates the potential energy savings of DCV systems in educational buildings in different U.S. locations.

Results:

After a theoretical analysis supported by some experimental data, the authors come to the conclusion that CO_2 is the best indicator to drive a ventilation system. It also provides a schematic (Figure B-1) of a double duct HVAC system with a CO_2 sensor control.

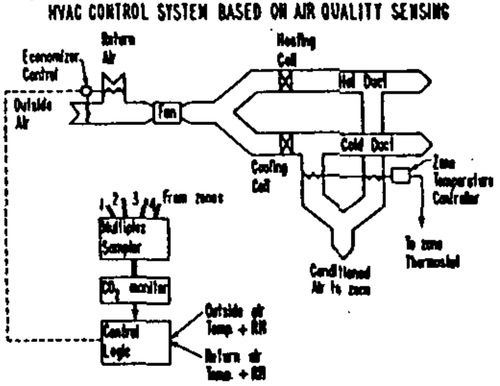

Figure: B-1 *Schematic of a double duct HVAC system with an air quality sensor control system.*

A simple evaluation of the economical feasibility of this type of system suggests that a typical school building of 4,650 m^2 in the Northeast or North Central U.S. would realize annual savings of between $4,300 and $5,600, assuming that the amount of fresh air is reduced by 17 $m^3/(h\ person)$. This would result in a pay back period of three to four years.

Reference:

Turiel I.; Hollowell C.D.; Thurston B.E.;
Automatic variable ventilation control systems based on air quality detection. Second Int. CIB Symposium on Energy Conservation in the Built Environment. Copenhagen, 1979
[AIVC # 1022]

1981/a CO_2 Based Ventilation

Description:

This paper provides a theoretical analysis of the potential energy savings resulting from the use of CO_2 controlled ventilating systems. The calculation is based on locating the sensor in the exhaust air. This study was completed in 1981 and the results are based on only a few experiments that had been published at that time.

An analysis of the best choice of sensor techniques was also made.

Results:

The analysis given states that it was more cost effective to install a CO_2 controlled ventilating system than air-air heat exchanger. Calculations indicated a 60% reduction of the mean air flow rate over 24 hours.

Infrared absorption technique was selected because of threshold limits, accuracy, stability, calibration interval size, durability, and price.

The conclusions were made before discussions about indoor air quality and sick buildings began.

Reference:

Thellier F.; Grossin R.;
CO_2 based ventilation in buildings, "Energy conservation in buildings-heating, ventilation and insulation" Proceedings Contractors Meetings Brussels 1981-1982, p. 364-368
[AIVC # 1181]

1982/a Subjective and Objective Evaluation of CO_2 Control - American school, Part I

Description:

This study took place in the music wing of a high school in Minnesota, U.S.A. For five days in 1980, the heating system was equipped with a CO_2 controlled variable ventilation system.

A control strategy was used in which the outdoor air dampers remained fully closed until the CO_2 levels reached a set point of 3,000 ppm, and would modulate up to 5,000 ppm!

Results:

CO_2 levels never exceeded 1,500 ppm during the test. The authors still concluded that CO_2 control was technically feasible, even though it was not in action during the test. The report contains no information about sensor location, control sequences or ventilation system design. The air quality was monitored by the Lawrence Berkeley Labs and nothing was found that is considered to be unhealthy, according to current standards.

The authors raise a series of probing questions such as:

1. Did the students respond to CO_2 concentrations or were they reacting to a combination of bioeffluents?
2. How much effect did the low ventilation efficiencies have on the objective and subjective results?
3. Why were less air movement and more staleness perceived when the CO_2 controlled system was in operation?
4. Why did the students perceive increased temperature at higher CO_2 levels?
5. Why did the students report that the room felt fresher and cooler, the air seemed less still and that they felt cooler and had cooler hands when the CO_2 controller was not in operation?

Reference:

J.E. Woods; G. Winakor; E.A.B. Maldonado; S. Kipp:
Subjective and objective evaluation of a CO_2 control variable ventilation system, preprint ASHRAE Transactions Vol. 88 No. 1, 1982 [AIVC # 1051]

1982/b CO_2 Controlled Ventilation - American School, Part II

Description:

This paper is a subsequent report on the same experiment summarized in 1982/a. It describes the ventilation system, the control strategy and set points in greater detail. The same questionnaire data is presented, collected under the same environmental conditions. In this report, the system was shown to be capable of controlling CO_2 at lower levels than the 3,000 to 5,000 ppm reported in 1982/a.

Six CO_2 sampling points (four zones, one return air and one outdoor air) were used, leading to a pump, a series of switching valves and a single non-dispersive infrared analyzer. Ventilation was controlled by the highest reading.

The fresh air dampers were modulated to achieve either temperature or CO_2 control, depending on which was calling for more outdoor air. The dampers for the two control variables were in parallel in the same ducts. This approach led to non-linearities in control, which could be eliminated in future designs.

Results:

After the questionnaire process was complete and in order to prove the effectiveness of the control system, the CO_2 levels were controlled at 825 ppm (dampers start to open) to 1,375 ppm (dampers fully open). The questionnaire was not reissued at the higher rate of ventilation. CO_2 control was shown to be feasible.

Ventilation efficiency was measured.

Reference:

Jansen J.E.; Hill T.J.; Woods J.E.; Maldonado E.A.B.: Ventilation for control of indoor air quality - a case study, Proc. of the Intern. Symp. on indoor air pollution, health and energy conservation, Amherst Mass. U.S.A. 13-16 Oct. 1981, Environmental Intern. Special Issue "Indoor Air Pollution", Vol. 8, No. 1, 1982 [AIVC # 1133]

1982/c Energy Savings with CO_2 Control - Great Britain

Description:

This paper outlines energy savings calculations in detail. In the first section, theoretical considerations about CO_2 control and energy savings are discussed, along with the impact of infiltration, occupancy and timed ventilation.

The second section deals with the field assessment. CO_2 levels were measured in a theatre and a store, then energy calculations were made. The impact of the building's heating or cooling load with respect to CO_2 is outlined.

Results:

In the theatre test, savings of 20% of fresh air were estimated. Tests in the store estimated cost savings of £924 per annum, versus £1,600 for the control system investment.

Reference:

Warren, B.F.:
Energy saving in buildings by control of ventilation as a function of indoor carbon dioxide concentration, Building Services Engineering Research and Technology, 1982, Vol. 3, No. 1
[AIVC # 961]

1983/a CO$_2$ Control - EKONO Office Building - Finland

Description:

These experiments were carried out in a Finnish office building. A balanced ventilation system with recirculated air is used as the air heating system. A CO$_2$ sensor was placed in the main exhaust air duct. The sensor regulates the amount of recirculating air flow by controlling the motors that regulate the dampers in the air ducts. The office building has a floor area of 4,700 m^2 and a volume of 14,800 m^3.

The supply air is introduced into each room by devices placed in the ceiling 1.5 m from the external wall. Air is exhausted through air grills.

The controlling sensor is Siemens 2FPBZ. It has a measuring range of 0 - 3,000 ppm, and accuracy of +/- 50 ppm. Three control cases were studied:

1. Constant outdoor air flow is as follows:
   08:00-17:00 (working hours) 8.5 l/s,person
   17:00-20:00 4.2 l/s,person
   20:00-08:00 (overnight)none
   (These are typical running conditions of ventilation systems.)

2. CO$_2$ control, set point 700 ppm.

3. Time-related control as follows:
   08:00-09:30 increasing from 0 to 8.5 l/s,person
   09:30-15:30 constant flow 8.5 l/s,person
   15:30-17:00 decreasing from 8.5 l/s,person to 0
   17:00-08:00 no outdoor air flow

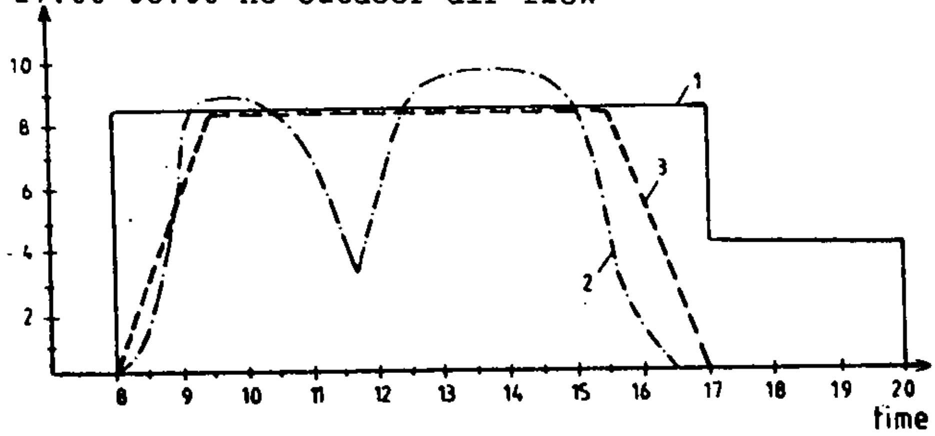

Figure: B-2: *Air flow rate versus time for three different control strategies.*

Results:

The carbon dioxide concentration was measured with a non-dispersive infrared instrument, ANDROS 302. Measurements were taken at several points in the return air duct, after the fan, and were found to be the same. This shows that the concentration does not vary in any part of the duct's cross section.

The concentration rose to 750-850 ppm when control case 1 was applied. The changes in CO_2 concentration correspond closely to the degree to which the office is occupied.

In control case 2, the CO_2 concentration in the recirculation air was approximately 700 ppm (set point).

When the outdoor flow was regulated according to control case 3 the CO_2 concentration corresponded fairly well to the conditions registered in control case 2.

Local variations of CO_2 concentration were measured in a typical office room, and registered the highest concentration just under the ceiling, near a window.

When control system 1 and 2 were used, employees were asked to comment on temperature, ventilation and air quality. There was no significant difference of opinion about comfort using either of the systems.

At the same time as CO_2 concentration was measured, a gas-chromatographic analysis of the indoor air was carried out over several days in order to study the connection between CO_2 concentration and the presence of other air pollutants. Results showed no apparent connection between CO_2 and other gases.

Energy savings are calculated to be 40% of the energy used for heating outdoor air, when the CO_2 controlling system has a set point of 700 ppm as opposed to constant flow (i.e. control case 2 compared to control case 1). When the CO_2 set point is 650 ppm, the energy conservation is estimated at only 10%.

The time-related control (control case 3) is calculated to save 30% more energy than constant flow (control case 1).

Installing a CO_2 control system in the central duct system of an office will result in potential energy savings with a reasonable pay-back time.

References:

The following references are based on the same study:

1. Södergren D.; Punttila A.;
A CO_2 controlled ventilation system. Pilot study. Swedish Council for Building Research Document D7:1983
[AIVC # 1218]

2. Södergren D.;
A CO_2 controlled ventilation system.
Proceedings from Indoor Air 1981, Amherst U.S.A.
[AIVC # 1132]

3. Södergren D.; Punttila A.;
Ventilation control according to need.
[AIVC # 1299]

4. Kuusela L.;
A CO_2 controlled ventilation system.
Proc. CIB workshop on indoor air quality and energy conservation, Helsinki, June 1983 ESPOO Report B3, p. XI.1-XI.5
[AIVC # 1418]

1983/b CO_2 Controller for Theatres, Retail Stores and Cinemas

Description:

A DCV system based on CO_2 control was introduced. The electronic controller controls the speed of the supply and the extract fans. No detailed technical description was given.

Results:

It should be mentioned that the author is a sales engineer of the company that produced the CO_2 control system, known as "The Breathaliser". The paper claims that cost savings of 30% can be achieved, resulting in a pay back time of 12-15 months. In a lecture theatre a pay back time of only six months was expected. Figures given are estimates and are not the result of measuring.

Reference:

Lyons M.;
The Breathaliser Test, Energy Manager, Vol. 6, No. 10,
p. 59-61, 1983, [AIVC # 1273]

1983/c Principles of a Photoacoustic CO_2 Sensor

Description:

This paper describes the general function principle of a photoacoustic CO_2 sensor. The sensor was designed at the Institute of Applied Physics, ETH Zürich.

Results:

Measuring accuracy was around 35 ppm for the prototype.

Reference:

Oehler O.;
CO_2 Gehalt als Führungsgrösse (CO_2 content as the command variable) Clima. Comm. Internat. Oct. 1983, Vol. 17, No. 10, p. 42
[AIVC # 1291]

1983/d Humidity Controlled Ventilation - French Dwellings

Description:

The concentration of air pollutants such as CO_2 and odour is closely related to the production of water vapour. The only exceptions are in kitchens and bathrooms, where vapour production predominates.

The ventilation system described in this article supplies outdoor air to the living room and bedrooms, and extracts air from the kitchen and bathroom. Humidity sensors in the exhaust air measure the average humidity and determine how much outdoor air is in total supplied to the flat. The proportion of outdoor air supplied to individual rooms is a function of each room's humidity level.

Both the kitchen and bathroom can have manually controlled short term supplementary air evacuation.

The system is very simple to install and causes surplus costs of approximately 1,500 F (1983, for a two- or three-bedroom flat).

No heat recovery device is mentioned.

Results:

Humidity control prevents condensation problems. Air infiltration through leaks is automatically taken into account. During cold periods the air exchange rate is automatically reduced because the outdoor air contains less vapour.

Energy savings in the range of 50-60% have been calculated (in comparison to ventilation systems using other means than humidity control). The estimated pay back time is five to six years.

Humidity sensors, air inlets and exhaust terminals have been tested for several years at the Laboratoire des Renardières (EDF) and Laboratoire du CETITAT to determine their reliability under different operating conditions.

Reference:

Anon; Un nouveau principe de ventilation mécanique - la ventilation hygroréglable; Chaud-Froid- Plomberie; Nov. 1983, Vol. 37, No. 37, in French [AIVC # 1318]

1983/e Is H_2 or CO_2 a Better Indicator for Controlling a Ventilating System in a Dwelling?

Description:

A numerical study was undertaken based on a simulation of a dwelling with CO_2 control. Assuming an occupancy profile over the day and applying ventilation rates according to French standards, a reduction of 60% of the mean flow was calculated. Other experiments were performed that give insight into the relationship between CO_2 and vapour concentration versus occupancy load.

Results:

A very good relationship was found between CO_2 and occupancy load, but a correlation between CO_2 and vapour concentration was difficult to establish. CO_2 concentration in different rooms of the 80 m^2 dwelling ranged between 400 and 750 ppm, having an extraction flow rate of 0.6 h^{-1}. The fan was controlled with two speeds. An average air change rate of 0.5-0.6 h^{-1} was sufficient to maintain the humidity in the house in the region of 60%. The high ventilation flow rate (0.8 h^{-1}) was only used about 30 minutes a day during meal preparation.

Reference:

Barthez M.; Soupault O.;
Control of ventilation rate in buildings using H_2O or CO_2 content, Energy Savings in Buildings Proc. CEC Inter. Sem. The Hague Netherlands 14-16 Nov. 1983, p. 490-494, [AIVC # 1370]

1983/f CO_2 Controlled Ventilation - British Supermarket

Description:

The building is a 6,700 m² supermarket located in South Wales. A single storey warehouse is attached to one corner, and two-storey offices, service rooms, preparation areas and cafes flank two sides of the sales area.

Roof-mounted air handling units were designed to serve the sales area with unit heaters and to serve in the ancillary areas with radiators and mechanical ventilation, as necessary. The units also provide refrigeration for the relevant gondolas in the sales area.

The six unit heaters in the store can modulate between full recirculation and full fresh air, the dampers being controlled according to occupancy.

Selection of the CO_2 set point for the controller (in parts per million) was achieved using recommendations from the Chartered Institution of Building Services Engineers (CIBS) guide.

Results:

The application of occupancy-linked variable fresh air control appeared ideally suited to a large retail trading centre like this where occupancy levels vary to a great extent depending on the time of day, day of the week, and time of the year.

Both carbon dioxide analysis and various types of occupancy-counting devices were considered as indicators of the rate at which fresh air was required. The latter system had a number of drawbacks, not the least of which was its inability to compensate for variations in the rate of natural infiltration. The CO_2 analyzing system automatically compensated for this. (In South Wales the wind often reaches 45 m/s).

After contacting a number of instrument and control manufacturers, the Horiba CO_2 analyzer was selected as the best equipment for the application in question.

Reference:

Ashley, S.;
Paying Dividends, Building Services, November 1983.
[AIVC # 1389]

1984/a Air Quality Control Strategies for Health, Comfort and Energy Efficiency

Description:

In general, the author discusses how to control the indoor environment rather than how to regulate ventilating systems. Strategies for achieving and maintaining a healthy building are discussed.

Results:

The paper deals with economic matters in an attempt to find a life-cycle cost for a building, taking into account the people living or working in it.

A proposed definition for IAQ is:

The quality of the air in an enclosed space is defined as an indicator of how well (i.e. bad-good, or 0-10) the air satisfies the following conditions:

- Thermal requirements
- Acceptable concentrations of CO_2 and O_2
- Concentrations (of gases, particulates, radon) should be below levels that can have bad effects.

The designs of ventilation systems and the building as a whole are discussed, taking into account one- and two-cell models, room air distribution factors and system air distribution factors. Finally, the conclusions suggest the possibility that new strategies for dilution control such as CO_2 controlled ventilation may increase energy efficiency and cost effectiveness without decreasing environmental acceptability.

Reference:

Woods J.E.;
Air Quality Control Strategies for Health, Comfort and Energy Efficiency. Indoor Air 1984, Part 1 [AIVC # 1450]

1984/b CO_2 Controlled Ventilation - American Library

Description:

The building studied was a library with a total floor area of 6400 m^2 at Brunel University. The authors evaluate the pay back times of different methods of reducing the ventilation load (VL) ($VL = \rho \cdot C_p \cdot Q = 16$ kW/K), and suggest a CO_2 controlled ventilation system as the best solution. (Pay back time of such a system is approximately 6.3 years.)

The proposed ventilation control system is illustrated in Figure B-3. A Horiba CO_2 analyzer is connected to the library exhaust air duct. The analogue signal from the analyzer is conveyed to the controller/data logger, which in turn adjusts the damper angle, through a servo motor. The exhaust dampers close when the concentration in the exhaust air is less than 500 ppm. A linear relation between damper angle and CO_2 concentration is assumed.

Results:

A small number of measurements, performed when the system was fully operating, showed that the system was always able to keep the concentration below 600 ppm, and that there was a reasonable correlation between the number of people in the library and the CO_2 level. A problem of underventilation was found in certain areas, suggesting that CO_2 analyzers should be installed on every floor of the library and that the controller should be programmed to respond to the maximum CO_2 level.

Reference:

Smith B.E.; Prowse R.W.; Owen C.J.;
Development of occupancy-related ventilation control for Brunel University Library, Proc. of 5th AIC Conference, Reno, Nevada, 1-4 Oct. 1984 [AIVC # 1590]

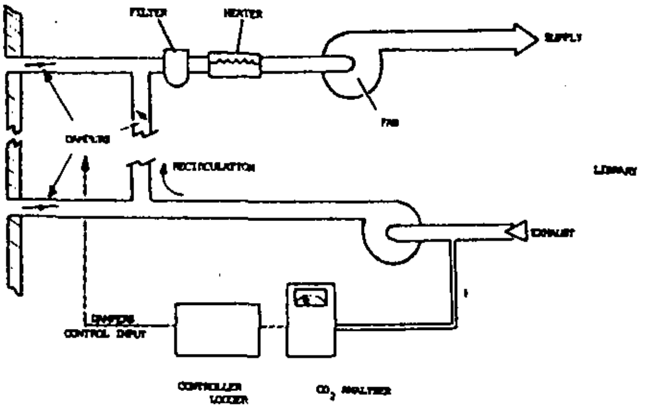

Figure: B-3: *Schematic of ventilation control system.*

1984/c Long-term Monitoring of Radon, Particulates and Carbon Dioxide - Sweden

Description:

Long-term monitoring of radon, particulate and carbon dioxide concentrations was carried out in two Swedish public buildings, a university building and a high-school building. Concentrations of particulates and CO_2 were measured in the exhaust air over a period of 25 days. Both buildings use modern, controllable ventilation systems, but only in the latter is the air recirculated and filtered. In both cases the occupancy and ventilation are periodic, i.e. confined to working hours. Several hundred people use these buildings daily.

Results:

In each case of long-term monitoring, a distinct periodic behaviour of pollutant concentrations was observed. CO_2 and particulates were at their greatest levels during working hours, but fluctuations of particulate concentration were faster and more irregular. The correlation coefficient of CO_2 and particulate concentrations was 0.94. This rather good correlation should not obscure the fact that the rapid and large fluctuations of the particulate concentration make its applicability to ventilation control questionable. However, the use of an particulate monitor could be justified in spaces where smoking is the dominant source of indoor particulates.

Simultaneous measurements of particulate concentrations in the exhaust air and in one of the high school classrooms showed that local concentrations can be considerably higher (up to three times) than the average concentration in the exhaust air.

A case study of CO_2 controlled ventilation was conducted in the university building. The fans were controlled by the indoor CO_2 concentration using a P-controller and frequency converters. The author assumes a linear relationship between the fan control voltage and the total energy consumption of the ventilation system. The daily energy savings varied between 13-20% in this experiment, and no significant changes in the pollutant concentrations could be observed.

Reference:

Kulmala V. et al;
Long-term monitoring of indoor air quality and controlled ventilation in public buildings. Indoor Air. Vol. 5. Buildings. Ventilation and Thermal Climate. Edited by B. Berglund, T. Lindvall, J. Sundell. Swedish Council for Building Research, 1984. 435-441. [AIVC # 1650]

1985/a Field Measurements of Air Quality Controlled Ventilation - Norway

Description:
This paper deals with field measurements in which the relationships between CO_2, particles and combustible gases in various buildings were measured and analyzed. Results from tests with an air quality controlled ventilation system in one building are also presented.

Results:

Comparison of AQ-sensor and particle load due to smoking:

Variations of CO_2 concentration, particle concentration and quantity of combustible gases in the indoor air were measured and recorded in 13 buildings for approximately one week each. Samples were taken from either room or exhaust air.

The measurements and analyses indicated that CO_2 level is an accurate and reliable indicator of air quality when driven by bioeffluents. However, when smoking is allowed, the CO_2 level alone is not a reliable air quality indicator. Cigarette smoke does not significantly affect the CO_2 level, although it certainly causes air quality to deteriorate.

The other two indicators measured, variation of particles and quantity of combustible gases proved to be more reliable in spaces where smoking is allowed, as both these indicators react to tobacco smoke. However, since neither of these indicators reacts reliably to occupancy load, they cannot be used either single or together as the only means to control air quality and ventilation.

The paper discusses different controllers (P-PI-PID controller). Information given in the paper about the controllers is vague, and it is therefore difficult to draw conclusions.

Reference:

Suomi U.; Seppänen O.;
Field measurements of air quality controlled ventilation.
Recent Advances in Control and Operation of Building HVAC Systems, May 22-23, 1985. Trondheim, Norway. p. 76-82.
[AIVC # 2021]

1985/b CO_2 Controlled Ventilation - Swedish Auditorium

Description:

This study took place in an auditorium with a seating capacity of 850 and room volume of 4,000 m^3. A balanced ventilation system with 2 m^3/s flow rate of supply and exhaust fan was in place. The Stäfa Control System odour sensor was mounted in the vicinity of the exhaust air terminal device. CO_2 was measured with an IR analyzer only for checking and comparison. The DCV system was controlled according to thermal and odour requirements, with the thermal control being dominant.

Results:

A very good correlation was found between CO_2 concentrations and occupancy patterns. Results are given both when heating load and air quality were dominant for control. When occupants are the only emitters of CO_2 and heat, temperature control will be dominant when the outdoor temperature is above 10°C and the desired CO_2 concentration is set at 1,200 ppm. (A graph is included in the paper.)

When CO_2 concentration is on the increase, odour concentration corresponds closely. However, when CO_2 concentration decreases, it does so continuously, while odour measurements appear to stop at a certain level. The explanation for this could be that the surfaces desorb substances which they adsorbed during times of high exposure, thus creating a dampening effect which tends to keep the odour level higher for longer.

Reference:

Södergren D.;
Requirement - controlled ventilation of an auditorium, Proc. of CIB Trondheim, Norway, 22-23 May, 1985 [AIVC # 2156]

1985/c RH Controlled Ventilation - French Dwellings

Description:

Mechanical ventilation (exhaust) systems were already installed in 60% of the new buildings for habitation in France. Since November 1983, French regulations have allowed variable exhaust air flow systems, controlled by indoor relative humidity, in order to limit air infiltration heat loss in dwellings. At that time, several systems were under development. A mathematical multizone ventilation model was used to compare constant air flow ventilation with adjustable ventilation according to indoor relative humidity.

Results:

Table B-1 gives the results on a yearly base.

Table: B-1: *Result on yearly base (assumptions: floor area 74 m^2, Θ_i - 15 °C, water vapour 6 kg/day, envelope leakage area: 300 cm^2).*

	Average exhaust flow rate m^3/h	Cross ventilation m^3/h	Average total flow rate m^3/h
Constant flow	105	12	117
Humidity controlled	56	27	83
Difference	-49	+ 15	-34

It shows that the exhaust flow rate is reduced by some 45% and there is an increase in cross ventilation, resulting in a total reduction of around 30%.

References:

Nicolas, C.;
Evaluation des performances d'une ventilation hygromodulante, Proc. of CLIMA 2000 World Congress on Heating, Ventilating and Air Conditioning, Copenhagen, Aug. 1985, Vol. 4, p. 339-343 (in French) [AIVC # 2111]

1986/a CO_2 Controlled Ventilation - American Bank

Description:

This experiment was carried out in a bank with a 440 m² ground floor that was used as an open area work place, a 140 m² mezzanine and a 350 m² basement. Total volume of the building was 3,200 m³. Two balanced supply and exhaust fan systems were in use, with temperature control designed for maximum 217 people at a minimum outdoor air ventilation rate of 2.4 l/s,person (5 cfm), giving a total outdoor air flow rate of 510 l/s. One system was designed to serve the basement (max. capacity 2,300 l/s) and the other system (max. capacity 5,400 l/s) served the main floor and mezzanine. One Honeywell-Yamatake sensor was installed in the basement and another in the hall at the same location as the temperature sensors, near the return air registers. The sensors were installed 1.5 m above the floor. Set point level was 1,000 - 1,200 ppm CO_2.

The results from this experiment were used to calculate the potential energy savings if the bank had been located in other cities with other climate conditions. Five calculations were carried out. The measurements were carried out during winter, spring and summer.

The ventilation systems were controlled by CO_2-sensors every first week and by temperature sensors every second week.

Results:

The main objective of saving energy by controlling the outdoor ventilating air for the building was achieved. Energy savings were almost 8% of the building's total energy for heating and cooling, and the pay back time is two to three years. The performance of a CO_2 controlled ventilation system is compared to that of a system controlled by electronic thermostat.

Local regulations require ventilation to be fixed at all times according to maximum design load of people, even if the occupant load is normally only about 10 - 15% of maximum. The designed air flow rate was used in the experiment.

The set point level was never reached and no significant contaminant concentrations were found. Nitrogen dioxide, formaldehyde, carbon monoxide and particulate levels were well below recommended limits. The formaldehyde level was higher in the basement due to smoking and emissions from paper and ink, but was still well below the recommended limit of 0.1 ppm. Outdoor air was the main source of particles.

The supply air was introduced at the ground floor and mezzanine by floor diffusers. The return air devices were installed 1.5 m above the floor. The air distribution pattern led to good mixing, and the ventilation effectiveness was measured to be 100% (complete mixing).

Subjective response of the occupants showed no differences between the two controlling conditions during winter. During summer, the occupants felt more comfortable during CO_2 control mode.

Figure B-4 shows the measured energy consumption in Pasco, Washington at different outdoor air temperatures.

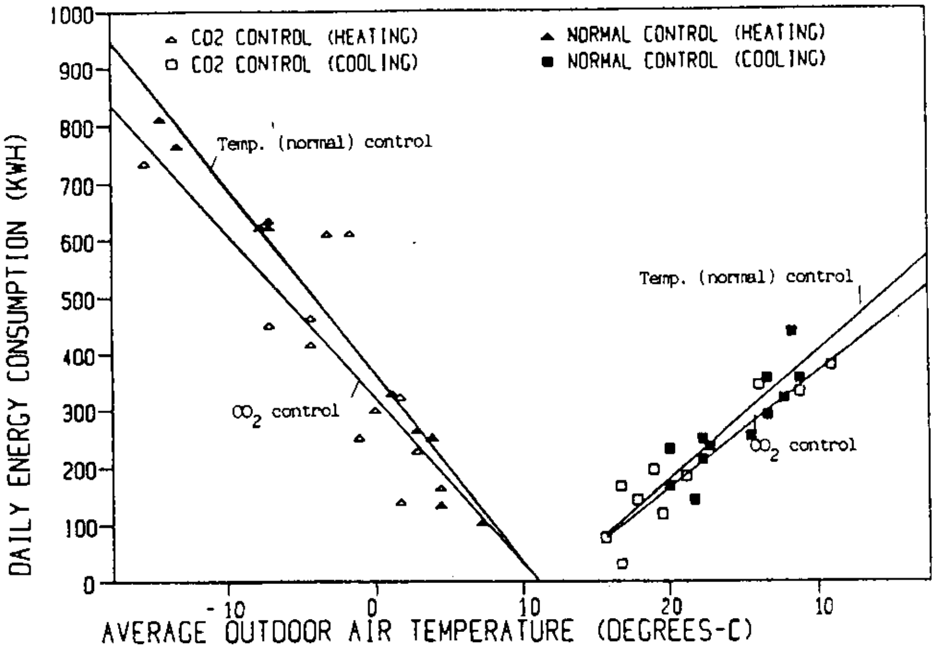

Figure: B-4: ***Energy consumption in a bank. Pasco, WA, U.S.A. CO_2 control mode compared to temperature (normal) control mode.***

Reference:

Gabel S.D.; Janssen J.E.; et al
Title: Carbon Dioxide Based Ventilation Control System Demonstration, DOE, Bonneville Power Administration, Conservation, Engineering Branch, Division of Resources Engineering, April 1986, [AIVC # 2333]

1986/b CO_2 Controlled Ventilation - Cinema, Social Club

Description:

The aim of the project was to show that energy consumption in two entertainment buildings could be significantly reduced by retrofitting a variable fresh air ventilation system controlled by a CO_2 detector. The two buildings were a social club and a cinema.

The club had a seating capacity of 1,500 and was open for approximately 11 hours a day. It was originally served by a manually controlled ventilation system and the total energy consumed was about 923,500 kWh/year.

The cinema was divided into one auditorium with a seating capacity of about 1,200, and two smaller auditoria of approximately 110 seats each. The cinema was open for 9.5 hours a day, and its total energy consumption was 583,000 kWh/year.

Results:

The two buildings were monitored for a period of two years in order to assess the energy savings. The fuel consumption, heat consumption provided by the heater battery, electricity consumption of the fresh air fan and internal temperatures were monitored. Also, CO_2, CO and $NO+NO_2$ were regularly measured.

The CO_2 reference level was 1,000 ppm (about 28 m^3/h,pers). The measured fuel savings were 17.4% for the club and 11.4% for the cinema, leading to pay back times of 2.4 and 4.8 years, respectively.

Although the CO_2 controlled ventilation system performed well throughout the monitoring period, a small drift in control sensitivity was observed, indicating a need for adjustment during annual maintenance.

The authors suggest a decision diagram (Figure B-5) to evaluate the suitability of CO_2 controlled variable ventilation.

Reference:

Anon: Ventilation control by measurement of carbon dioxide levels in public entertainment buildings. ECD Partnership, Final Report ED/85/172, ETSU, Harvell, July 1986 [AIVC # 2599]

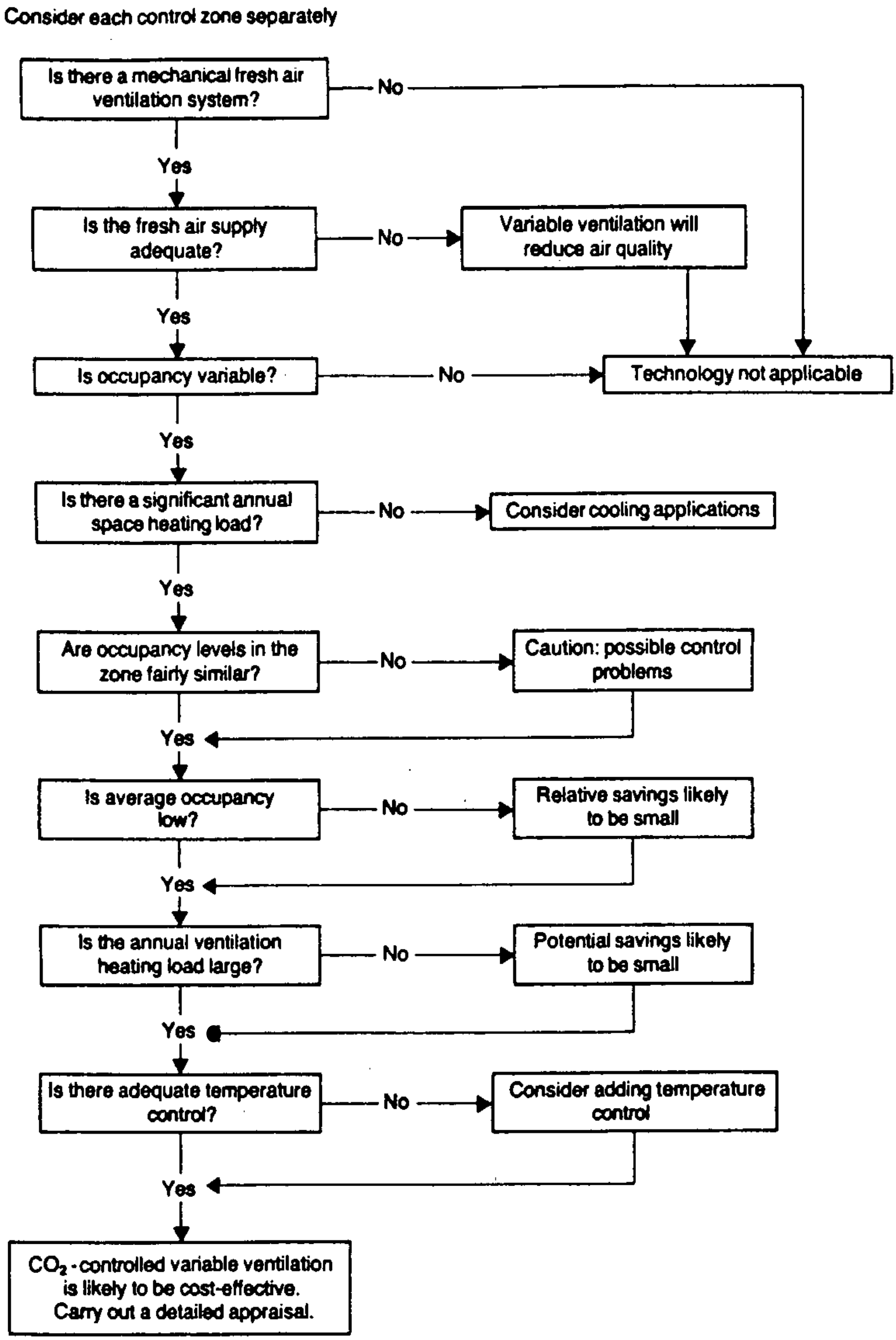

Figure: B-5 *Decision diagram for suitability of CO_2 controlled variable ventilation.*

1986/c CO_2 Sensor Controlled Auditorium - Swiss Hospital

Description:

In summer 1986 an Arox 425 AA2E3 - CO_2 sensor from Aritron CH was mounted at the ceiling of the auditorium close to the exhaust air terminal. The sensor was connected to a two-point controller to control the fan speed. The fan was operated in mode 1 for CO_2 concentrations higher than 700 ppm and in mode 2 for concentrations higher than 1,000 ppm.

Before the demand control was installed, the ventilation system was automatically switched to mode 1 during the day. If the temperature rose or fell beyond certain limits, the ventilation system was switched to mode 2.

Results:

This system had been operated as a DCV for approximately four months as of summer, 1986. During this period the running time of the system was drastically reduced from approximately 10 hours a day to an average of 22 minutes a day.

The CO_2 sensor and the controller worked without problems. The registered CO_2 levels did not rise beyond comfort limits.

On the other hand, serious problems concerning thermal comfort had to be faced. The auditorium is not used regularly, and 30 to 40 people can enter or leave the room within a few minutes. This thermal load causes the room temperature to rise beyond comfort limits. Once the temperature had risen so far, the maximum air flow was not large enough to reach thermal comfort again.

Because of frequent complaints, the ventilation system is now operating with a time and temperature control as it was prior to the installation of the CO_2-sensor).

Reference:

Sauter AG, Basel; Bruderholzspital, Basel.

1987/a Humidity control - German Residential Buildings

Description:

Theoretical calculations on how to control humidity in a room are outlined. The goal is to supply no more air than the minimum required to avoid mould growth. The condition for mould growth outlined in this paper is surface condensation. (New results from IEA Annex 14 prove that this condition is not sufficient.)

Results:

It is shown that the minimum air flow rate is a function of room temperature, outdoor temperature, u-value of the exterior wall and supply air temperature and humidity. Each variable has an impact on the supply air flow to some degree. The paper is a good basis for developing a more sophisticated humidity control, but whether such a system is cost effective and saves energy is still unproven.

Reference:

Raatschen, W.; Trepte, L.;
Ventilation Requirements and Demand Controlled Ventilation,
8th AIVC Conference Überlingen (FRG), Sept. 1987

1987/b CO_2 Control and Sensor Development - Swedish Office

Description:

The function of a CO_2 sensor developed by AF-Energi in Malmö and Lund University was tested in Sweden in 1984. The sensor principle was based on infrared absorption. The range was 0-2,000 ppm, and accuracy was +/-20 ppm during the measurements. After two months a drift was detected; at 2,000 ppm the sensor signal was 200 ppm above, at 600 ppm the signal was 50 ppm above the actual concentration. The stability due to changes was stated as +/-100 ppm, response time was a little slower than the comparing instruments.

The CO_2 sensor was installed in the exhaust air duct, regulating a damper which controls the outdoor air flow and the recirculated air flow rate. The CO_2 concentrations were measured in the supply and exhaust air ducts and in several places in the room by a SIEMENS IR analyzer. As the employees had made some complaints about the indoor air quality, other measurements were made, together with questionnaires.

Results:

With sensor control, response times of the ventilation system were higher, i.e. short peaks detected by the IR analyzer were levelled out.

Two different CO_2 reference levels were tested resulting in two different percentages of recirculated air (50% and 90%). The set point during test 1 was 450 ppm, and 550 ppm during test 2. Measurements were made in the main office at different work stations. CO_2 level was 540 ppm during test 1 (set point 450 ppm), and 730 ppm during test 2 (set point 550 ppm). Ventilation efficiency was the same during both tests, and there were no differences in higher or lower return air flow with respect to air velocity, temperature, relative humidity, and occupants' perception of draught, odour and lightning. The difference of the CO_2 level in the occupied zone and the sensor location is due to non-complete mixing and a dilution process from the source point to the exhaust duct, where the sensors were installed.

Energy savings were considered to be two-thirds of the energy used prior to sensor installation.

Reference:

Jansson I.; Ahlbeck B.; Andersson S.;
Behovstyrd Ventilation, Rapport R19, 1987 (in Swedish), ISBN 91-540-4681-5

1987/c CO_2 Controlled Ventilation - Office - Switzerland

Description:

To test whether the control of fresh air supply using measurements of the CO_2 content of room air is practicable, several investigations were made in three offices. At the same time, measurements were taken of temperature and electricity consumption (light and heating), in order to make statements about energy saving.

Results:

The following measurements were made:
1) CO_2 content of room air and amount of fresh air supply.
2) Comparative measurements with an air quality sensor.
3) Temperature of room air, fresh air, window glass and outdoor air.
4) Relative humidity of indoor air, supply air and fresh air.
5) Electricity consumption of light and heating.

The first measurements of the natural ventilation in the three offices showed that the amount of natural ventilation was too high (1.0 h^{-1}, 1.2 h^{-1}, 0.9 h^{-1}). It was because of this that the CO_2 content of room air rarely exceeded 500 ppm. To remedy this, the ventilation control had to be modified so that the fresh air damper opened only when the CO_2 content passed over 500 ppm. Figures B6 - B8 show the CO_2 content of the room air in one office, the fresh air ratio of total supply air and air quality sensor signal during one working day. Calculations about energy savings could not be made because of the high level of natural ventilation.

Conclusions: The principle of a CO_2 controlled DCV works well in rooms in which smoking is prohibited.

Reference:

Fecker, I.;
Frischluftbedarf und Regelung der Lüftung in klimatisierten Räumen, Diss. ETH Nr. 8361, Zürich 1987, Kapitel 7, p. 78-84, in German.

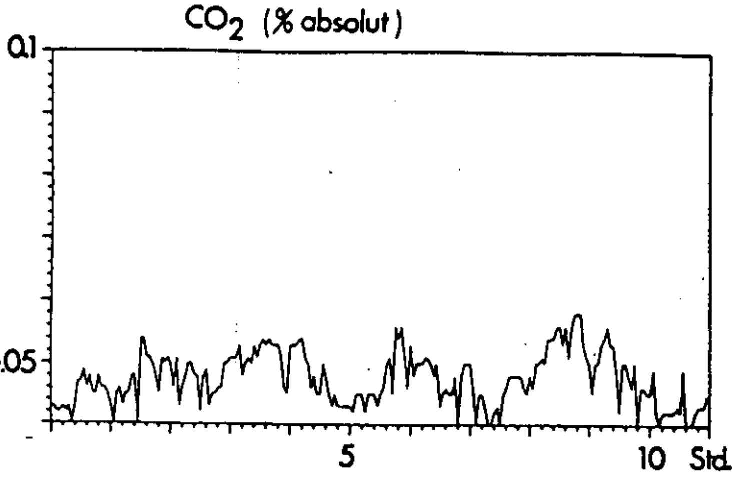

Figure: B-6: *CO_2 content of room air in an office during one working day (Std. = hours).*

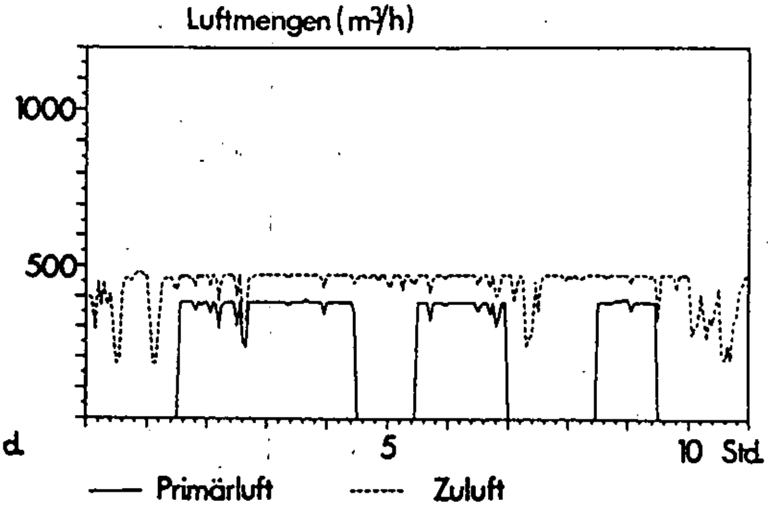

Figure: B-7: *Fresh air ratio of total supply air (Primärluft = fresh air supply; Zuluft = recirculated air supply).*

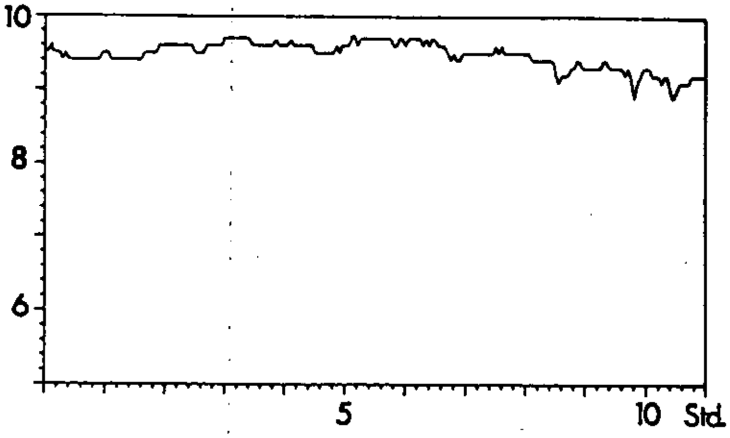

Figure: B-8: *Air quality sensor signal (10 Volt: very fresh air; 0 Volt: very stuffy air).*

1987/d Air Quality Control - Swiss Lecture Hall, Oslo Concert Hall

Description:

The paper deals with two cases:

a) In a lecture room of the Swiss Federal Institute of Technology, Zurich, an air quality sensor and a CO_2 sensor were installed in the exhaust air duct. The outside air volume was controlled by the air quality sensor. Measurements were made of CO_2 content of room air, air quality sensor signal and return air velocity.

b) The air conditioning system of an Oslo concert hall was also controlled by an air quality sensor. The position of the outside air damper was also monitored.

Results:

Figure B-9 shows the measured air quality signal, the CO_2 content and the return air velocity (low return air velocity means a high fresh air demand) in the Zurich lecture room during an assembly with 300 people. The required heating energy is also illustrated. The outside air temperature was 6°C on the day measurements were taken. The room air temperature was 22°C. As the air quality deteriorated, the return air volume was reduced because more outside air was required. As the room air quality improved during lunch break, a lower outside air volume was required.

Figure B-10 shows the measured damper positions in the air conditioning system in the Oslo concert hall. Four phases of occupancy of the concert hall and the corresponding outside air damper position (percentage of opening) are illustrated. The more people present, the more fresh air was supplied and the more open the damper position. Energy savings are estimated at 40%.

Reference:

Geerts J.;
Air quality control - measurements and experiences, in: Energy-saving control applications (2): The use of controls to improve energy efficiency in HVAC systems, Staefa Control System AG, 1987, p. 3-8, company information.

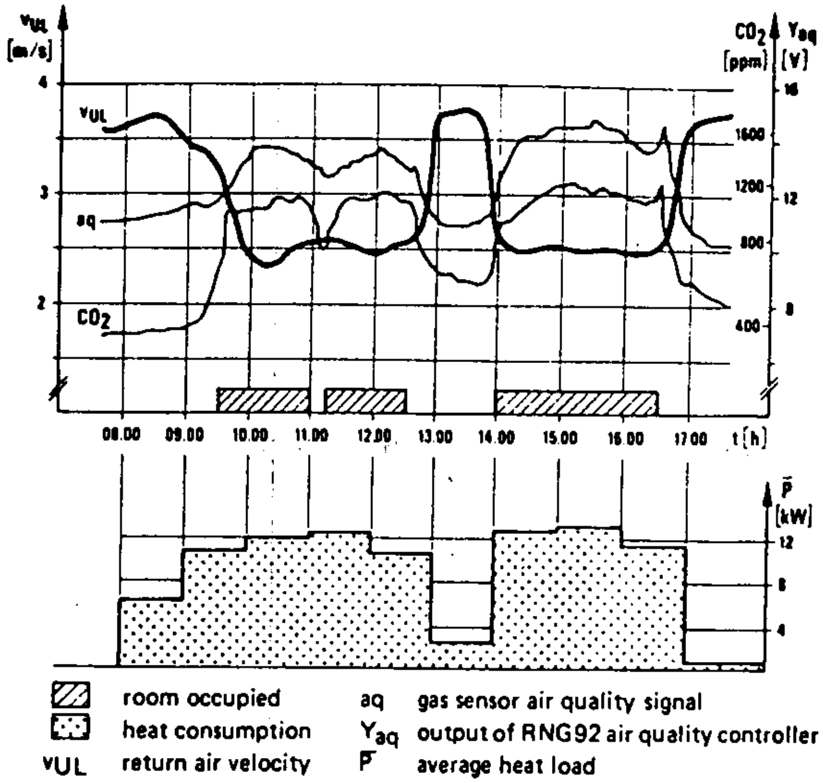

Figure: B-9: *Sensor signals, return air velocity and heat consumption (lecture room in Zurich).*

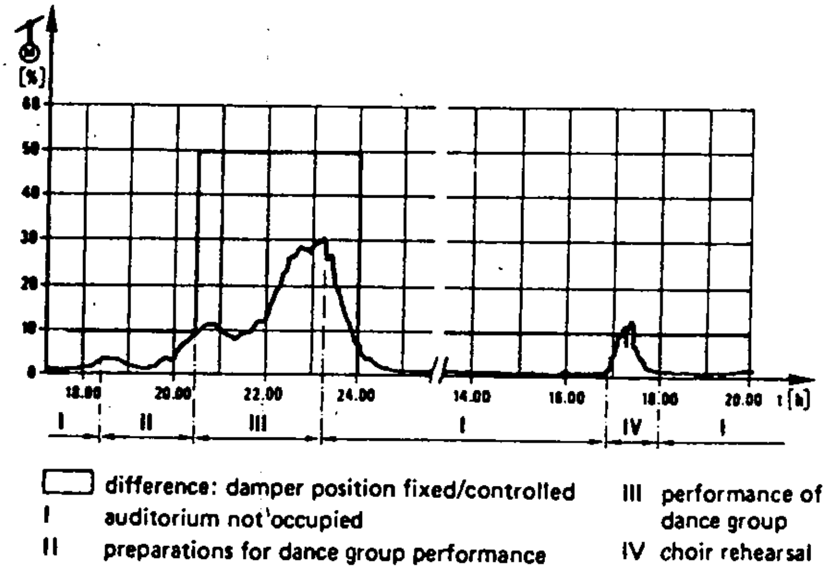

Figure: B-10: *Damper position in the system installed in the Oslo concert hall.*

1987/e Comparison of Mixed Gas Sensor versus CO_2 Sensor - Norway

Description:

The measurements were made in a lecture hall of Trondheim University, in several sports halls and rooms in which occupants smoked, to compare the measurement signals of an air quality sensor and a CO_2 sensor.

Results:

Figure B-11 shows the measured response signal of the air quality sensor and the CO_2 sensor, measured in the exhaust air duct of the lecture hall. Smoking was not permitted. Both sensors responded quickly to changes of occupancy. There was a good correlation between the two sensors. Figure B-12 shows that the air quality sensor responded very quickly to the presence of tobacco smoke, while the CO_2 content in the room air increased by only a negligible amount. The CO_2 content of room air cannot be taken as a criterion for air quality in this case. The comparative measurements in sports halls showed that there is a high emission of CO_2 and body odour. The air quality sensor responded with a delay of 30 minutes. The authors presumed that the body odour was first absorbed by the clean clothing before being emitted to the air.

Reference:

Geerts J.;
Air quality control - measurements and experiences, in: Energy-saving control applications (2): The use of controls to improve energy efficiency in HVAC systems, Staefa Control System AG, 1987, p. 3-8.

The synopsis is taken from a paper written as part of commercial documentation from the producing company.

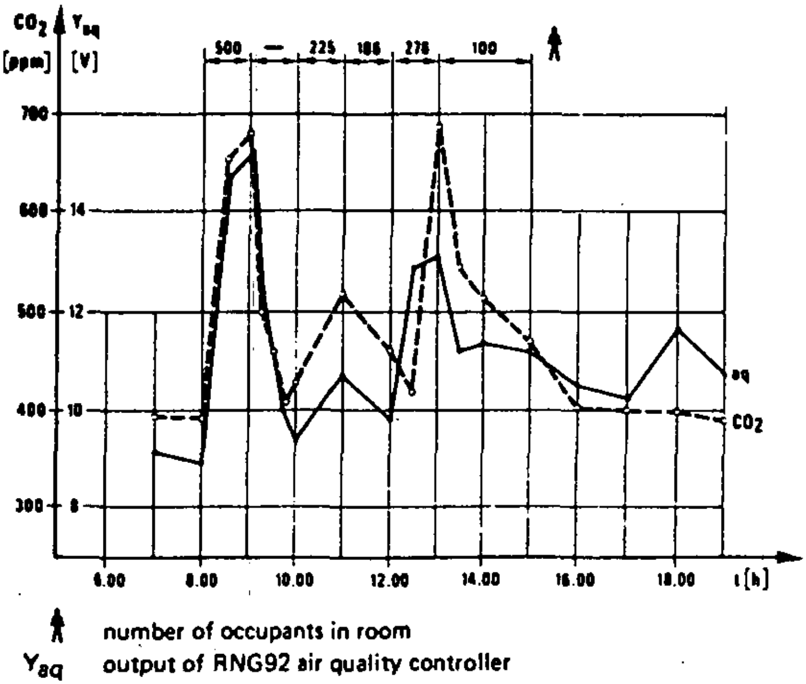

Figure: B-11: ***Lecture room at Trondheim University: comparative measurements.***

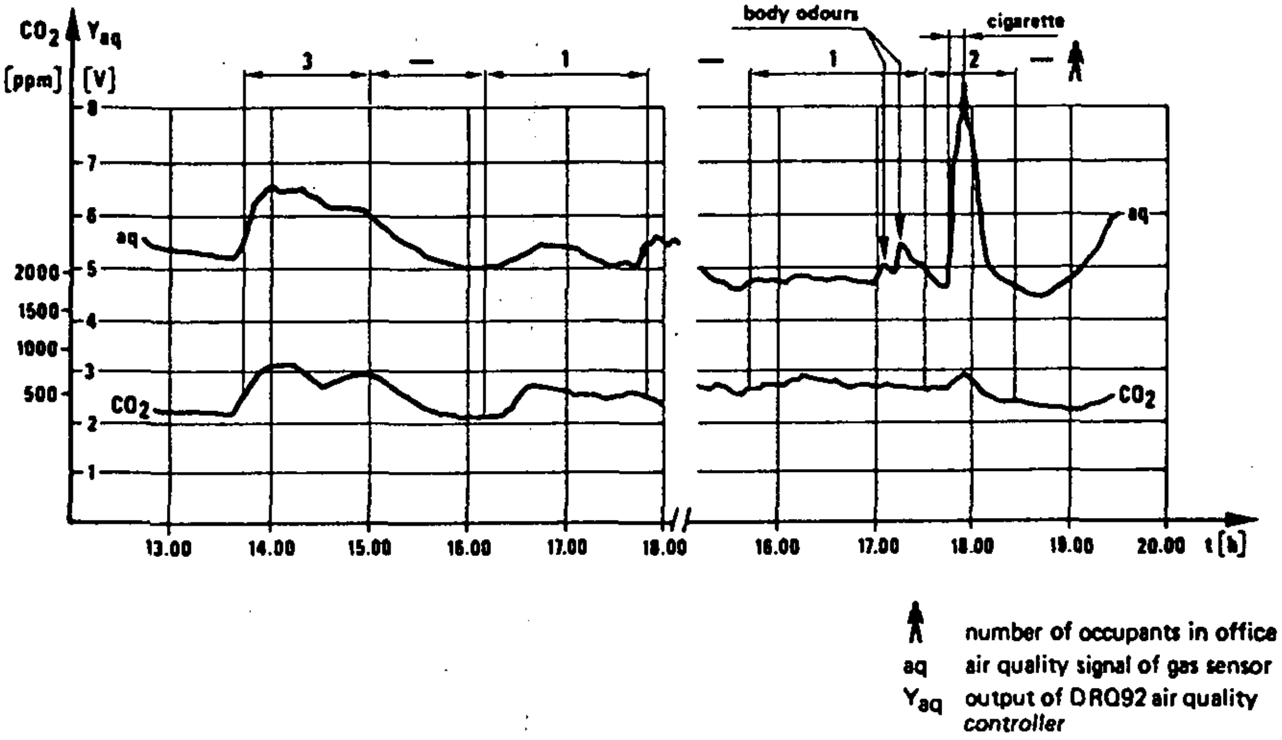

Figure: B-12: ***Comparative measurements between CO_2 content and gas sensor signal (measurement of air quality) in a smoker's office.***

1987/f Measured CO_2 Concentrations in a Swiss School

Description:

The school building Gumpenwiesen in Dielsdorf has a mechanical ventilation system with heat recovery (heat exchanger and heat pump). The overall energy consumption, including electricity, is 183 MJ/m²a (51 kWh/m²a).

During the time the ventilation system is operating, an air exchange rate of approximately 0.5 h^{-1} is supplied to the classrooms. When the classroom is fully occupied the teacher can open a damper which increases the air exchange rate to 1.0 h^{-1} (corresponding to 10 m³/h Pers).

CO_2 concentrations were measured during the 1985 to 1987 heating periods. Measurements were made using a gas analyzer (Binos, Leybold Heräus).

Results:

Assuming a perfect mixing in the room, the CO_2 concentrations can be very well predicted if the number of persons, the length of occupancy, the CO_2 production per person (activity) and the room volume are given.

Measurement results showed that the teacher usually opened the damper when the air quality in the room was already bad. In that situation, even the maximum air flow was not capable of reducing the CO_2 level. During occupation time the 1,500 ppm set point was exceeded 13.7% of the time. After the first measuring period the teacher was told to open the damper earlier, but he did so infrequently.

The manual control of the ventilation system is not fully satisfactory. An automatic two-point control with IR-presence sensors would probably be the better solution. The expensive installation of CO_2 sensors is only considered to be meaningful in connection with real VAV systems.

References:
Baumgartner T.; Brühwiler D.;
"Simulation of CO_2 concentration for determining air exchange rate"; 8th AIVC Conference, Suppl. to proceedings; 1987

"Demonstrationsprojekt Schulhaus Gumpenwiesen"; Dokumentation D 035; SIA/BEW; January 1989; Final Report; in German.

1987/g Comparison of CO and CO_2 Sensor Signals Case Studies in Two German Office Rooms

Description of experiment 1, meeting room:
CO was analyzed with a mixed gas sensor (Sauter ERQ1, which has a Figaro sensor) only qualitatively. No concentration measurement was possible. CO_2 was measured quantitatively with a CO_2 sensor (Sauter EGQ10).

Results:

A good correlation was detected between the CO_2 concentration and the odour level.

The mixed-gas sensor (CO sensor) responded poorly to stale air, but responded well to tobacco smoke. Sensor location was not reported.

Description of experiment 2, office room:
The room was a single person office, (room volume 18 m³) occupied by a smoker with people entering and leaving. A natural ventilating system was in place, and CO_2 levels increased due to occupancy density. IAQ was poor at 800 ppm, and at 1,000 ppm was no longer tolerable, so that the window and door were opened. The CO-sensor reacts promptly to cigarette smoke.

Results:

Good relationships were reported between the CO_2 sensor and stale air, and between the CO sensor and tobacco smoke. After working hours when the room was unoccupied, there was an undefined increase in the CO level.

The CO sensor reacts not only on CO but also on other contaminants. It reacts to non-oxidized gases since it is a metal oxide sensor. Therefore, the reported CO level should not be looked at as a selective CO concentration but as a qualitative value of non-oxidized gases.

Reference:

Sautter, L.;
Kombinationsmessung der Raumluftqualität, HLH, Bd 38 (1987), Nr. 8, in German.

1988/a CO_2 Controlled Ventilation - Norwegian Lecture Hall

Description:

An auditorium with space for 500 people at the University of Trondheim was equipped with a DCV system. The amount of fresh air was controlled by recirculation. The ventilation system was designed for complete mixing with diffusors in the ceiling and exhaust air devices under the seats.

An infrared CO_2 sensor (prototype) from Simrad Optronix A/S was used as reference for the DCV system. The sensor was mounted in the exhaust-air duct.

Another CO_2 analyzer (Intralyt T) was used for recording the CO_2 level in the supply, exhaust and at several locations inside the room. The recorded data also included variations in the personal load.

The full scale trial was carried out during the spring of 1984. The maximum CO_2 concentration allowed was set at 700 ppm.

Results:

The DCV system failed to establish a constant CO_2 level in the auditorium due to short circuiting between the supply and the exhaust devices of the auditorium.

An investigation of the flow conditions in the room showed that the extent of the short circuiting depended on the load. Complete mixing was achieved only when the auditorium was empty.

Reference:

Drangsholt F.;
Ventilation by Demand, SINTEF report STF15 A88038, draft of Oct. 1988, Trondheim, Norway.

1988/b CO_2 Controlled Ventilation - Two Swiss Auditoria

Description:

The ventilation rate of two auditoria (Auditorium A: 442 seats, Auditorium B: 150 seats) at the University of Zurich is controlled by CO_2 sensors. A computer programme was made to control the ventilation dependent on room temperature and/or CO_2 concentration. Measurements of CO_2 content in room air, room air temperature and outdoor damper position (i.e. the amount of fresh air in supply air) were carried out to verify whether the system was working in the desired mode. Calculations of the heat-energy gain were made at the same time.

Results:

The ventilation was turned on at level 1 at a CO_2 concentration level of 750 ppm, with an air supply rate of 36 m^3/h,person for auditorium A and 41 m^3/h,person for auditorium B. Fresh air content varied between 20% (750 ppm) and 50% (1,500 ppm), depending on the actual CO_2 concentration. At a CO_2 level of 1,500 ppm, the ventilation is turned to level 2 (43 m^3/h,person, 53 m^3/h,person) with a variable fresh air content between 20% (1,500 ppm) and 75% (2,000 ppm). It was shown that the system works in the desired manner. The measurements done from April to July 1987 gave the following results:

1) The CO_2 concentration of room air in the two auditoriums never exceeded 2,000 ppm.

2) The running time of the ventilation system could be decreased by about 70%.

3) The energy consumption for heating and cooling could be decreased by 90% when a heat exchanger was also used.

4) The electrical energy consumption could be decreased by about 90%.

5) Maintenance costs of the ventilation system could be decreased by 20%.

Reference:

Brechbühl B.;
Laufzeit und Luftmengenoptimierung von Lüftungsanlagen mittels CO_2 Steuerung, Vortragsmanuskript KHW-Statusseminar vom 8/9 September 1988, "Energieforschung im Hochbau", p. 309-316, in German.

1988/c RH Controlled Ventilation - Canadian Residence

Description:

The report covers one week of monitoring in a single family residence in Vancouver, British Columbia, Canada. The building ventilation was controlled by Aereco relative humidity controlled ventilation devices installed in the walls and in the building exhaust system. Temperatures, CO_2, CO, humidity, building pressurization, extractor fan flow, wind speed and wind direction were recorded.

Results:

CO_2 was found to rise and fall with activity levels and occupancy. At times peak levels exceeded 1,000 ppm and might have reached 1,500 ppm if the building had been occupied by the full family on a continuous basis for a full day. Predicted CO_2 values based on assumed metabolic rates, measured ventilation rates and actual occupancy were found to match measured values well.

Relative humidity levels did not track occupancy very well and remained fairly constant. This resulted in constant ventilation rates since the extractor air flows were humidity controlled.

The building was depressurized by the extractor fan to -9 Pa. Neither the overall level of depressurization nor the air exchange rate were affected greatly by wind speed or direction. CO levels were low throughout the test period as were formaldehyde levels.

In summary, the relative humidity levels in the house did not respond to occupancy nor did the ventilation rates. CO_2 did respond to occupancy quite quickly and was thought to be a good indicator of pollution levels where those levels are proportional to occupancy. CO_2 if affordable, would provide a far better means of controlling ventilation requirements.

The energy savings theoretically available from the Aereco system were thought to be no better than those available from a heat recovery ventilation system. In the latter case, much more fresh air would be supplied.

The Aereco system might be more effective in a drier climate due to a larger range of humidities to react to.

After the report was written, it was found that not all data may be accurate due to some small leaks in the hot water and furnace flues. A similar experiment is now being rerun in the Ottawa area on a house with electrical heat and hot water.

Reference:

Phase 1, preliminary results of "Evaluation of the Aereco Ventilation System in the VIS Residence"; for Canadian Home Builders Association, Ottawa report prepared by Sheltair Scientific Ltd., Vancouver, March 1988.

1989/a CO_2 Controlled Ventilation - Swedish Auditorium

Description:

An auditorium with a seating capacity of 60, floor area 100 m^2 and room volume of 390 m^3 was studied. The ventilation system is a Variable Air Volume (VAV) System with rotary heat exchanger and without recirculated air. The supply air is cooled or heated in a central unit. Supply air flow rate can be varied between 220-500 l/s. A basic flow rate of 50 l/s is supplied in a separate system. Air is supplied at floor level and exhausted with long-slot-type devices located in the ceiling.

One temperature sensor and one CO_2 sensor were installed to control the air flow. They are located three metres above the floor.

One of the control strategies was to regulate the air flow rate to meet both the requirement of 22°C and maximum allowable CO_2 of 750 ppm with increasing air flow at 600 ppm. The CO_2 sensor is manufactured by Aritron (type AROX 425 A) and operates on the photo-acoustic principle.

The main objective is to maintain good air quality with minimum energy consumption in rooms with varying occupant loads. This experiment aimed to determine whether this objective could be achieved with today's technical equipment.

Results:

The results from three different occupant load situations indicate that with the auditorium half full, an air flow rate of 380 l/s (75 % of maximum capacity) is sufficient. If the system is running on minimum of 220 l/s (45 % of maximum capacity), the IAQ is not acceptable after 20 minutes with 44 persons present.

A VAV system can easily be supplemented with CO_2 control and is a good solution in spaces such as rooms and auditoria with irregular levels of occupancy and/or many people coming and going.

Reference:

Strindehag O.; Persson P.G.;
Auditorium with demand controlled ventilation.
Air Infiltration Review, Vol. 10, No. 2, Feb. 1989
[AIVC # 3251]

Appendix C: Theoretical Example of the Influence of the Ventilation Strategy on Indoor Air Quality and Average Ventilation Rate

1. INTRODUCTION

The effects of ventilation strategies on indoor air quality and energy are given in the following example. The assumptions, and boundary conditions are well defined.

2. ASSUMPTIONS

2.1 Characteristics of room:

The calculations were done for an ordinary classroom with the following characteristics:

floor area: 56 m^2 (7 x 8 m^2)
volume: 168 m^3 (height = 3 m)
maximum capacity: 25 persons
(see occupancy pattern in figure C-1)

2.2 Strategies considered:

Strategy A: Natural ventilation with a constant air change rate

This strategy corresponds to the assumption of a naturally ventilated building without controllable air inlets and outlets and without an open window.

Two levels of air change rate are supposed:

$n = 0.1\ h^{-1}$	this is representative of a rather airtight building (n_{50} ~ 2 h^{-1}) under average weather conditions.
$n = 2\ h^{-1}$	this is representative of a leaky building under average weather conditions, or a building with moderate airtightness during periods of high wind speeds and/or low external temperatures.

Strategy B: Natural ventilation with intensive ventilation during recreation times

As in strategy A, this does not have a controllable air inlet or outlet, but has a high ventilation rate because windows are opened during break times. A value of $n = 10\ h^{-1}$ during these periods is assumed.

Strategy C: Classical mechanical ventilation

This corresponds to a very airtight building with an infiltration rate of 0.1 h^{-1}. The mechanical ventilation system operates from 08:00 to 17:00.

<u>Note:</u> This strategy is also representative of a natural, well designed ventilation system with self-regulating devices guaranteeing a more or less constant flow rate, independent of the pressure difference.

The mechanical flow rate during hours of operation corresponds to the required flow rate for keeping the CO_2 level in the classroom with 25 persons below either 1,000 ppm or 1,400 ppm. This means respectively 833 and 500 m^3/h, or $n_{mech} = 5\ h^{-1}$ and $n_{mech} = 3\ h^{-1}$.

Strategy D: Ideal demand controlled ventilation

The following assumptions were made:

- room with perfect mixing
- DCV system with continuously variable air flow and no inertia
- set point of 1,000 or 1,400 ppm

2.3 Calculation of the evolution of CO_2 levels:

The evolution of the CO_2 level is calculated assuming perfect mixing. The following formula has been derived from the equation of continuity for CO_2:

$$c(t+\Delta t) = c(t) \cdot e^{-n\cdot\Delta t} + (c_b + \frac{N\cdot q}{n\cdot V})\ (1-e^{-n\cdot\Delta t})$$

where:

$c(t+\Delta t)$ = concentration at time $t+\Delta t$ (vol/vol)
$c(t)$ = concentration known at time t (vol/vol)
n = air change rate between time t and $t+\Delta t$
c_b = background concentration (vol/vol)
assumption: cb = 0.0004 (= 400 ppm)
q = CO_2 production rate per person (m^3/h)
assumption: $q = 0.02\ m^3/h$ (20 l/h)
N = number of occupants
V = volume of the room (m^3)
assumption: $V = 168\ m^3$

The calculations were done using a time step of Δt = 30 minutes. For all cases a concentration of 400 ppm in the classroom at t = 00:00 was assumed, corresponding to the situation for the first day of the week (Monday).

3. RESULTS OF CALCULATIONS

The results for the four strategies are given in Figures C-2 to C- 7, showing the concentration level and, in some cases, the number of air changes versus time.

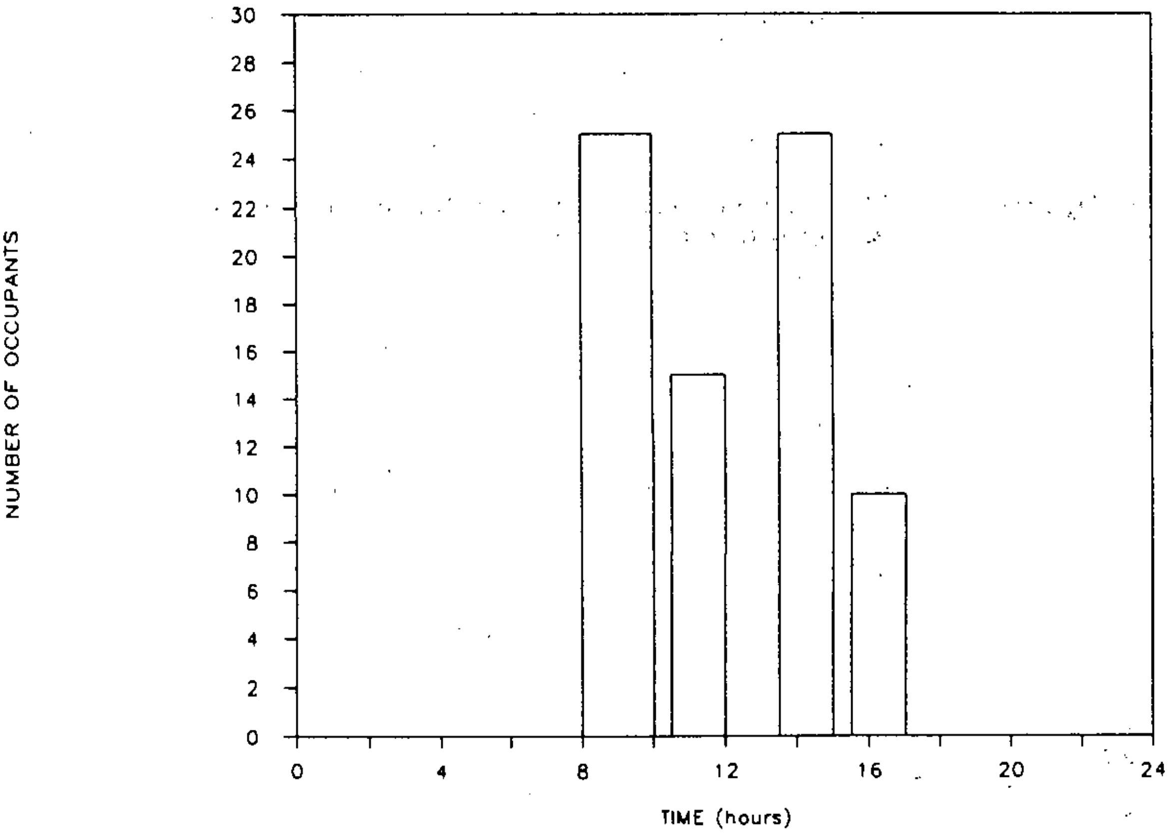

Figure: C-1: *Occupation pattern of the school room.*

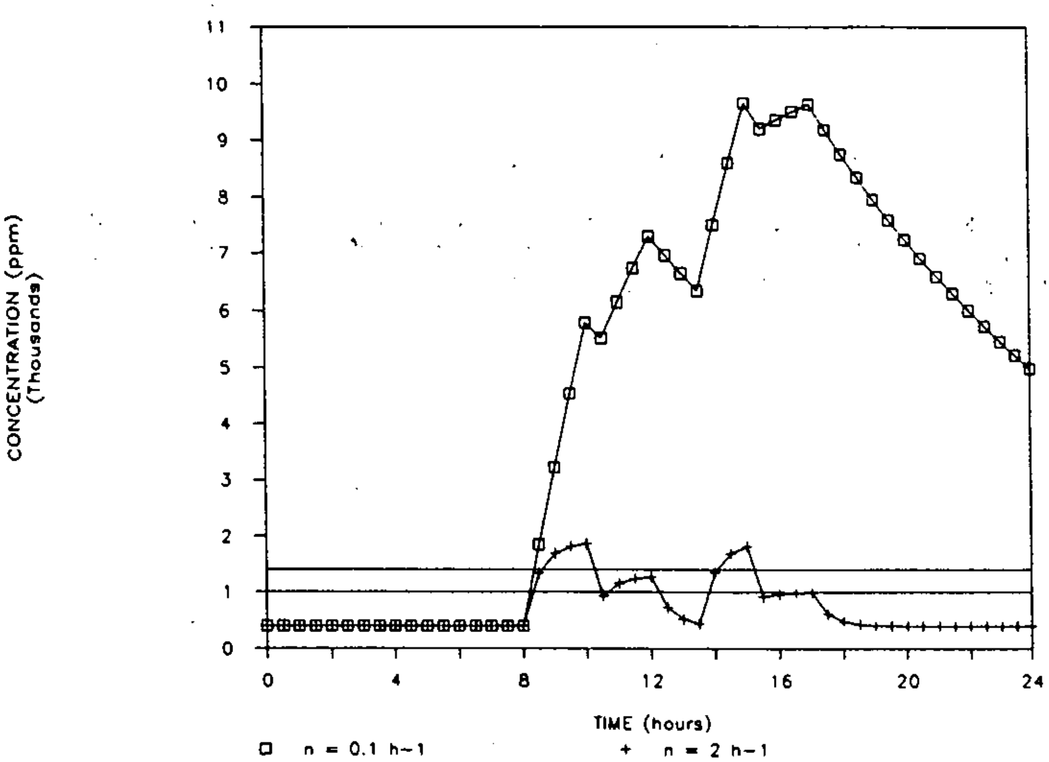

Figure: C-2: ***CO_2 concentration plot for a naturally ventilated classroom with two different air change rates.***

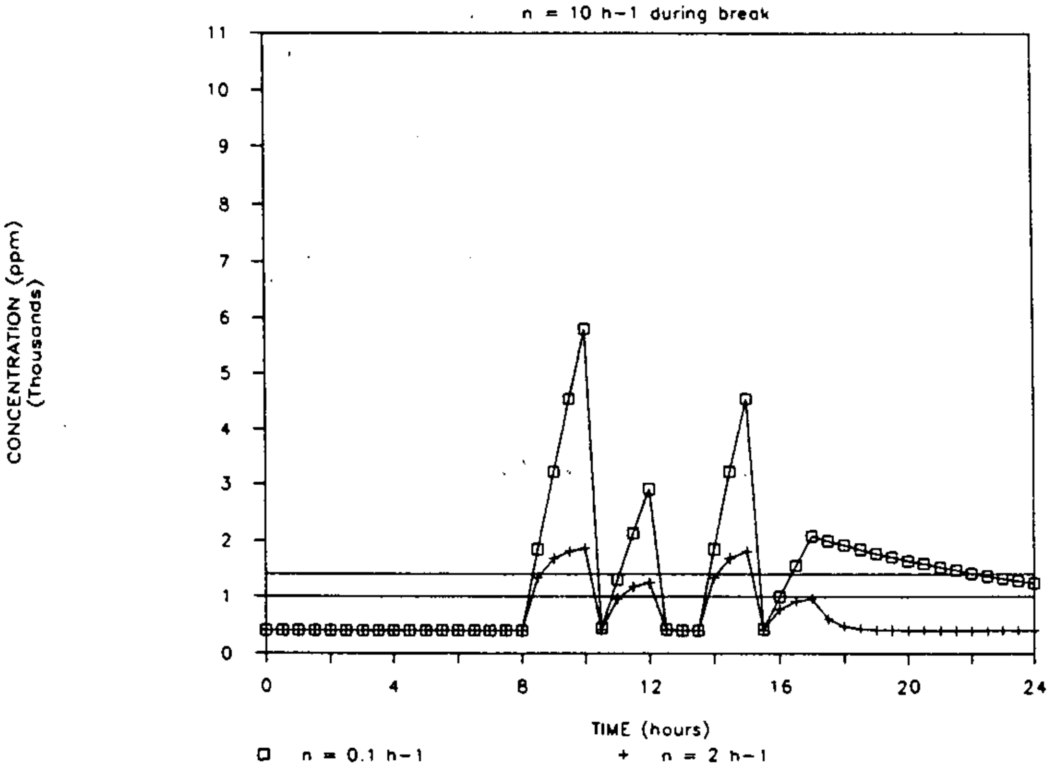

Figure: C-3: ***CO_2 concentration plot for a naturally ventilated classroom with intensive airing during breaks.***

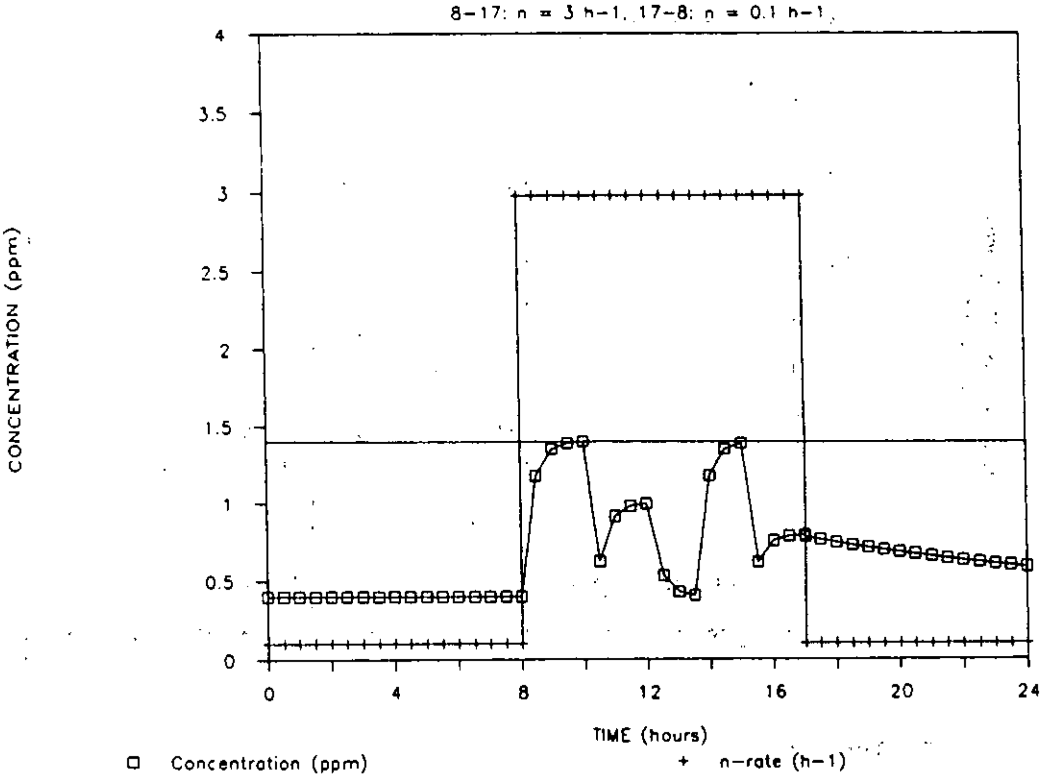

Figure: C-4: ***CO_2 concentration plot for a mechanically ventilated classroom.***

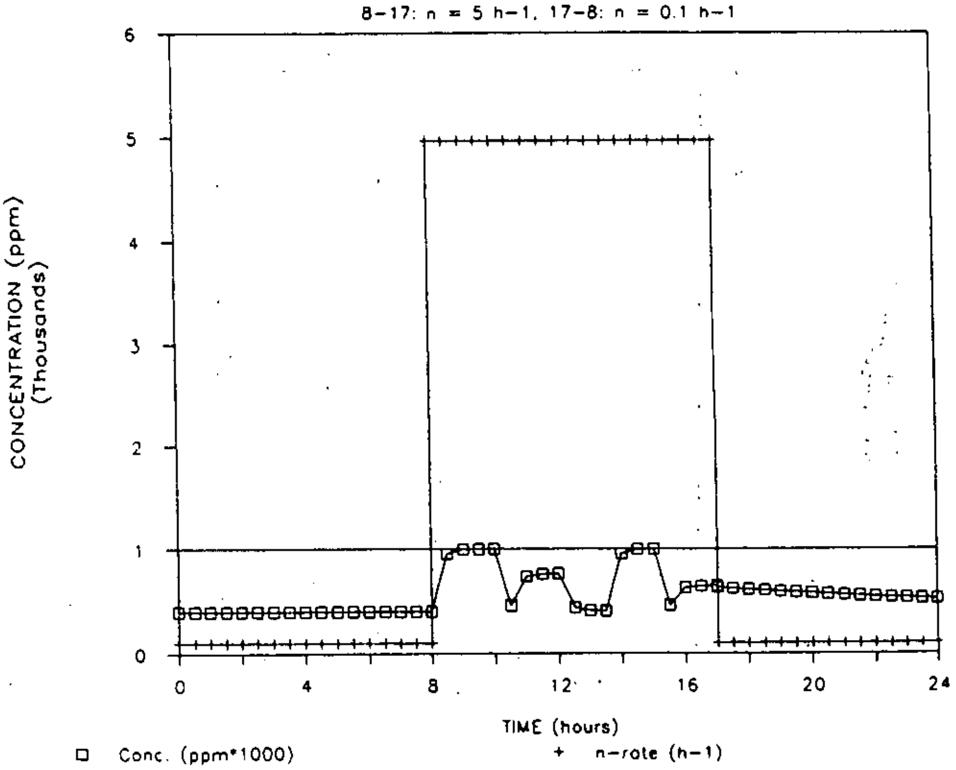

Figure: C-5: ***CO_2 concentration and air change rate versus time plot for a mechanically ventilated classroom.***

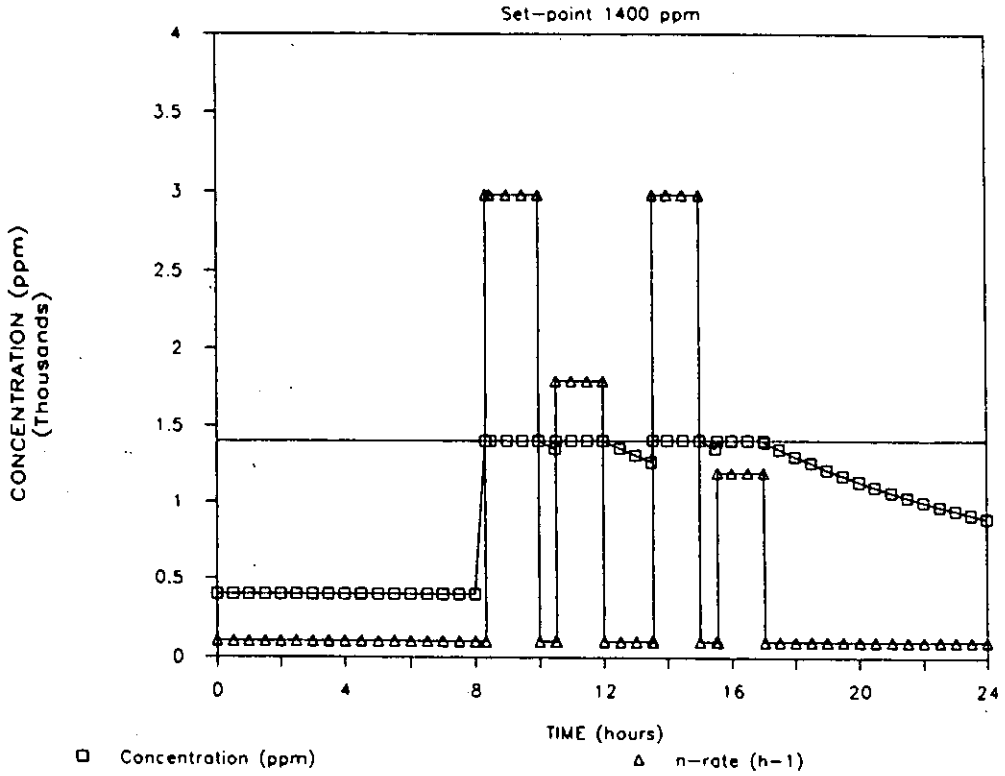

Figure: C-6: ***CO_2 concentration and air exchange versus time plot for a classroom with a CO_2 controlled ventilating system (reference level 1400 ppm).***

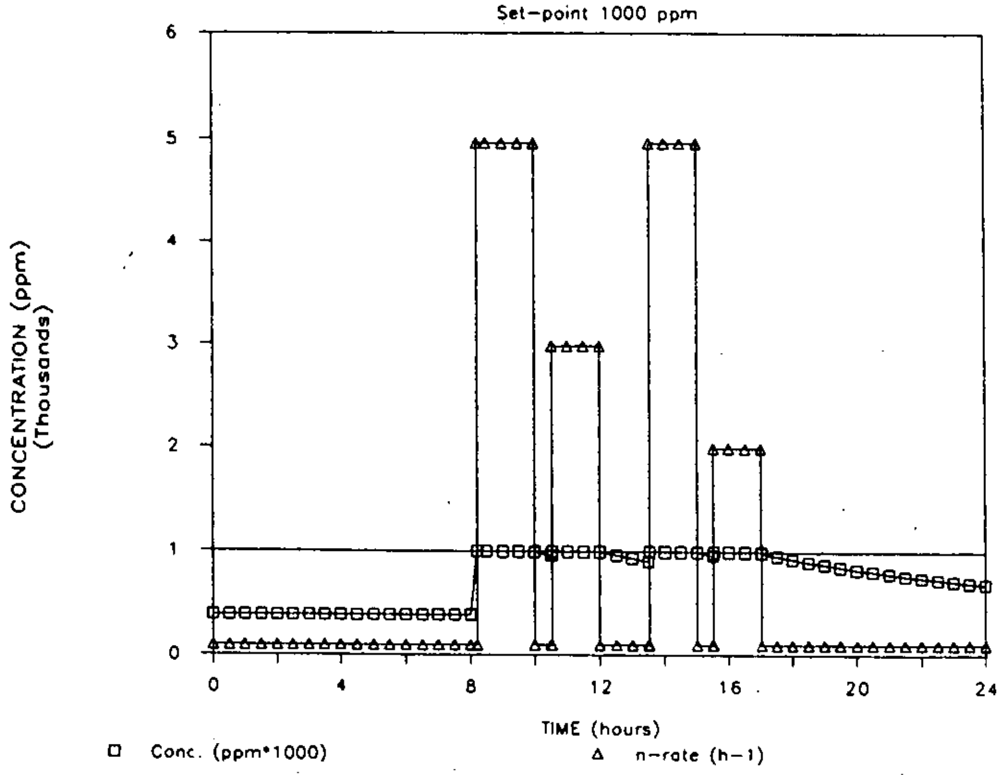

Figure: C-7: ***CO_2 concentration and air exchange versus time plot for a classroom with a CO_2 controlled ventilating system (reference level 1000 ppm).***

4. CONCLUSIONS

A number of conclusions can be drawn from this simple example. Although they have been derived from a specific case, these conclusions may be extended to any other building, provided the occupation pattern shows a strong variability, especially if the variability is unpredictable.

- Natural ventilation without well-dimensioned air inlets and/or outlets is definitely not a good strategy if the building is very airtight because of the bad air quality (see Fig. C-2). Air quality improves if the building is leaky, but the energy performance of the building will become very poor.

- The normal strategy of opening the windows during break times leads to lower concentrations of CO_2 (Fig. C-3), although the acceptable indoor concentrations (AIC) are often exceeded. Furthermore, the average number of air changes will dramatically increase, especially in the tight building case (see Table 1.1, Section 1).

- A well sized classical ventilation system running from 08:00 to 17:00 guarantees an acceptable air quality, though at the expense of a higher average ventilation rate (see Fig. C-4 and C-5). One can also observe that reducing the CO_2 concentrations from 1,400 ppm to 1,000 ppm increases the average number of air changes by approximately 60 %.

- Finally, the ideal DCV system, while maintaining an acceptable air quality, allows a significant reduction of average ventilation rates (see Fig C-6 and C-7). It should be pointed out that the percentage reduction of air change rates achieved does not depend on the specified CO_2 reference level chosen.

Appendix D: Addresses of Contacted Companies for Sensor Survey

1. Ados GmbH, D-5100 Aachen, Trierer Str. 23-25,
+49-241-59041

2. AB Gemlaplast, P.O. Box 7, S-36002 Gemla, Sweden
+46-470-67510
Fresh, Gesellschaft für Lüftungseinrichtungen mbH,
P.O. Box 3, D-3360 Osterrode 22, +49-5522-81197

3. AF-Energi, Malmö, Sweden

4. Ahlborn Mess- und Regeltechnik, P.O. Box 1260,
D-8150 Holzkirchen

5. Antechnika GmbH, P.O. Box 1127, D-7505 Ettlingen,
+49-7243-14061

6. Aritron AG, Lohwiss-Str. 30, CH-8123 Ebmatingen,
+41-1-9803381

7. Auer MSA, D-1000 Berlin, +49-30-6813028

8. Bulluf, Gebhard, D-7303 Neuhausen, +49-7158-4041

9. Bayer Diagnostik und Elektronik GmbH, D-8000 München 70
Steinerstr. 15, +49-89-724931

10. Beru-Ruprecht GmbH & Co KG, Werner Str. 35,
D-7140 Ludwigsburg, +49-7141-132-1

11. Bieler & Lang GmbH, Oberkirchstr. 21, D-7590 Achern,
+49-7841-3886

12. Centra-Bürkle GmbH, P.O. Box 1164, D-7036 Schönaich
+49-7031-557-01

13. COM air b.v., P.O. Box 7, Industrieweg 5, NL-5527 AJ
Hapert, +31-4977-2990

14. Coreci GmbH, Hochburger Str. 23, P.O. Box 1570,
D-7830 Emmendingen, +49-7641-8365

15. Dräger AG, Moislinger Allee 53/55, D-2400 Lübeck 1,
+49-451-882-0

16. Driesen + Kern GmbH, P.O. Box 1126, D-2000 Hamburg-Tangstedt, +49-4109-6633

17. EGE-GmbH, Ravensberg 34, D-2303 Gettorf, +49-4346-5658

18. Elektronik GmbH, Holbeinstr. 21, D-8500 Nürnberg 70,
+ 49-911-66870

19. Galltec GmbH, Boschstrasse 4, D-7031 Bondorf,
+49-7457-8158

20. Heidolph-Elektro GmbH & Co KG, Starenstr. 23,
D-8420 Kalkheim, +49-9441-7070

21. Honeywell-Regelsysteme, D-Offenbach/Main, +49-69-8064-0

22. Horiba Europe GmbH, Industriestr. 8, D-6374 Steinbach/Ts.,
+49-6171-7755

23. HY-Cal Engineering, 9650 Telstar Ave., El Monte,
California
91731-3093, U.S.A.

24. Wilh. Lamprecht GmbH, Friedländer Weg 65-67,
D-3400 Göttingen, +49-551-49580

25. Landis & Gyr, Friesstrasse 20-24, D-6000 Frankfurt 60,
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26. Murata Erie Electronic GmbH Kreuzsteinstr. 1A,
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27. Neuberger Messinstrumente GmbH, Rainbachweg 16, D-8092
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28. Preussag AG Minimax, P.O. Box 1260, D-2060 Bad Oldesloe,
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29. Rotronic AG, Badenerstr. 435, CH-8040 Zürich,
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30. Sauter Cumulus GmbH, Hans-Baute-Str. 15, D-7800 Freiburg
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31. Simrad Optronics A/S, P.O. Box 6114 Etterstad,
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32. Stäfa Control System AG, CH-8712 Stäfa, +41-1-9286111
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33. Siemens AG, Bereich Energie- und Automatisierungstechnik,
Postfach 211262, 7500 Karlsruhe 21, +49-721-595-0

34. System Controls LTD, 4 Lennox Mall, Basingstoke, Hants,
RG22 4DF, UK, +44-256-478855

35. Testoterm GmbH & Co, Kolumban-Kayser-Str. 17,
D-7825 Lenzkirch, +49-7653-681-0

36. Thies, A. GmbH & Co KG, Hauptstr. 76, D-3400 Göttingen

37. Umwelt und Prozesskontroll GmbH (UPK), Hauptstr. 95,
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38. Unitronic GmbH, P.O. Box 330 429, Münsterstr. 338,
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39. Vaisala, P.O. Box 26, SF-00421 Helsinki

40. Valvo GmbH, P.O. Box 106323, D-2000 Hamburg 1,
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Appendix E: Addresses of National Representatives of Annex 18

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This book gives the State of the Art Review of Demand Controlled Ventilating Systems. It is the result of a collaboration of 10 countries within the International Energy Agency.

Knowledge in these countries of air quality control by the ventilating system is gathered and weighed. In the report is given examples of how to use air quality demand controlled ventilating system for different users in different types of domestic, office and school buildings.

As a background the international standards for a few pollutants in the indoor environment is given together with some examples of measured pollutant levels in various building types.

In the overview of the sensor market is explained the function principle of humidity, carbon dioxide and mixed-gas sensors.

Summaries of more than 30 projects over the last 10-years were reviewed with respect to air quality demand controlled ventilating systems.

Conclusions are given about suitable pollutants to govern the system, the capability of sensors, and other influencing factors saving energy without sacrifying the indoor air quality. It is also a guide to the future test-work of the 10 countries in Annex 18 Demand Controlled Ventilating Systems.

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