International
Energy
Agency

Demand Controlled
Ventilating Systems

Sensor Tests

Per Fahlén
Helena Andersson
Svein Ruud

SP
Swedish National Testing and Research Institute
Energy Technology
SP REPORT 1992:13

Per Fahlén
Helena Andersson
Svein Ruud

Demand Controlled Ventilating Systems - Sensor Tests

SP
Swedish National Testing and Research Institute
Energy Technology
SP REPORT 1992:13

Abstract

A test programme has been designed to evaluate the performance characteristics of sensors for the automatic control of ventilation rates. The test programme consists of two main parts, one being the evaluation of sensor performance in laboratory tests and the other referring to long term characteristics of sensors in actual buildings. Included in the present evaluation are nine different types of humidity sensors, two carbon dioxide sensors and five mixed gas sensors.

The test results indicate that capacitive humidity sensors are well suited for the control of humidity levels in buildings. The combined error of linearity, hysteresis and repeatability is normally below 5% relative humidity at 20 °C. The cross-sensitivity to variations in the ambient temperature and power supply (voltage and frequency) are acceptable and the cross sensitivity to hydrocarbons, carbon dioxide and tobacco smoke is negligible. A plastic strip humidity sensor on the other hand proved unsuitable due to excessive hysteresis and linearity errors.

Carbon dioxide sensors show acceptable performance for control purposes but sensor calibration and/or adjustment may be a time consuming process. These sensors are sensitive to humidity below a threshold value. The mixed gas sensors show a mixed behaviour. Some react strongly to tobacco smoke, some slightly and one hardly at all. The characteristic curve was determined using a gas cocktail consisting of equal parts of one alifatic hydro carbon (nonane), one aromatic hydro carbon (toluene) and one aldehyde (octanal). Tests were also made with one component at a time but there was little difference in the response to the individual components.

All sensors endured the climatic tests reasonably well. Mechanical vibration on the other hand caused some of the sensors to break. Radiated electromagnetic fields affected all sensors and electric shocks, due to a simulated strike of lightning, proved too much for most of the sensors.

Key words: CO_2, carbon dioxide, demand control, humidity, sensor, ventilation, VOC, volatile organic compounds.

SP RAPPORT 1992:13
ISBN 91-7848-331-331-X
ISSN 0284-5172
Borås 1992

Swedish National Testing and Research Institute
SP REPORT 1992:13

Postal address:
Box 857, S-501 15 BORÅS,
Sweden
Telephone + 46 33 16 50 00
Telex 36252 Testing S
Telefax + 46 33 13 55 02

Contents

Page

Appendices

List of symbols and abbreviations

Symbols

f	frequency (Hz)
ℓ	leakage factor (=leakage flow rate/circulated flow rate)
M	molar mass (kg/kmol)
m	mass (kg)
p	pressure (Pa)
p_s	saturated vapour pressure (Pa)
q_m	flow rate, mass (kg/s or kg/h)
q_V	flow rate, volume (m^3/s or m^3/h)
s_x	estimated component of the uncertainty of measurement of variable x
$s_{\bar{x}}$	standard deviation of the mean value of variable x
t	dry bulb temperature (°C)
t_d	dew point temperature (°C)
t_w	wet bulb temperature (°C)
u_x	combined uncertainty of measurement of variable x
U_x	total uncertainty of measurement of variable x ($=k \bullet u_x$)
U	voltage (V)
V	volume (m^3 or dm^3)
w_x	expected component of the uncertainty of measurement of variable x
x	moisture content (kg water vapour/kg dry air)
x_s	saturated moisture content (kg water vapour/kg dry air)
x_{CO2}	carbon dioxide concentration (kg CO_2/kg air or ppm)
x_{VOC}	concentration of volatile organic compounds (kg VOC/kg air or mg/m^3)
$\bar{x}$	mean value of variable x
φ	relative humidity (Pa/Pa or %)

Indices

a	air
amb	ambient conditions
c	cold side (saturator chamber)
CO_2	carbon dioxide
dp	dew point
h	hot side (calibration chamber)
ℓ	leakage
m	mass
s	saturated condition
V	volume
w	water, water vapour
wb	wet bulb
0	total (i.e. total air pressure)

Abbreviations

ACH	Air Changes per Hour
AH	Absolute Humidity
AQ	Air Quality
ASD	Acceleration Spectral Density
BIPM	Bureau International des Poids et Mesures
BFR	The Swedish Council for Building Research
CETIAT	Centre Technique des Industries Aerauliques et Thermiques
CIPM	Conference Internationale des Poids et Mesures
DCV	Demand Controlled Ventilation
DPT	Dew Point Temperature
DMM	Digital Multimeter
DVM	Digital Voltmeter
HC	Hydro Carbon
IEA	International Energy Agency
NIST	National Institute for Standards and Technology
NPL	National Physical Laboratory
NRC	National Research Council
RH	Relative Humidity
RMS	Root Mean Square
SCR	Silicon Controlled Rectifier ("thyristor")
SIB	The Swedish Building Research Institute
SP	The Swedish National Testing & Research Institute
STU	The Swedish Board for Technical Development
USD	United States Dollars
VOC	Volatile Organic Compounds
WBT	Wet Bulb Temperature

Acknowledgements

The design and construction of the calibrator described in this report was made at the department of energy technology at the Swedish National Testing & Research Institute (SP). In this context we would like to express our gratitude to Mr. Hedlin of the Prairie Regional Station, National Research Council of Canada (NRC), for sharing his experience and some design values from a similar set up operated by NRC. We would also like to acknowledge the financial support of the Swedish Council for Building Research (BFR) and the Swedish Board for Technical Development (STU). The project was jointly financed by BFR, SP, and STU.

The authors would also like to express their gratitude to the participating manufacturers of sensors as well as to the Swedish Tobacco Company for the use of an "artificial smoker".

Preface

International Energy Agency

In order to strengthen co-operation in the vital area of energy policy, an Agreement of an International Energy Programme was formulated among a number of industrialized countries in November 1974. The International Energy Agency (IEA) was established as an autonomous body within the Organization for economic Co-operation and Development (OECD) to admininster that agreement. Twentyone countries are currently members of the IEA, with the Commission of the European Communities (CEC) participating under special arrangement.

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 were 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 programmes
- building monitoring
- comparison of calculation methods
- ventilation and air quality
- studies of occupancy

Sixteen countries and 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 (completed projects are identified by *):

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
23 Multizone Air Flow Modelling
24 Heat-, Air-, Moisture Transfer in New Retro-fitted Insulated Envelope Parts
25 Real Time Simulation of HVAC-systems for Building Optimisation, Fault Detection and Diagnosis
26 Energy Efficient Ventilation in Large Enclosures

Official reports from above mentioned completed IEA annexes can be ordered or borrowed from:

AIVC
University of Warwick Science Park
Barclays Venture Centre
Sir William Lyons Road
Coventry CV4 7EZ
Great Britain
Fax: +44-203-416306

Annex 18 - Demand Controlled Ventilating Systems

Many IEA countries face an increasing problem with the indoor air quality. Studies concerning odour, threshold limits, outgassing from building material as well as factors depending on human activities and habits have been undertaken. The experiences from all these indoor air quality studies may give as a result a demand for increasing the outdoor air supply. One of the options is demand controlled ventilating systems to serve the occupants with a good indoor air quality without unnecessary waste of energy.

The objectives of the Annex 18 has been to develop means, methods, and strategies for demand controlled ventilating systems and to contribute to an implementation of the knowledge accumulated during the work within the Annex. The work has been directed towards ventilating systems in different types of buildings exemplified by

- single family houses and apartment buildings
- schools and day nurseries
- commercial buildings
- auditoria

Airborne pollutants may affect the occupants of a building and the 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 fungae) may result in an acute health response in the short term, and in more severe health risks in 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 pollutants, 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 a good indoor air quality, the two most important strategies are

- source control and
- 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 operated so as to adjust the flow rate of supply (and exhaust) air to the demand, significant energy savings may result, along with an improved quality of the indoor air.

The strategy for demand controlled ventilating systems will depend on the type and function of the buildings in which they are installed, and on the type of pollutant(s) present. In non-industrial buildings, the 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. Methods to cope with radon, combustion products (except moisture from gas fired household apparatuses), etc, will not be covered in the source book. The intention is that the final source book of the Annex 18 will serve as a general guidance on how to design and operate demand controlled ventilating systems.

Arrangement of the work within Annex 18

To fulfil the objectives ot the Annex the work has been divided into the following subtasks:

A. Review of existing technology

B. Sensor tests and case studies

  1) Long term tests of sensors in the laboratory and in the field
  2) Trials in unoccupied test buildings or test rooms
  3) Full scale tests in buildings in use

C. Compilation in a source book of general conclusions and recommendations on the design and operation of DCV systems

Reports

The titles of the reports are:

1 Demand Controlled Ventilating Systems
State of the Art Review
ISBN 91-540-5169-X

2 Demand Controlled Ventilating Systems
Sensor Market Survey
ISBN 91-540-5417-6

3 Demand Controlled Ventilating Systems
Sensor Tests
ISBN 91-7848-331-331-X

4 Demand Controlled Ventilating Systems
Case Studies

5 Demand Controlled Ventilating Systems
Source Book

Appointed Experts

The following experts have contributed to the results of the final report of annex 18, i.e. the source book (report no. 5):

Country	Name	Institute	Rep 1)	Exp 2)
Belgium	P Wouters	CSTC/WTCB	x	x
Canada	B Davidge	Public Works	x	x
	T Hamlin	CMH		x
Denmark	G Clausen	Technical University of Denmark		x
Finland	M Luoma	VTT-Technical Research Centre	x	x
Germany	W Raatschen	Dornier	x	x
Italy	G Fracastoro	Universitá della Basilicata	x	x
Netherlands	J J M Cauberg	Cauberg-Huygen Eng:s	x	x
Norway	F Drangsholt	SINTEF	x	x
Sweden	L-G Månsson	LGM Consult *(operating agent)*	x	x
	S A Svennberg	Ramas Teknik	x	x
	H Stymne	SIB		x
	L Norell	Fläkt Indoor Climate		x
	P Fahlén	SP	x	x
	T Nilsson	SP		x
	H Andersson	SP		x
	S Ruud	SP		x
	O Strindehag	Fläkt AB		x
	T-G Malmström	Royal Technical University of Stockholm		x
Switzerland	C Filleux	Basler & Hofmann	x	x
	M Zamboni	Basler & Hofmann		x
	J Fehlmann	ETH		x

---

1) Rep = Representative of Annex 18

2) Exp = National Expert

1 Introduction

1.1 Background

Indoor air quality and ventilation rates are topics of increased concern in most industrialized countries. One possibility of optimizing the balance between indoor air quality and energy use is to adapt the ventilation rate in accordance with the actual demand, so called Demand Controlled Ventilation (DCV). Therefore IEA (the International Energy Agency) instituted a specific annex (no. 18) in 1986 to deal with questions concerning this topic. Sweden is the operating agent of the work, which is subdivided into three subtasks,

- Subtask A:	Review of existing technology
- Subtask B:	Trials
- Subtask B1:	Long term test of sensors in the laboratory and in the field
- Subtask B2:	Trials in unoccupied test buildings or test rooms
- Subtask B3:	Full scale trials in buildings in use
- Subtask C:	A source book on the design and operation of demand controlled ventilating systems

A fundamental prerequisite for demand controlled ventilating systems is the possibility to find a measurable "indicator" of the air quality. Another important factor is the existence of commercially available sensors for the measurand, which have acceptable sensitivity, accuracy, long term characteristica and price level.

Different types of "indicators" can provide different types of information concerning the ventilating requirements of a specific building. Furthermore, different types of sensors for the same "indicator" can give different results. Such sensors must be sensitive enough to detect changes in the air quality requiring increased or decreased supplies of outdoor air and simultaneously be stable enough to function satisfactorily over long periods in varying environments.

Hence it is of great value to increase our knowledge concerning questions such as

1) which "indicators" are suitable
2) which sensors are possible for the planned "indicators"
3) how do the different "indicators" read relative to each other
4) how do different sensors for one particular "indicator" read in the short term as well as in the long term.

It is the task of IEA annex 18 to provide answers to such questions and in particular to The Swedish National Testing & Research Institute (SP) in Borås to answer question number 4. SP was contracted to perform the work of subtask B1 under the auspices of IEA annex 18. This work has been jointly financed by the Swedish Council for Building Research, the Swedish Board for Technical Development and SP.

1.2 Project description

Sensors for the following types of indicators (in accordance with the scope of IEA Annex 18) were included in a laboratory performance test:

- Water vapour (RH, WBT, DPT)
- Carbon dioxide
- Non-oxidized gases (VOC, e.g. C_mH_n, CO, etc).

The tests consisted of two main parts. In the first part one specimen of each sensor type was extensively laboratory tested and in the second part one specimen of each sensor type was exposed to normal indoor climatic conditions (e.g. in an office building).

Thus a minimum of two specimens of each sensor type were included. To limit the size and cost of the project, testing was planned for a maximum of fifteen sensors (seven for water vapour, three for carbon dioxide and five for non-oxidized gases). In the actual test it was not possible to include more than two carbon dioxide sensors due to time considerations. Several suppliers expressed an interest to participate in the test but only two actually delivered any sensors. Instead another humidity sensor was included to give the same total number of sensors.

The experience in using this test procedure has been reasonably good and thus a continuation of the project with other types of sensors is possible. Feed back from the tests however indicate a need to revise some of the procedures (see chapters 6 and 7). In particular the tests of VOC-sensors are difficult to specify since the sensors have dramatically different sensitivities for different substances.

As a reference gas for VOC-sensors a mixture of equal parts of one alifatic hydrocarbon, one aromatic hydrocarbon and one aldehyde was originally chosen. The reason for this choice is illustrated in figure 1.1. This figure is a fairly typical display of the various types of hydrocarbons found in indoor air. Alifatic hydrocarbons such as nonane, undekane etc are present in various quantities. Toluene is an important aromatic hydrocarbon found in glues and solvents whereas aldehydes such as formaldehyde, octanal and nonanal originate from glues, paints, putties and floorings.

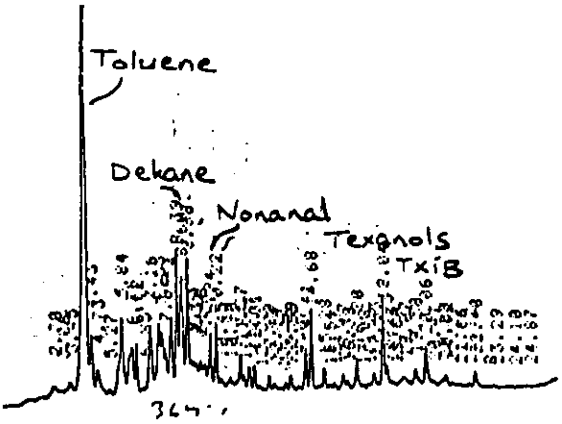


Figure 1.1. Analysis of an air sample from an office building. Sampling was made with Tenax sorption tubes. In healthy office-buildings the VOC-concentration is usually below 0.4 mg/m^3.

The laboratory tests consisted of four main parts (see the detailed description in chapter 3). These main parts were

- Checking of the manufacturers' data sheets and instructions
- Determination of the performance of new sensors including comparisons with data sheets
- Determination of the cross-sensitivity of sensors exposed to various combinations of the three chosen indicators as well as variations in the power supply, atmospheric pressure, temperature and air velocity
- Environmental tests concerning exposure to dry heat, dry cold, humidity, temperature change, vibration, electromagnetic radiation and electrostatic discharge.

The long term tests in occupied buildings also consisted of four main parts. In this case the major parts of the test included

- Determination of the performance of new sensors including comparisons with data sheets
- A building status control
- Exposure to ambient conditions in a conference room and in a cell type office
- Renewed performance control

Results relating to the specific makes of sensors are presented in chapter 5. Before this publication of the test results, the supplier/manufacturer of a sensor was permitted to study the results and express his opinion.

The test equipment used to obtain the results in this presentation is described in appendix A. In appendix B a discussion of the uncertainty of the test results is conducted.

2 Sensor types

It is well recognized that the most commonly used sensor for demand controlled ventilation at present is the temperature sensor. This type of sensor is well known and will therefore not be covered by this report. Only sensors responding to the composition of the indoor air or the occupancy of a building space will be treated. Such sensors may include active elements sensitive to

- humidity
- carbon dioxide
- volatile organic compounds
- occupancy (e.g. infrared sensors)

The market of sensors as of June 1989 has been surveyed and the result has been presented in a report on sensors performed by IEA Annex 18, subtask A (ref.5). A second survey was undertaken in July 1991 (Raatschen,1991, ref. 10). The surveys include sensors for humidity, carbon dioxide and mixed gases such as volatile organic compounds (VOC). In this chapter some of the commonly used sensor types are briefly described and the findings are commented upon and summarized. Numerical values are derived from reference 1 and from the findings of this investigation.

Please note that only some of the sensor types described in this generic chapter were subjected to the tests discussed in this report. The sensors that were actually tested are described in chapter 3. It is also worth mentioning that this generic chapter will also be included to its full extent in the source book of IEA annex 18.

2.1 Generics

It is important to bear in mind that no sensor measures the "quality" of air. "Quality" is a term that is difficult to quantify and that has a large portion of subjective content. Control systems, on the other hand, respond only to quantitative, measured signals. Furthermore there is not always a direct coupling between the perception of air quality, the concentration levels of various substances and their toxicity or irritability. The perception will depend both on the substance and the individual person exposed to the substance.

Thus it is of primary importance to carefully consider the meaning of "air quality" in each application and to identify possible sources of contamination. Before selecting the appropriate type of sensor, or indeed before contemplating a DCV-system at all, possible obnoxious substances ("indicators") should be identified and their threshold levels quantified. Suggestions concerning commonly used indicators for different applications are presented in the Source Book of IEA annex 18. In control applications the most important *measuring characteristics* of a sensor are:

- A high sensitivity to the chosen indicator and a low sensitivity to other influence factors (a low cross-sensitivity)
- Measuring and general operating ranges that are relevant to the application
- A good reproducibility combined with a low level of hysteresis
- A short rise time (a rapid response) compared to the rise time of the indicator of a particular application
- A good stability
- A suitable output signal
- A possibility of subsequent periodic calibrations
- Immunity to climatic, mechanical and electro-magnetic interference.

Other, less important measuring characteristics, may be compensated by suitable signal processing intelligence. Such characteristics are for instance accuracy and linearity.

Consideration should also be given to the *installation, operation and maintenance characteristics* of a sensor. Such characteristics may include:

- Ease and durability of installation
- Type of mounting (wall or duct mounting)
- Type of filter (if required)
- Type of casing and its protection class
- Size and weight
- Type of power supply
- Required maintenance and calibration and their respective intervals
- Expected lifetime

Last, but not least, the *purchasing characteristics* of a sensor should be contemplated. Possible items of consideration are:

- Availability (alternative suppliers)
- Price and delivery time
- Documentation

2.2 Active elements

Sensors used in present day DCV applications include types for the monitoring of indicators such as:

- Humidity (relative humidity, wet bulb temperature, dew point temperature)
- Carbon dioxide
- Mixed gases (volatile organic compounds, "VOC")
- Occupancy
- Particles

In the following paragraphs the active elements of commonly used sensors of the first four types are briefly described.

2.2.1 Humidity Sensors

Humidity sensors may be classified as sensors responding to either *relative humidity* or *absolute humidity*. Numerous principles are employed to sense either of these quantities. Some of the most common types in use are presented below.

Dimensional Change Hygrometers (human hair, plastic strips, wood fibres)

A large class of relatively inexpensive hygrometers utilizes the dimensional change of a sorbing substance. Many types of organic fibres such as human hair, wood fibres and various plastic materials are sufficiently sensitive to changes in relative humidity to act as sensing elements. The dimensional change of human hair due to a change in *relative humidity* by 100 % is approximately 2 %. Nylon fibres have a corresponding change of about 3 %.

Dimensional change sensors may act directly on a simple switch for the on/off control of a fan. In other cases the dimensional change may operate on e.g. a variable resistor to produce an analogue control signal.

Advantages:	Simple and inexpensive. Large operating humidity range.
Disadvantages:	Requires frequent reconditioning and recalibration. Substantial hysteresis (up to 15 % RH). Inaccuracy below 5 % may require daily single point calibration. Response is relatively slow and temperature dependent.

Electrical Impedance Hygrometers

Certain hygroscopic substances change their dielectric and/or their conductive properties in relation to changes in *relative humidity*. These changes can be measured as changes in capacitance and/or changes in resistance of the sensing element.

Dunmore Cells commonly use lithium cloride and/or polyvinyl alcohol on a plastic support as the sensing element. The operating resistance change may cover 2-4 decades in response to a change in relative humidity by 30 %.

Advantages:	Low inaccuracy (< 1.5 %) and low hysteresis (< 0.5 %). Good stability (drift < 0.5 % per year).
Disadvantages:	Limited operating range and high electric impedance. Sensitive to certain vapours (e.g. sulphur dioxide, some acids, alcohols), salts and high humidity or free water. Temperature dependent rise time and drift in calibration.

Aluminium oxide hygrometers use an anodized material sandwiched between electrodes consisting of a metal base and a porous metallic film. Changes in relative humidity cause changes in the capacitance and/or the resistance between the electrodes.

Advantages:	A fairly large operating range and very quick response times (< 1 s).
Disadvantages:	A fair amount of hysteresis (several percent). Sensitivity to high humidity levels or free water.

Other impedance type hygrometers use a plastic foil as the humidity dependent dielectric material. The change in capacitance is used to provide an electric output. This type of sensor seems to be less sensitive to high humidity and has a very low level of hysteresis.

Weight Change Hygrometers

The mass of water accumulated in a sorbing substance can be made to change the resonant frequency of a piezoelectric crystal. The sorbed quantity depends on *relative humidity* and the selected sorbing material.

Advantages:	Immunity to interference and easy A/D conversion (the sensor is inherently digital).
Disadvantages:	Expensive and not commonly used in control applications outside industries.

Dew Point Hygrometers

The dew point of water vapour is a temperature uniquely related to the *absolute humidity*. This temperature is normally detected by chilling a metal surface until water just begins to condense on this surface. Condensation changes the reflection of light from a light emitting diode and this change is detected by a photo transistor.

Advantages:	Direct, simple relationship between the measurand and the output signal. Low inaccuracy (< 0.2 K dew point temperature) and low hysteresis. Good stability under conditions of clean air. Low output impedance (e.g. 100 ohm for a platinum resistance type temperature sensor).
Disadvantages:	Expensive. Relatively slow response. Requires an air pump or a minimum air velocity in a duct.

Wet and Dry Bulb Psychrometer

The latent heat exchange caused by the evaporation of water results in a well defined reduction of temperature in an adiabatic system, thus relating the *absolute humidity* to a set of temperatures. This temperature change can be measured by comparing the temperatures of one thermometer that measures the normal air temperature (dry bulb) and one that measures the temperature of a wick soaked in water (wet bulb). Equations relating the dry- and wet bulb temperatures to the absolute (or relative) humidity assume the heat exchange to be entirely convective.

Advantages: Direct thermodynamic relationship between the humidity and the output signal. Low electric output impedance. Well proven and reasonably accurate method.
Disadvantages: Requires a supply of distilled water and a specified air flowrate. Slow response. Sensitive to impurities and heat exchange by radiation.

Saturated Salt Solutions

The vapour pressure of a saturated salt solution varies with temperature. A hygrometer using this concept is made by fitting a pair of electrodes to a substrate covered in salt, commonly lithium cloride. Water vapour is absorbed by the salt until a balance is reached between the pressure in the salt and the absolute vapour pressure in the air. If the sensing element is heated the vapour pressure will rise until it exceeds the vapour pressure in the air. At this point the salt will be saturated, water will start to evaporate and the electrical resistance will change abruptly. The temperature of the sensing element at this point serves as a measure of the *absolute humidity*.

Advantages: Reasonable measuring range (-29 to +71°C dew point temperature) and fairly low inaccuracy (< 1 K dew point temperature). Reasonably quick response (a few minutes).
Disadvantages: Salts may become contaminated. Requires regular reconditioning of the sensor.

2.2.2 Carbon Dioxide Sensors

Sensors designed to selectively measure the carbon dioxide content of air use absorption of infrared light (NDIR, Non Dispersive Infra Red). A light source transmits light through a selective infrared filter into a measuring cell. The room air is passed through this cell and absorption of the infrared light excites vibrational energy bands of the carbon dioxide molecules. The filter ensures that only wavelengths typical of carbon dioxide are transmitted into the cell. There appears to be a requirement concerning a minimum amount of water vapour in the air to stimulate the vibrational action of the carbon dioxide molecule. Two methods of detecting the absorption are commonly used, the *photoacoustic* method and the *photometric* method.

Photoacoustic Infrared Detection

The increase of molecular vibration by absorption of light leads to an increase in temperature of the absorbing gas. Using a closed cell this change in temperature also leads to a change in pressure. Modulation of the light source creates a pressure change with the modulating frequency and an amplitude dependent on the concentration of absorbing gas. The pressure changes are detected by a sensitive microphone.

Advantages: Low cross-sensitivity, low hysteresis, reasonable inaccuracy (10-100 ppm) and linearity.
Disadvantages: Discontinous measuring principle (the cell has to be closed off between samples), slow response (rise times may be in excess of 10 minutes), little long-term experience.

Photometric Infrared Detection

Absorption of light in the cell results in less light coming out at the end of the cell. The light emerging from the cell is measured by a photodetector and converted to an electric output signal. To achieve sufficient absorption at low concentrations the light path is increased by multiple reflections in mirrors.

Advantages: Low cross-sensitivity, low hysteresis, reasonable inaccuracy (10-100 ppm) and linearity.
Disadvantages: Inverted reponse (low gas concentration gives high transmission), fairly slow response (rise times of up to10 minutes).

2.2.3 Mixed Gas Sensors

There are three principally different types of solid state sensors used to monitor the presence of certain gases in air: homogenous metal oxide sensors, MOS-FET sensors and catalytic gas sensors. These sensors are commonly called "air quality sensors" providing an output signal scaled as 0-100 % air quality.

Homogenous Metal Oxide Sensors (Taguchi sensors)

The most commonly used homogenous metal oxide sensors use n-type polycrystalline semi-conductors such as SnO_2 or ZnO. The sensor is heated and combustible gases can react with oxygen on the heated surface. The reactions excite electrons into the conduction band of the semi-conductor thus changing the resistance of the sensor.

Advantages: Sensitive to a broad range of human-generated odours, cigarette smoke and emissions from building materials. Inexpensive.
Disadvantages: Sensitivity varies widely with the type of gas and not necessarily in relation to toxicity or irritability. Greatly affected by variations in temperature and humidity. Slow and gas/temperature dependent response. Difficulty in knowing what to calibrate against.

Use of thin-layer technology can reduce response times and increase the sensitivity to simple gases, e.g. H_2S, CO, NO_2, CH_4 and C_2H_5OH.

MOS-FET Sensors (Field Effect Transistors)

In contrast to the Taguchi sensor, which is a surface effect device, MOS-FET sensors are volume effect devices. Gas molecules diffuse into the sensor and react at the gate of the transistor thereby changing the current through the device. By choosing different metals as the gate material the sensor can be made highly selective to specific types of gases.

Advantages: Rapid and specific response. Possibility of the sensor being integrated in an amplifier circuit.
Disadvantages: Contaminants must be known in advance. At present sensors are expensive and experience is limited.

Catalytic Gas Sensors

The heat of exothermic reactions at the surface of a sintered body will increase its temperature and thus also increase its resistivity. To enhance the reaction rate of the non-oxidized gases the sensor is heated by an embedded heating wire and the surface is covered by a thin catalytic layer.

Advantages: Sensitive to a broad range of human-generated odours, cigarette smoke and emissions from building materials. Inexpensive.
Disadvantages: Sensitivity varies widely with the type of gas and not necessarily in relation to toxicity or irritability. Greatly affected by variations in temperature and humidity. Slow and gas/temperature dependent response. Difficulty in knowing what to calibrate against.

2.2.4 Occupancy sensors

There are various methods of detecting a *change in occupancy* that have been devised for military purposes or for burglar alarms. Detection may be accomplished by sensing infrared radiation emitted from people (passive IR-sensors), interruption or reflection of infrared beams (active IR-sensors), change in impedance for microwave radiation, vibration or noise.

In case of DCV-applications it is not only the change in occupancy that is important but also the occupancy as such. Thus a sensor must detect the presence of people even if no movements occur for a considerable time. Therefore the passive IR-sensor technique seems to be most suited for use in DCV-systems.

2.3 Connection of sensors to control systems

The control of a DCV system aims at providing quick and correct reactions to changes in the concentration of the selected indicator/contaminant.The reaction should not be influenced by the presence of other substances in the form of gas, vapour or particles (cross-sensitivity). Nor should the reaction be affected by environmental factors such as temperature, vibration and electromagnetic fields. Thus, the correct connection of sensors to the control system is of the utmost importance, and so is the design and construction of all devices being part of the control system.

2.3.1 Types of control systems

Sensors are normally used to control the rate of exhaust air flow and the supply of fresh air by operating the speed of fans and/or the position of dampers. Control may be exerted by means of either *on-off control* or *continous control.*

On-off control

This is a simple and inexpensive type of control frequently used to limit e.g. humidity levels in dwellings. In the case of hygrostats the sensing element is often directly acting on an electric switch which operates the fan or damper. In other cases the magnitude of the current to be switched may require an intermediate relay.

Continuous control

Controllers operating with continuous control can be classified in two main categories, Local Controllers (LC) and Direct Digital Control (DDC). Local controllers may be of the traditional analogue type or operate digitally inside but with an analogue output. Modern control systems often operate a number of local controllers, so called Programmable Local Controllers (PLC), from a central computer. Whatever the type of controller a variety of different control strategies may be used (see for instance the Source Book of IEA annex 18).

2.3.2 Sensor location

If the sensor is to respond correctly it is obvious that it must be located in a representative position. Suitable positions will depend on the application and the type of sensor. This is further discussed in the Source Book of IEA annex 18. It is recommended to avoid the mounting of sensors where they are liable to be exposed to excessive amounts of dust, grease, vibration or electromagnetic fields.

2.3.3 Connection to the control device

To facilitate connection to systems employing continous control the sensor should have a standardized current or voltage output. Input signals to controllers are normally 0-20 mA, 4-20 mA, 0-5 V or 0-10 V. Digital communication may be of a series or parallel type. In this case standardized and well specified transmission protocols and baud-rates should always be used.

Standard precautions concerning shielding and electric separation of low voltage signals and high voltage/current power conductors should be taken to avoid electromagnetic interference. Immunity to electromagnetic interference should be part of an evaluation of sensors (see for instance the test program in chapter 4). It goes without saying that all requirements concerning electrical or other safety aspects should be complied with.

The service life time of a DCV control system will depend on various aspects of individual components such as component life time, installation, manner of operation and the requirements and possibilities of service. It will also depend on the overall configuration of the system. Regarding sensors this means that the installation must be made in such a way that subsequent service, calibration and adjustment are easy to perform. The cost of different types of sensors may vary considerably but in general the cost of on-site service or calibration will be close to or even exceed the cost of a new sensor. Therefore long-term stability and reliability are important features of a sensor installation. A target value for the service life time of a sensor should be at least 10 years.

2.4 Test Laboratories and primary calibration facilities

Official testing laboratories directly involved in the IEA Annex 18 evaluation of sensors and control systems have been:

- SIB (National Swedish Institute of Building Research)
  Box 785
  S-801 29 Gävle
  Sweden

- SINTEF
  N-7034 Trondheim-NTH
  Norway

- SP (Swedish National Testing and Research Institute)
  Box 857
  S-501 15 Borås
  Sweden

A number of institutions around the world perform accurate calibration of humidity sensors, for example:

- CETIAT (Centre Technique des Industries Aérauliques et Thermiques)
  B.P. 6084
  F-69604 Villeurbanne Cedex
  France

- NIST (National Institute for Standards and Technology)
  Gaithersburg, Maryland
  USA

- NPL (National Physical Laboratory)
  Teddington, Middlesex
  TW11 O1W, England

- NRC (National Research Council)
  Ottawa, Ontario K1A OR6
  Canada

Carbon dioxide and VOC-gases are normally analyzed by well equipped chemical laboratories. Sensors for these substances can probably also be tested by such institutions. In Sweden the Swedish National Testing and Research Institute has carried out intial investigations according to the test program in chapter 4.

2.5 Testing and Rating

Sensors and other components for the operation of DCV systems should be tested according to standardized methods. Results of such tests must be presented in a form that is comprehensible and that makes meaningful comparisons possible. In chapter 3 such a test program is presented and the required test equipment is described in appendix A.

Regular functional tests and, if necessary, calibration should be carried out on site. Some sensors have inherent control facilities such as test signals or warning lights. Other sensors may be checked by special service and test instruments. Calibration is normally carried out using either of the following two methods:

- Comparison with a calibrated reference instrument exposed to the same atmosphere

- Exposing the sensor to a well known reference atmosphere

Many humidity sensors can be checked by using saturated salt solutions of different types (see for instance ref. 1). If the salt solutions are regenerated regularly this is a method that is sufficiently accurate for control applications. Suitable salts are for instance potassium acetate (21-23 % RH), sodium iodide (37-41 % RH), sodium bromide (57-60 % RH) and potassium chloride 84-86 % RH).

Caution: Some sensor types are adversely affected by certain salts. This should always be checked with the manufacturer before exposing the sensor.

Carbon dioxide sensors can be calibrated by the use of bottles with reference gas of a known composition. Such gas may be obtained from some of the suppliers of sensors or from major suppliers of liqiufied gas. A suitable concentration of a calibration gas is in the range of 1000 - 1500 ppm.

Caution: IR-sensors for carbon dioxide rely on the presence of a minimum humidity level of 10-20 % RH. Therefore it is not possible to apply carbon dioxide out of a bottle directly to the sensor without first adding some humidity. The sensor output will also depend on the pressure and therefore care must be exercized to avoid exposing the sensor to the pressure of the bottle.

Mixed gas sensors can be checked in much the same way as sensors for carbon dioxide by means of certified reference gases. Selective sensors, such as some of the experimental FET-devices, should obviously be checked with the gas they were optimized to detect. Broad band devices, such as the Taguchi-type semi conductor sensor, will require careful consideration before one or several calibration gases are chosen. Manufacturers of the sensing elements will normally provide data concerning the relative sensitivity of the sensor to various gases.

Caution: This type of sensing element is also sensitive to water vapour (i.e. humidity) and it is highly influenced by the operating temperature. It must also be recognized that the sensors and their housings may themselves be strong sources of VOC-emissions. If this is the case it will not be possible to perform calibration inside a closed space.

Unless the exact indicator(s) is (are) known the following gases could be used to calibrate mixed gas sensors:

Application (source of contamination)	**Type of gas**	**Concentration**
Occupancy (body odour)	Acetone(C_3H_6O)	1-100 ppm
Smoke (tobacco 1-2 ppm, car exhaust 10-100 ppm)	Carbon monoxide (CO)	1-100 ppm
Volatile Organic Compunds (building materials, photo copiers, printed documents etc.)	Nonane (C_9H_{20})	1-10 mg/m^3

Laboratory tests of 5 mixed gas sensors have been conducted using nonane, toluene and octanal as reference gases. The results are presented in chapter 5. In this case the sensors displayed roughly the same sensitivity to a specific gas concentration irrespective of the type of gas used as a single component or mixed in equal parts.

2.6 Conclusions

Experience from a great number of research projects and practical applications of DCV control systems has been summarized in reference 5. During the course of the IEA Annex 18 activities further experience concerning different types of sensors has been gained. Conclusions concerning the state of the art of sensors for humidity, carbon dioxide and mixed gases (volatile organic compounds) are summarized below.

2.6.1 Humidity sensors

Application: The main field of application of humidity sensors is in dwellings to control the humidity levels in bath rooms, laundry rooms and kitchens. The principle reason is to avoid deterioration of the building structure and to minimize the risk of mould growth. Mould growth is augmented by a high relative humidity and will therefore generally commence on room surfaces with the lowest temperatures. Surface temperatures will change due to changing outdoor temperatures as well as changing room temperatures. Thus it is beneficial to use an advanced humidity controller, which adjusts the set point in accordance with the prevailing room conditions (see Raatschen, 1991, ref. 8 and 9).

Other applications concern control of humidification or dehumidification systems, e.g. in indoor swimming pools or ice-rinks. It is in general much easier to control specific activity related rather than occupancy related emissions by means of humidity sensors. Unless the basic ventilation is extremely poor the occupancy related humidity variations will be smaller than those caused by climatic variations and some sort of advanced controller will be required to distinguish between occupancy related and natural humidity changes.

Availability: There is an abundance of humidity sensors of different makes and types in all price ranges. Most electronic sensors come with a choice of standardized output signals. Thus availability should not be a problem.

Price: From 1-2 USD for simple sensing elements up to 10 000 USD for sophisticated dew point hygrometers. Typical, good quality, capacitive sensors cost in the range of 100-600 USD including the necessary electronics.

Performance: Electrical impedance change sensors, e.g. capacitive sensors, in general have excellent performance characteristics with good linearity, low hysteresis and quick response.
Caution: Some sensors will not tolerate condensation of water on the sensor element. Sintered filters may slow the sensor time response considerably. Dimensional change sensors, e.g. hair or plastic strip hygrometers, in general are less accurate than the impedance change hygrometers. For control purposes the relatively slow response and large amount of hysteresis may prove to be important disadvantages.

Service life: The service life of most humidity sensors is expected to exceed 10 years. Calibration or functional control intervals should be approximately 1-2 years depending on the type of sensor and its application.

2.6.2 Carbon dioxide sensors

Application: Carbon dioxide is at present the best documented indicator of occupancy and thus carbon dioxide sensors are frequently being applied to control occupancy related emissions. This type of sensor, however, hardly responds at all to tobacco smoke. Therefore other measures must be taken to avoid problems in premises where smoking may occur.

Availability: Carbon dioxide has previously been measured with costly and bulky laboratory equipment. In recent years a number of manufacturers have started making small size sensors with prices that are still high but not exuberant. Size and type of output signal are fairly similar for different makes and therefore availability should not be a problem.

Price: Prices range between 250-2000 USD.

Performance: The error of measurement is normally well within ± 50 ppm at a measured level of 1000 ppm and this should be sufficient for control purposes (this corresponds to an uncertainty in the controlled flowrate of ± 8 %). Stabilization time after initial connection to the power supply may be as much as 1-2 weeks. Some sensors are fairly slow which may be a disadvantage in control applications.

Service life: Long term experience is still limited but continuous operation over a period of one year seems to cause no problems. Possible sources of maintenance are the IR-lamp, the air pump (if any) and cleaning of the optical filter. Calibration check-ups should be performed annually.

2.6.3 Mixed gas sensors

Application: Mixed gas sensors are used in very diverse applications such as in warning devices for gas leaks, occupancy related DCV-systems (including tobacco smoke) and in ventilation control of garages and tunnels. The broad range sensitivity is both the strength and the weakness of this sensor.

Availability: Although there are a number of suppliers of mixed gas sensors, nearly all of these suppliers use sensing elements from the same manufacturer. At present, therefore, there are few alternatives on the market.

Price: Prices range between 20-400 USD depending on whether the price pertains to the sensing element or a complete sensor including the controller.

Performance: Mixed gas sensors are difficult to assess in terms of ordinary performance criteria since these sensors react on such a large variety of substances. Furthermore there is no direct relationship between the sensitivity of the sensor to a certain gas and the effect of this gas on the indoor air quality. In most cases the user of the sensor does not know the cause of a change in output signal. There may be substantial scatter between individual elements of the same type and there is a required "burn in" time of several weeks before a stable output is reached. Experiments have shown that sensors using the same sensing element but different electronics may react quite differently. The output is very sensitive to the temperature of the sensing element and therefore also to the supply voltage of the sensor heating element. The electronics may contain compensation circuitry, e.g. for the influence of temperature and humidity.

Service life: Long term experience of mixed gas sensors in DCV-applications is scarce. The effect on the sensing element of extended exposure to for instance dirt and grime has yet to be documented.

2.6.4 Occupancy sensors

Application: Occupancy sensors are commonly used in burglar alarms to detect the presence of people. A few applications in DCV-systems (e.g. in schools) have also been reported.
Caution: The actual positioning of the sensor is crucial if the entire space is to be covered. Also when a room is entirely filled with people there is a risk that the sensor will detect this as an elevated back-ground temperature.

Availability: There are several suppliers of occupancy sensors. Therefore availability should not be a problem.

Price: Prices range between 100-200 USD for the sensing element including some signal processing intelligence (e.g. time delay functions, sensitivity adjustments etc.).

Performance: The operating principle is often based on IR-sensing elements that detect the heat radiation from human beings. They seem to work well in burglar alarm systems and there is also some positive feed-back from DCV-systems although the experience is still limited. One negative aspect is the lack of feed-back signal of the actual effect the occupancy has on indoor air quality. This means that occupancy sensors will generally operate in on-off control systems.

Service life: Long term experience of occupancy sensors in burglar alarms is abundant. The effect on the sensing element of extended exposure to for instance dirt and grime has yet to be documented.

2.6.4 Future developments

If DCV-systems are to attain a widespread application sensors must above all be inexpensive, easy to check and calibrate and have a good stability and a long service life. Humidity and carbon dioxide sensors are already sufficiently accurate but can still do with improvements concerning the other aspects mentioned above. Mixed gas sensors, on the other hand, need improvements regarding possibilities to control the response to various substances. For all types of sensors the low cost of intelligent electronics makes extensive use of self-checking features feasible.

The rapid progress in hybrid electronic circuitry using thin film and thick layer technology in combination with micromechanics may in the future provide us with integrated multi-sensor devices. Such a device could for instance include a temperature sensor to control cooling requirements, a humidity sensor in case humidification or dehumidification is needed, a CO-sensitive solid state sensor responding to tobacco smoke and sensitive solid state devices reacting to some specific human related emissions. Even sensing elements for specific emissions related to building materials could be included.

3 Presentation of the tested sensors

The tested sensors have been intended for the measurement of the following three types of indicators:

- Relative humidity (RH)
- Carbon dioxide (CO_2)
- Volatile organic compounds (VOC)

As an introduction to the work within IEA Annex 18 a sensor market survey was carried out. In this survey, different manufacturers were asked to participate in a laboratory test program. However, there were fewer manufacturers than expected to show an active interest in the test program and hence retailers in Sweden were also asked to participate.

Those sensors that were finally included in the evaluation are briefly described in this chapter. The compilations of data for each sensor are based on the data sheets supplied with the sensors and completed by further information directly from the manufacturers. The prices mentioned were provided by Swedish retailers in March 1992 unless otherwise stated. The current rate of exchange (March 1992) is 1 USD = 6.05 SEK.

3.1 Sensor S1

Manufacturer: Staefa
Model: FRA-Q1
Measurand: VOC

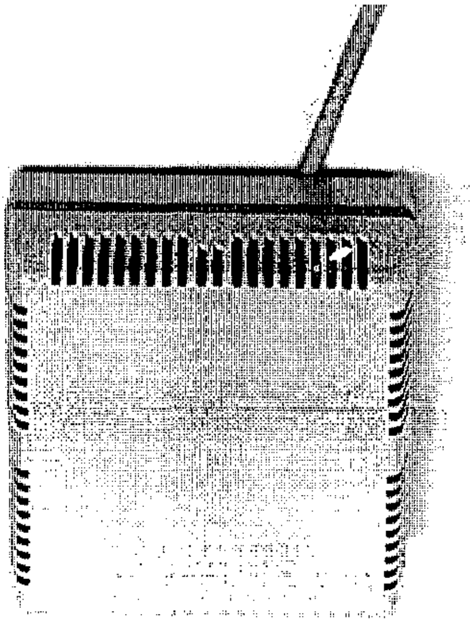


Figure 3.1. Sensor S1

Table 3.1. Compilation of the manufacturer's data for the sensor S1

Manufacturer	**Staefa**
Sensor designation	FRA-Q1
Sensor type	Semi-conductor
Measured parameter(s)/substance(s)	Volatile organic compounds
Power supply	24 V AC/DC +15/-10%
Output signal	0-10 V
Calibration facilities	1000 ppm methane, 21 °C, 50 %RH gives an output signal of 3.5 V
Signal processing intelligence	None
Operating range (max/min) for ambient conditions	0-50 °C
Warming-up time	Depends on the time the sensor has been disconnected
Measuring range	0-100 %AQ. The sensor element TGS 812 is tested at 400-6000 ppm of methane, carbon monoxide, isobutane, hydrogen and ethanol according to the data sheet by Figaro
Uncertainty of measurement	No information provided
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	Depends on the environment
Zero drift	No information provided
Rise time	No information provided
Supply voltage influence	< 0.5 %AQ/V
Supply frequency influence	No information provided
Temperature influence	< 0.2 %AQ/°C
Humidity influence	< 0.4 %AQ/ % RH
Atmospheric pressure influence	No information provided
Air velocity influence	None for normal applications
Other influence factors	Range of dispersion between sensor elements ≈5 % of the output signal (0-10 V). Measuring AQ of very dry air (< 1g/kg) can cause a change in calibration
Required maintenance	Depends on the environment
Maintenance intervals	Depends on the environment
Calibration intervals	Depends on the environment
Expected lifetime	10 years
Size and weight	80×80×44 mm, 0.5 kg
Price	SEK 1625:-
Additional information	Heater voltage $V_H = 5 \pm 0.2$ V

3.2 Sensor S2

Manufacturer: Landis & Gyr
Model: QPA 61.1
Measurand: VOC

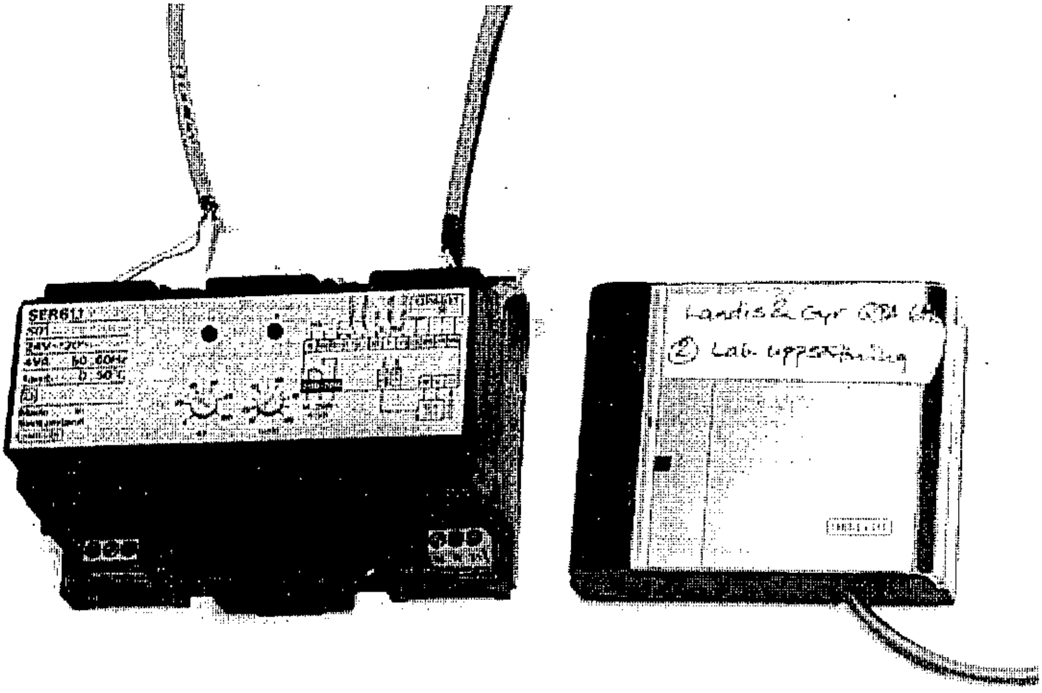


Figure 3.2. Sensor S2

Table 3.2. Compilation of the manufacturer's data for the sensor S2

Manufacturer	**Landis&Gyr**
Sensor designation	QPA 61.1
Sensor type	Semi-conductor
Measured parameter(s)/substance(s)	Volatile organic compounds
Power supply	5.8 V DC (sensor), 24 V AC ±20% (controller)
Output signal	0-10 V DC output from the controller
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	No information provided
Warming-up time	No information provided
Measuring range	0 - 100 % AQ
Uncertainty of measurement	No information provided
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	No information provided
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	No information provided
Humidity influence	No information provided
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No information provided
Calibration intervals	No information provided
Expected lifetime	No information provided
Size and weight	100×81×32.4 mm, 0.14 kg
Price	SEK 1075:- (sensor), SEK 1735:- (regulator)
Additional information	No information provided

3.3 Sensor S3

Manufacturer: X
Model: Y
Measurand: VOC
Comment: After the test production of this sensor was discontinued

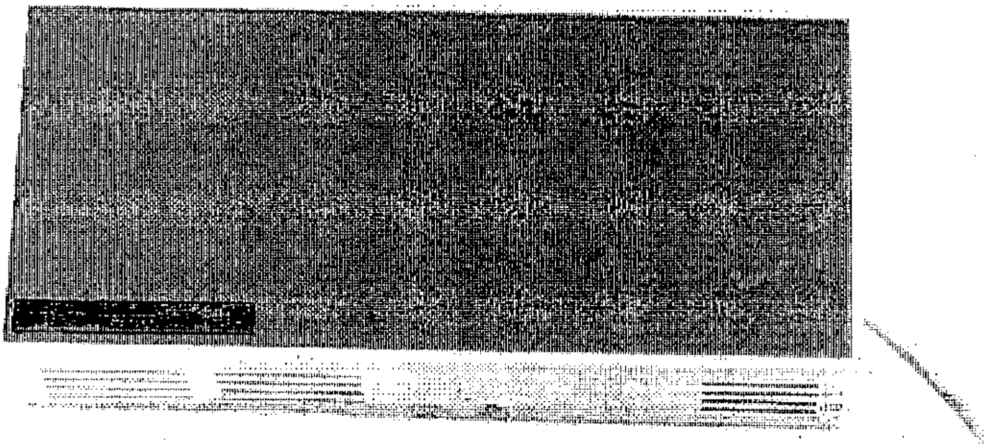


Figure 3.3. Sensor S3

Table 3.3. Compilation of the manufacturer's data for the sensor S3

Manufacturer	**X (production has been discontinued)**
Sensor designation	Y
Sensor type	Semi-conductor
Measured parameter(s)/substance(s)	Volatile organic compounds
Power supply	24 V AC
Output signal	0-10 V
Calibration facilities	No
Signal processing intelligence	No
Operating range (max/min) for ambient conditions	0-45 °C
Warming-up time	At least 5 minutes
Measuring range	0 - 100 % AQ, adjustable sensitivity
Uncertainty of measurement	No information provided
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	No information provided
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	No information provided
Humidity influence	No information provided
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No requirements
Calibration intervals	No information provided
Expected lifetime	10 years
Size and weight	No information provided
Price	DM 463:- (july 1990)
Additional information	No information provided

3.4 Sensor S4

Manufacturer: Sauter
Model: ERQ 1 F 001
Measurand: VOC

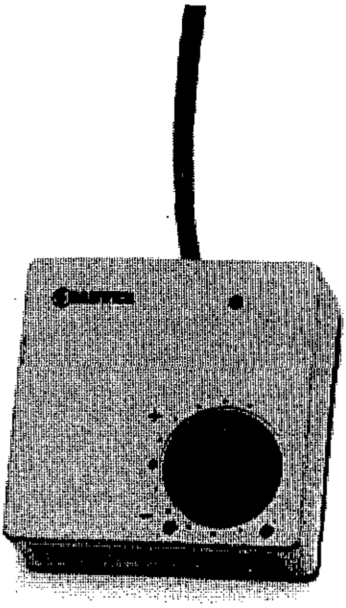


Figure 3.4. Sensor S4

Table 3.4. Compilation of the manufacturer's data for the sensor S4

Manufacturer	**Sauter-Cumulus**
Sensor designation	Sauter ERQ 1 F 001
Sensor type	Semi-conductor
Measured parameter(s)/substance(s)	Volatile organic compounds
Power supply	24 V AC
Output signal	0-10 V or 0-620 mV
Calibration facilities	Calibration in arbitrary units of tobacco smoke. Individual calibration is recommended.
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	0-40 °C, 30-70% RH
Warming-up time	1 min
Measuring range	0-10; arbitrary units of tobacco smoke
Uncertainty of measurement	±15%
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	(53 ±18) %/ 2 years
Rise time	<30 s lag time, <60 s time constant (63%)
Supply voltage influence	24 V AC ± 20 %, none
Supply frequency influence	50 Hz/60 Hz, none
Temperature influence	<2%/°C
Humidity influence	<1.1%/% RH
Atmospheric pressure influence	Not observed
Air velocity influence	Not observed
Other influence factors	Long power failures cause reversible contamination of the sensor
Required maintenance	No special maintenance required
Maintenance intervals	Maintenance when necessary
Calibration intervals	Individual calibration as one thinks fit
Expected lifetime	> 5 years
Size and weight	0.1 kg
Price	SEK 1700:-
Additional information	No information provided

3.5 Sensor S5

Manufacturer: Aritron
Model: AROX 425 AB
Measurand: CO_2

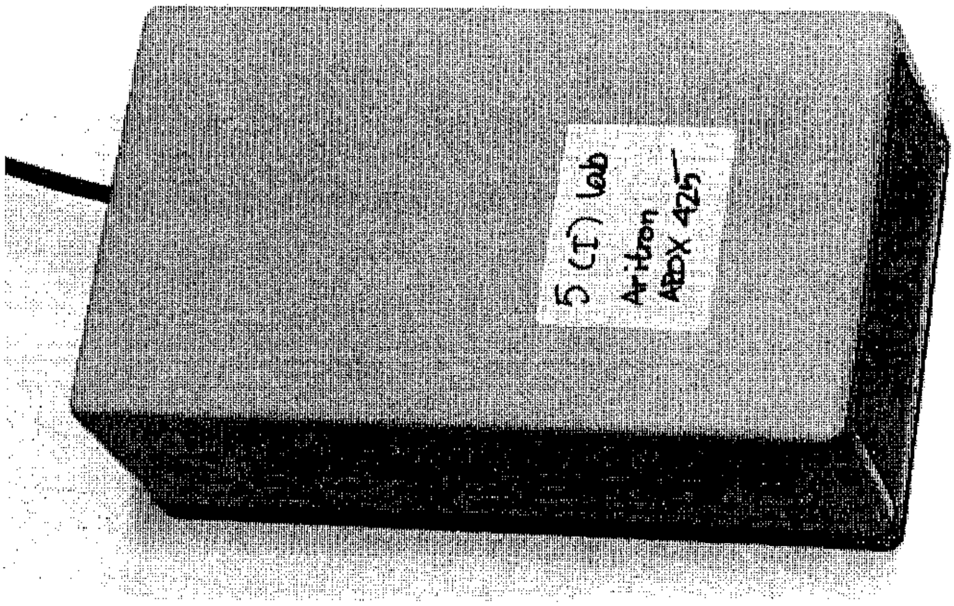


Figure 3.5. Sensor S5

Table 3.5. Compilation of the manufacturer's data for the sensor S5

Manufacturer	**Aritron Instrumente**
Sensor designation	AROX 425 AB
Sensor type	NDIR photo-acoustic
Measured parameter(s)/substance(s)	Carbon dioxide
Power supply	24 V AC (+10%, -15%)
Output signal	0-10 V / 0-20 mA
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	0-40 °C, 20-99% RH
Warming-up time	30 sec
Measuring range	0-2000 ppm carbon dioxide, other measuring ranges are also available
Uncertainty of measurement	No information provided
Hysteresis	No information provided
Linearity	< 2% FS
Repeatability	< 2% FS (IEC528)
Stability	+0.3%/°C, +0.06%/% RH
Zero drift	5 % / 18 months
Rise time	<10 min (time constant), τ_{90} = 8 min
Supply voltage influence	0.8 % FS/V
Supply frequency influence	Calibration is related to supply frequency
Temperature influence	0.3 %/°C
Humidity influence	0.06 %/% RH
Atmospheric pressure influence	0.1 % FS/mbar
Air velocity influence	No information provided
Other influence factors	Cross-sensitivity: Methane: 5 ppm CO_2/1 % CH_4 CO/SO_x/NO: <0.5 ppm/1 %
Required maintenance	Change of IR source and filter membrane for the gas
Maintenance intervals	18 months
Calibration intervals	18 months
Expected lifetime	10 years
Size and weight	188×110×70 mm, 0.62 kg
Price	SEK 8500:-
Additional information	Vibration: No influence. Air flow <0.15 *l*/min; wall-mounted unit working by diffusion.

3.6 Sensor S6

Manufacturer: Sauter
Model: EGQ 10 F 001
Measurand: CO_2

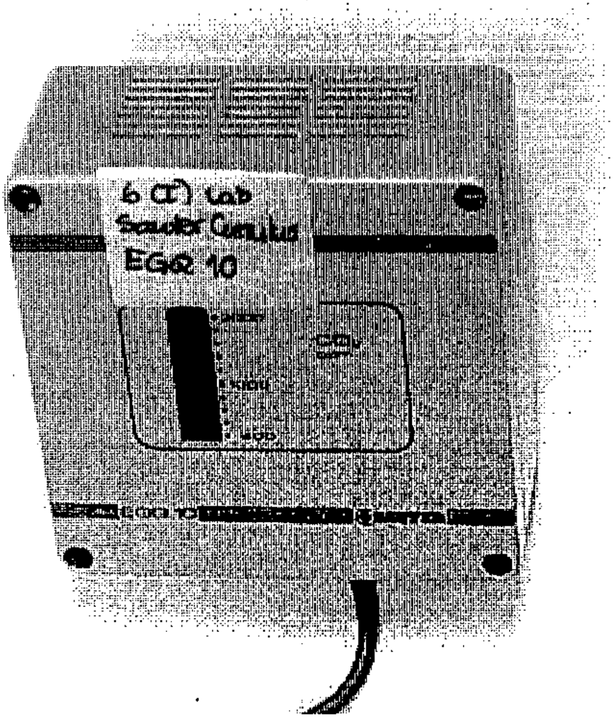


Figure 3.6. Sensor S6

Table 3.6. Compilation of the manufacturer's data for the sensor S6

Manufacturer	**Sauter-Cumulus**
Sensor designation	EGQ 10 F 001
Sensor type	IR spectroscopy, NDIR
Measured parameter(s)/substance(s)	Carbon dioxide
Power supply	24 V AC (+10%, -15%)
Output signal	0-10 V / 0-20 mA
Calibration facilities	Calibration gas mixture 1000 ppm; Tests at 1800 and 5000 ppm
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	5-45 °C, 20-95% RH
Warming-up time	5 min
Measuring range	0-2000 ppm carbon dioxide or 0-6000 ppm
Uncertainty of measurement	±100 ppm at 1000 ppm
Hysteresis	None
Linearity	< 5%
Repeatability	0.7%
Stability	No information provided
Zero drift	<5% of the measuring range
Rise time	<1 min lag time, <5 min time constant (63%), <8 min time constant (90%)
Supply voltage influence	24 V (+10% -15 %) < 2 %
Supply frequency influence	50 Hz/60 Hz, None
Temperature influence	6 ppm/°C
Humidity influence	None
Atmospheric pressure influence	<2 ppm/mbar
Air velocity influence	None
Other influence factors	No information provided
Required maintenance	No special maintenance required
Maintenance intervals	>2 years
Calibration intervals	>2 years
Expected lifetime	>10 years
Size and weight	0.6 kg
Price	SEK 8000:-
Additional information	Condensation can cause reversible malfunction. Rate of temperature change: <1.5 °C/min

3.7 Sensor S7

Manufacturer: Vaisala
Model: HMD 20 UB
Measurand: RH

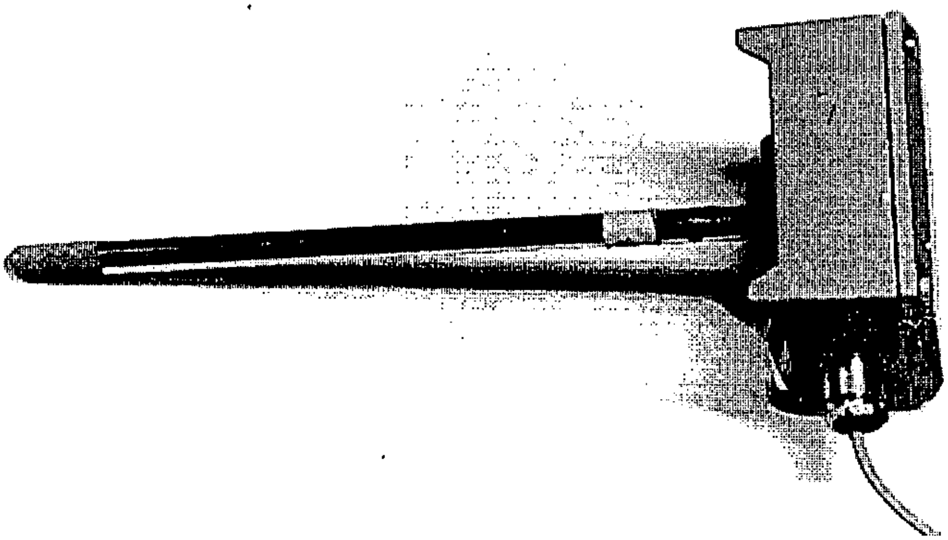


Figure 3.7. *Sensor S7*

Table 3.7. Compilation of the manufacturer´s data for the sensor S7

Manufacturer	**Vaisala**
Sensor designation	HMD20UB
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity
Power supply	10-35 V DC
Output signal	4-20 mA
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	-5 to 80 °C for the sensor head, -5 to +55 °C for the electronics
Warming-up time	< 10 sec
Measuring range	0-100 % RH
Uncertainty of measurement	±2% RH (0-90% RH), ±3% RH (90-100% RH)
Hysteresis	< 0.5 % RH (one hour excursions 10 - 75 - 10 % RH, see H Humicap specification
Linearity	Better than 1 % RH
Repeatability	Better than 0.5 % RH
Stability	Better than 1 % RH/year in normal air conditions (0 - 70 % RH, -40 - +35 °C)
Zero drift	Negligible
Rise time	15 s (90 % response time for a step change 0 - 75 % RH with a filter)
Supply voltage influence	Negligible
Supply frequency influence	Not applicable
Temperature influence	±0.04% RH/°C
Humidity influence	-
Atmospheric pressure influence	None
Air velocity influence	None
Other influence factors	No information provided
Required maintenance	Calibration check with an electronic one-point calibrator
Maintenance intervals	Depends on application
Calibration intervals	1 year in normal applications
Expected lifetime	No information provided
Size and weight	100×100×60mm + 250 mm (probe)
Price	SEK 2766 :-
Additional information	No information provided

3.8 Sensor S8

Manufacturer: Vaisala
Model: HMP 35 A
Measurand: RH

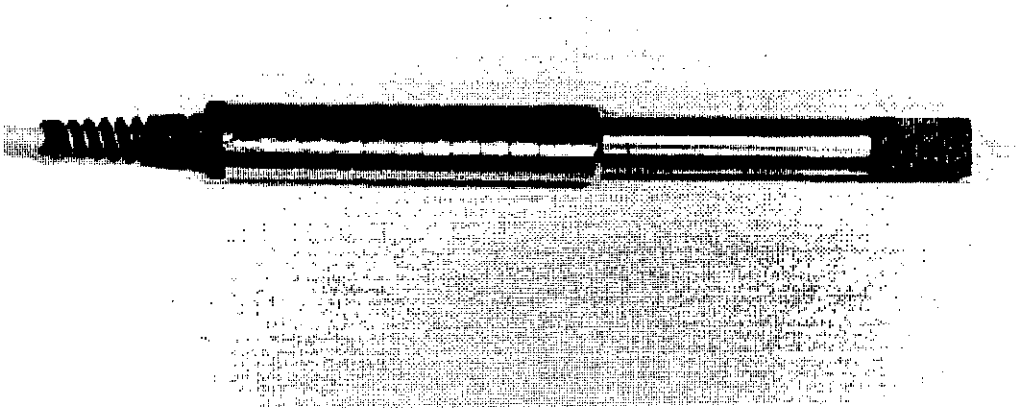


Figure 3.8. *Sensor S8*

Table 3.8. Compilation of the manufacturer's data for the sensor S8

Manufacturer	**Vaisala**
Sensor designation	HMP35A
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity and temperature
Power supply	7-35 V DC
Output signal	0-1 V DC
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	-20 to 60 °C
Warming-up time	<1 sec
Measuring range	0-100 % RH
Uncertainty of measurement	±2% RH (0-90% RH), ±3% RH (90-100% RH)
Hysteresis	<0.5 % RH (one hour excursions 10-75-10 % RH, see H Humicap specification)
Linearity	Better than 1 % RH
Repeatability	Better than 0.5 % RH
Stability	<1% RH/year in normal air conditions (0-70 % RH, -40 - +35 °C)
Zero drift	Negligible
Rise time	15 s (90 % response time for a step change 0-75 % RH with a filter)
Supply voltage influence	Negligible
Supply frequency influence	Not applicable
Temperature influence	±0.04% RH/°C
Humidity influence	-
Atmospheric pressure influence	None
Air velocity influence	None
Other influence factors	No information provided
Required maintenance	Calibration check with an electronic one-point calibrator
Maintenance intervals	Depends on application
Calibration intervals	1 year in normal applications
Expected lifetime	No information provided
Size and weight	Length 235 mm, Ø 18.5 mm, 0.18 kg
Price	SEK 2760:-
Additional information	Maximum ambient concentrations for some groups of organic compounds are listed

3.9 Sensor S9

Manufacturer: Landis & Gyr
Model: QFA 62.1
Measurand: RH
Comment: After the test this sensor has been replaced with a new model designated QFA64

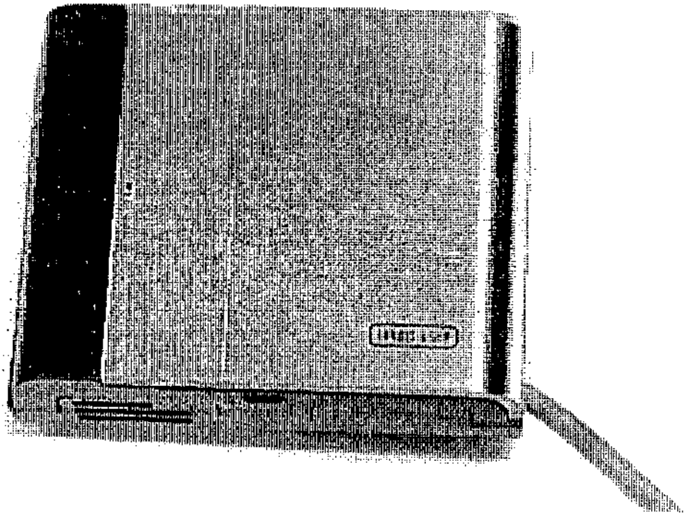


Figure 3.9. Sensor S9

Table 3.9. Compilation of the manufacturer´s data for the sensor S9

Manufacturer	**Landis&Gyr**
Sensor designation	QFA 62.1
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity and temperature
Power supply	24 V AC ±20%
Output signal	0-10 V
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	0-50 °C
Warming-up time	No information provided
Measuring range	20-90% RH, 0-50 °C
Uncertainty of measurement	±6% RH (20-40% RH), ±3% RH (40-60% RH), ±6% RH (60-90% RH)
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	2.7 min (RH), 6.5 min (temperature)
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	No information provided
Humidity influence	-
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No information provided
Calibration intervals	No information provided
Expected lifetime	No information provided
Size and weight	10×81×32.4 mm
Price	SEK 2065:-
Additional information	No information provided

3.10 Sensor S10

Manufacturer: Landis & Gyr
Model: QFM 61.1
Measurand: Absolute humidity. The relative humidity has been calculated from the QFM output signal and the prevailing ambient temperature for comparison with the other sensors.
Comment: During the autumn of 1992 this sensor will be replaced with a new sensor designated QFA64

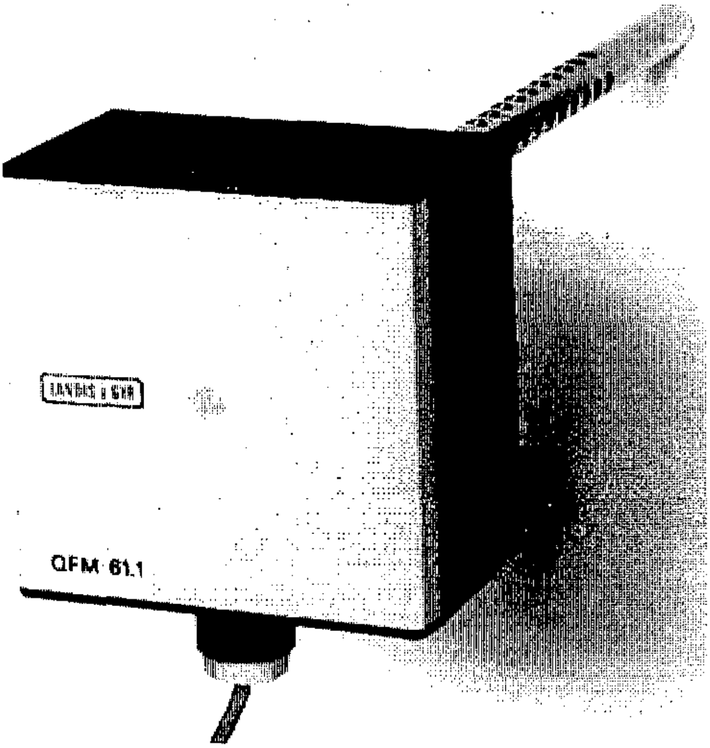


Figure 3.10. Sensor S10

Table 3.10. Compilation of the manufacturer's data for the sensor S10

Manufacturer	**Landis&Gyr**
Sensor designation	QFM 61.1
Sensor type	Plastic strip
Measured parameter(s)/substance(s)	Absolute humidity (calculated from RH and temperature)
Power supply	24 V AC ±2%
Output signal	0-10 V DC
Calibration facilities	No information provided
Signal processing intelligence	The absolute humidity is calculated from RH and temperature
Operating range (max/min) for ambient conditions	-15 to 50 °C. Maximum air velocity 20 m/s
Warming-up time	No information provided
Measuring range	1-20 g water/kg dry air
Uncertainty of measurement	No information provided
Hysteresis	No information provided
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	1-3 min (time constant), 0.1-0.3 min (lag time)
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	No information provided
Humidity influence	-
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No information provided
Calibration intervals	No information provided
Expected lifetime	No information provided
Size and weight	102×102×70mm + 224 mm (probe), 0.43 kg
Price	SEK 4215:-
Additional information	No information provided

3.11 Sensor S11

Manufacturer: Coreci
Model: Humicor CHRTA/H310
Measurand: RH

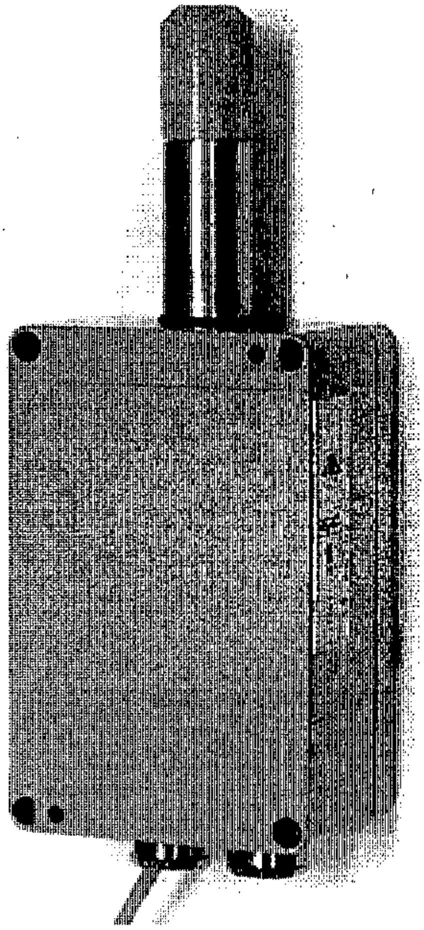


Figure 3.11. Sensor S11

Table 3.11. Compilation of the manufacturer's data for the sensor S11

Manufacturer	**Coreci**
Sensor designation	Humicor CHRTA/H310
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity and temperature
Power supply	12-33 V DC
Output signal	4-20 mA
Calibration facilities	No information provided
Signal processing intelligence	None
Operating range (max/min) for ambient conditions	0-100 °C, 0-100% RH, 0.04-30 bar
Warming-up time	< 3 sec
Measuring range	0-100% RH, 0-100 °C
Uncertainty of measurement	±2% RH (10-90%RH), ±3% RH (>90% RH), ±0.3 °C + Pt100 tolerance
Hysteresis	<0.5% RH
Linearity	<2.5% RH
Repeatability	±1%
Stability	<2 % for a six month period (0 - 100 % RH)
Zero drift	Diagram shown in data sheet
Rise time	<1 s (τ_{63}), <2 s (τ_{90}). This is valid in the interval 45-95% RH
Supply voltage influence	None in the range 12-32 V
Supply frequency influence	None (DC)
Temperature influence	Above 70 °C
Humidity influence	-
Atmospheric pressure influence	None between 0.03 and 30 bar
Air velocity influence	Calibrated at zero velocity
Other influence factors	No information provided
Required maintenance	None
Maintenance intervals	None
Calibration intervals	1 year in normal conditions
Expected lifetime	10 years
Size and weight	125×80×57 mm + 88 mm (probe), 0.65 kg
Price	SEK 2590
Additional information	Maximum humidity 150 g water/kg dry air or 98% RH

3.12 Sensor S12

Manufacturer: Rotronic
Model: F4C-31
Measurand: RH

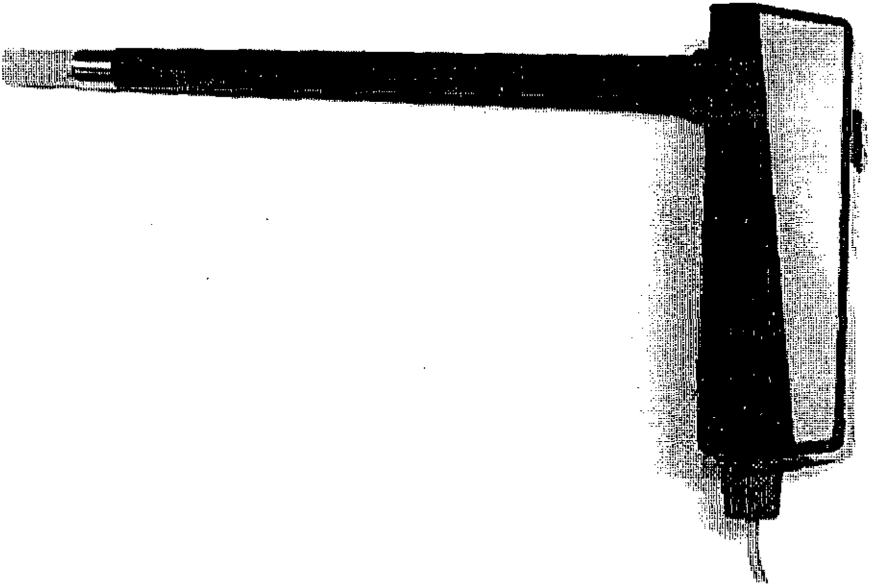


Figure 3.12. Sensor S12

Table 3.12. Compilation of the manufacturer's data for the sensor S12

Manufacturer	**Rotronic**
Sensor designation	F4C-31
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity and temperature
Power supply	10-35 V DC
Output signal	4-20 mA
Calibration facilities	No information provided
Signal processing intelligence	None
Operating range (max/min) for ambient conditions	-15 to 55 °C
Warming-up time	150 sec
Measuring range	0-100% RH, 0-50 °C
Uncertainty of measurement	±2% RH (30-95%RH), ±3% RH (20-100% RH), ±0.5 °C
Hysteresis	<0.5 % RH for a cycle 10-95-10 % RH, air velocity 1 m/sec
Linearity	<0.7 % RH at 20 °C
Repeatability	<0.6% RH/0.1 °C
Stability	<1% RH/year
Zero drift	None
Rise time	<10 s RH, <3 s temperature (time constant)
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	Compensated
Humidity influence	-
Atmospheric pressure influence	None
Air velocity influence	None up to 3 m/sec
Other influence factors	No information provided
Required maintenance	Cleaning of filter
Maintenance intervals	Depends on contaminant level in the environment
Calibration intervals	1 year
Expected lifetime	15 years
Size and weight	154×73×48 mm + 250 mm (probe), 0.29 kg
Price	SEK 2440:-
Additional information	No information provided

3.13 Sensor S13

Manufacturer: Rotronic
Model: F22C-31
Measurand: RH

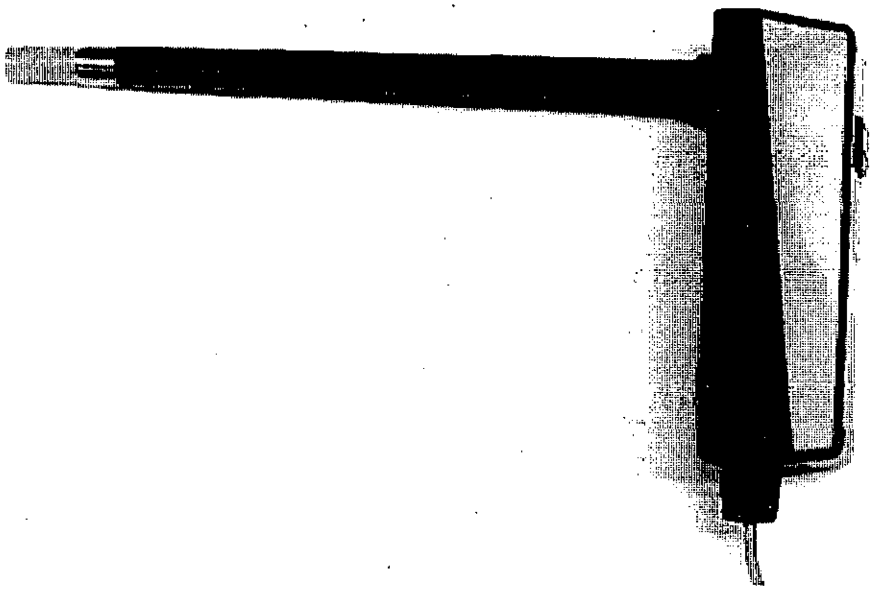


Figure 3.13. Sensor S13

Table 3.13. Compilation of the manufacturer's data for the sensor S13

Manufacturer	**Rotronic**
Sensor designation	F22C-31
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity and temperature
Power supply	10-35 V DC
Output signal	4-20 mA
Calibration facilities	No information provided
Signal processing intelligence	None
Operating range (max/min) for ambient conditions	-15 to 55 °C
Warming-up time	150 s
Measuring range	0-100% RH, 0-50 °C
Uncertainty of measurement	±2% RH (30-95%RH), ±3% RH (20-100% RH), ±0.5 °C
Hysteresis	<0.5 % RH for a cycle 10-95-10 % RH, air velocity 1 m/sec
Linearity	<0.7 % RH at 20 °C
Repeatability	<0.6% RH/0.1 °C
Stability	<1% RH/year
Zero drift	None
Rise time	Time constant <10 s (RH), <3 s (temperature)
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	Compensated
Humidity influence	-
Atmospheric pressure influence	None
Air velocity influence	None up to 3 m/s
Other influence factors	No information provided
Required maintenance	Cleaning of filter
Maintenance intervals	Depends on contaminant level in the environment
Calibration intervals	1 year
Expected lifetime	15 years
Size and weight	154×73×48 mm + 250 mm (probe), 0.29 kg
Price	SEK 2440:-
Additional information	No information provided

3.14 Sensor S14

Manufacturer: TKE Vento
Model: P.L.S.
Measurand: RH and VOC

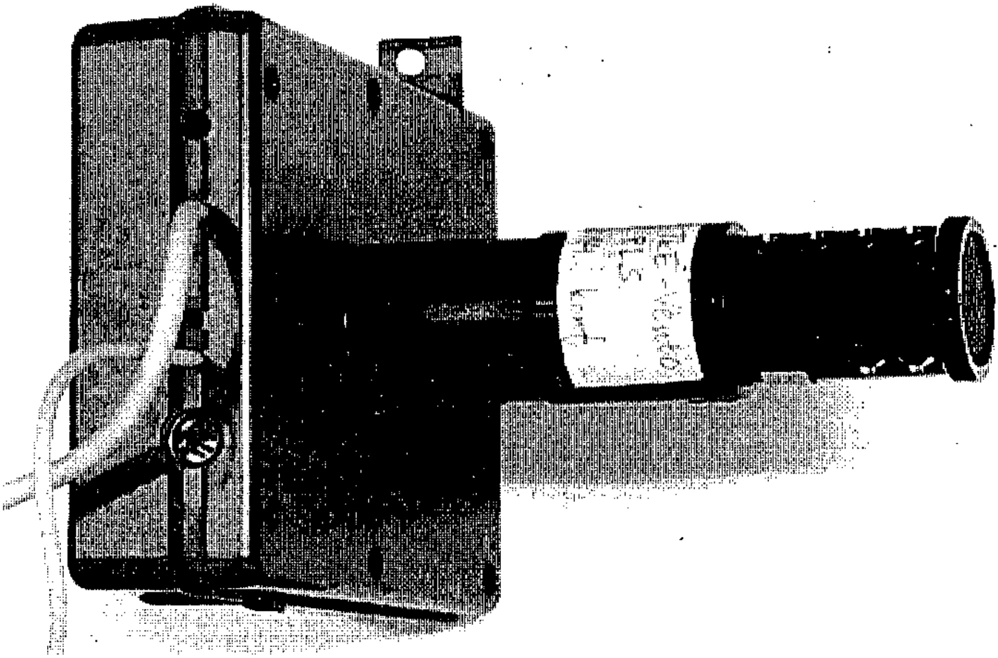


Figure 3.14. *Sensor S14*

Table 3.14. Compilation of the manufacturer's data for the sensor S14

Manufacturer	**TKE Vento**
Sensor designation	P.L.S.
Sensor type	Semi-conductor (VOC), capacitive (RH)
Measured parameter(s)/substance(s)	VOC and relative humidity
Power supply	220 V AC
Output signal	0-1 V
Calibration facilities	No information provided
Signal processing intelligence	No information provided
Operating range (max/min) for ambient conditions	No information provided
Warming-up time	At least 24 h for the VOC sensor
Measuring range	0-100% AQ, 15-90% RH
Uncertainty of measurement	10% after 24 h, 5% after 7 days (VOC), 5% (RH)
Hysteresis	+3% (RH)
Linearity	No information provided
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	No information provided
Supply voltage influence	No information provided
Supply frequency influence	No information provided
Temperature influence	No information provided
Humidity influence	-
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No information provided
Calibration intervals	No information provided
Expected lifetime	No information provided
Size and weight	No information provided
Price	No information provided
Additional information	35 ppm CO in the air gives an output signal of 0.7 V

3.15 Sensor S15

Manufacturer: Staefa
Model: FRA-H2.
Measurand: RH

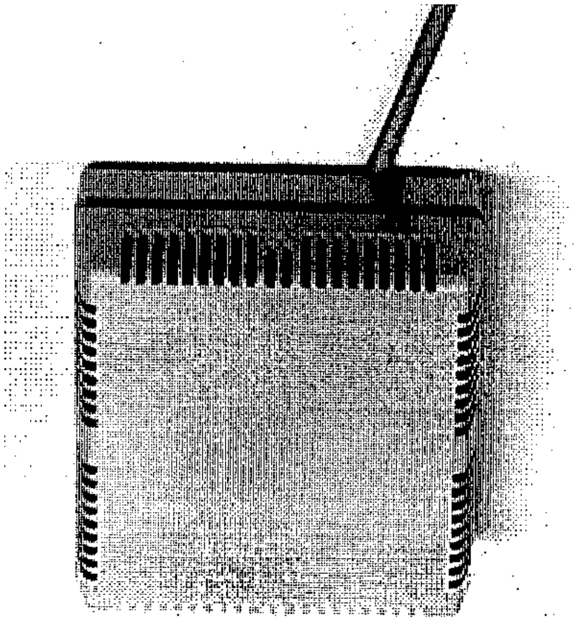


Figure 3.15. Sensor S15

Table 3.15. Compilation of the manufacturer's data for the sensor S15

Manufacturer	**Staefa**
Sensor designation	FRA-H2
Sensor type	Capacitive
Measured parameter(s)/substance(s)	Relative humidity
Power supply	15 V DC ±5%
Output signal	0-10 V
Calibration facilities	20 % RH = 1.88 V (tolerance ±10 mV), 50 % RH = 5.2 V
Signal processing intelligence	None
Operating range (max/min) for ambient conditions	0-50 °C, (operating range for the sensor head is 0-85 °C)
Warming-up time	≈5 min
Measuring range	10-90% RH
Uncertainty of measurement	<5 %
Hysteresis	≈3 % for a cycle 10-90-10 % RH
Linearity	<5 % in the range 10-90 % RH
Repeatability	No information provided
Stability	No information provided
Zero drift	No information provided
Rise time	10-43 % RH: 3 min, 43-90 % RH: <5 min
Supply voltage influence	15 V DC ±5 %: no influence
Supply frequency influence	No information provided
Temperature influence	0.1 % RH/°C
Humidity influence	-
Atmospheric pressure influence	No information provided
Air velocity influence	No information provided
Other influence factors	No information provided
Required maintenance	No information provided
Maintenance intervals	No information provided
Calibration intervals	No information provided
Expected lifetime	10 years (if not used with salty air)
Size and weight	Size: 80×80×44 mm, weight: 0.28 kg
Price	SEK 1590:-
Additional information	No information provided

4 Test program

The test program was intended for the evaluation of sensors for the following types of indicators (in accordance with the scope of IEA Annex 18):

- Water vapour (RH, WBT, DPT)
- Carbon dioxide (CO_2)
- Non-oxidized gases (H_mC_n, CO, etc).

The tests consisted of two main parts. In part one, one specimen of each sensor type was extensively laboratory tested and in part two three specimens of each sensor type were exposed to normal indoor climatic conditions (e.g. in an office building). Thus four specimens of each sensor type were required.

The laboratory tests consisted of four main parts (see the separate detailed descriptions in paragraphs 4.1 - 4.4).

- Checking of the manufacturers' data sheets and instructions
- Determination of the performance of new sensors including comparisons with data sheets
- Determination of the cross-sensitivity of sensors exposed to various combinations of the three chosen indicators as well as variations in the power supply, atmospheric pressure, temperature and air velocity
- Environmental tests concerning exposure to dry heat, dry cold, humidity, temperature change, vibration, electromagnetic radiation and electrostatic discharge.

The field tests also consisted of four main parts (see the separate detailed descriptions in paragraph 4.6).

- A control of the status of the building and its ventilation system
- Determination of the performance of the sensors as new (the same procedure as for part one of the laboratory testing)
- Exposure of the sensors to normal ambient conditions in an office building (including continuous monitoring of their output signals)
- A renewed control of selected performance parameters after one year of exposure.

4.1 Sampling and preparation

Sensors were to be selected and tested by the respective manufacturer prior to delivery to the testing laboratory. Special care was to be taken in packaging and handling the selected sensors in order to avoid unrepresentative test results due to delivery mishaps. All necessary instructions concerning general description, installation, operation and maintenance were to be included in the delivery of the sensors.

The sensors were installed by the testing laboratory as described by the manufacturer's instructions. The reference ambient testing conditions were (unless other values were specified in the individual test procedures):

Temperature:	20 ± 2 °C
Relative humidity:	40 ± 10 %
Pressure:	101 ± 1 kPa(a)
Air velocity:	< 0.5 m/s
Supply voltage:	Nominal ± 5 %
Supply frequency:	Nominal ± 5 %
Air quality:	Normal indoor air (CO_2 350 ± 50 ppm, VOC <0.4 mg/m^3)

The test room was kept free of strong electric or magnetic fields and the input power to the sensors was supplied via magnetic stabilizers (except during tests with electromagnetic radiation).

A reference gas for testing broadband sensors (for non-oxidized gases) was composed of the following constituents (volatile organic compounds, VOC):

One aldehyde:	Octanal ($C_7H_{15}CHO$)
One aromatic HC:	Toluene (C_7H_8)
One aliphatic HC:	Nonane (C_9H_{20})

4.2 Data sheets and general information

The following information was noted as background information for the test results:

Manufacturer:	
Sensor designation:	
Sensor type:	
Measured parameter(s)/substance(s):	
Power supply:	
Output signal:	
Calibration facilities:	
Signal processing intelligence:	
Operating range (max/min) for ambient conditions:	
Warming up time:	
Measuring range:	
Uncertainty of measurement:	
Hysteresis:	
Linearity:	
Repeatability:	
Stability:	
Zero drift:	
Rise time:	
Supply voltage influence:	
Supply frequency influence:	
Temperature influence:	
Humidity influence:	
Atmospheric pressure influence:	
Air velocity influence:	
Other influence factors:	
Required maintenance:	
Maintenance intervals:	
Calibration intervals:	
Expected lifetime:	
Size and weight:	
Price:	
Additional information:	

4.3 Determination of the performance of new sensors

The sensor performance was to be defined in terms of the following parameters.

- Warming up time
- Linearity
- Repeatability
- Hysteresis
- Stability
- Accuracy
- Sensitivity
- Rise time
- Zero drift
- Sensitivity to influence factors (cross-sensitivity).

4.3.1 Warming up time

The warming up time was to be measured by inserting the sensor into a test chamber with all parameters except the primary measurand at the reference conditions (see 4.1). The measurand (e.g. humidity) was held constant to correspond to an output signal of 40-60 % of the measuring range of the sensor.

The sensor was left 24 h with the power switched off. The power was then switched on and the sensor output was measured. The time from switching on the power supply until the output was stable within the claimed uncertainty of measurement was recorded as the warming up time.

4.3.2 Determination of the sensor characteristic curve

The output from the sensor was to be recorded for values of the measurand according to table 4.1.

Table 4.1. Values for determination of the sensor characteristic curve

Measurand	**Test condition number:** 1	2	3	4	5	6	7	8	9
Relative humidity (%)	-	20	40	60	80	60	40	20	-
Carbon dioxide (ppm)	200	500	1000	1500	2000	1500	1000	500	200
VOC (mg/m^3)	0	0.5	1.0	1.5	2.0	1.5	1.0	0.5	0

The VOC-cocktail was normally composed of equal parts of the three constituents. At test point 3 (1.0 mg/m^3) tests were also performed with the total concentration consisting of only one of the reference gases at a time.

VOC-sensors were also tested with tobacco smoke corresponding to two levels of smoke concentration at each of three different ventilation flowrates (minimum flow for a non-smoking environment, minimum flow for a smoking environment and a maximum flow-rate).

4.3.2.1 Linearity

Linearity was calculated as the maximum deviation between any measured value and a straight line between points 1 and 5 in table 4.1.

4.3.2.2 Hysteresis

Hysteresis was calculated as the maximum deviation between points 2 and 8, 3 and 7, 4 and 6.

4.3.2.3 Sensitivity

Sensitivity was calculated as the change in output between points 3 and 4 in table 4.1, divided by the corresponding change in input (e.g. V/% RH).

4.3.3 Repeatability

The sensor was to be tested at points 2 and 5 alternatively 5 times. The repeatability was defined as the maximum deviation between any measured value and the corresponding mean values for the respective test points.

4.3.4 Stability

The sensor was to be kept at point 4 in table 4.1 for 24 hours. The stability was defined as the maximum deviation between any measured value and the mean value during the measuring period.

4.3.5 Rise time

The sensor input was changed from point 2 to point 4 and then from point 4 to point 2. The rise time and fall time respectively were calculated as the time between a change of input until the output had changed by 90 % of difference between the steady state values.

The air flowrate passing the sensor was to be specified by the manufacturer. If no specification was made, the flow-rate should be 3 m/s for sensors mounted in ducts and less than 0.15 m/s for wall mounted units.

4.3.6 Cross-sensitivity

The sensitivity of the sensor to various influence quantities was tested by varying each influence quantity, one at a time, according to table 4.2.

Table 4.2. Variation of influence factors.

Influence factor	Test condition number:													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Temperature (°C)	20	30	10	20	20	20	20	20	20	20	20	20	20	20
Relative humidity (%)	40	40	40	80	20	40	40	40	40	40	40	40	40	40
Voltage (U/U_n)	1.0	1.0	1.0	1.0	1.0	1.2	0.8	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Frequency (f/f_n)	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.1	0.9	1.0	1.0	1.0	1.0	1.0
Pressure (kPa)	101	101	101	101	101	101	101	101	101	105	97	101	101	101
CO_2 (ppm)	500	500	500	500	500	500	500	500	500	500	500	1000	500	500
VOC (ppm)	0	0	0	0	0	0	0	0	0	0	0	0	1	0
Tobacco smoke	No	No	No	No	No	No	No	No	No	No	No	No	No	Yes

The cross-sensitivity was defined for each influence factor as the ratio between the total change in output and the total change in input.

4.4 Environmental tests

Environmental tests were performed to check the resistance of a sensor to possible extreme situations in the environment within the field of application of the sensor. Tests were carried out concerning

* Climatic parameters
* Mechanical parameters
* Electrical parameters.

Reference is made to Bergsten et al (ref.3) regarding the selection of relevant test procedures. Only one of the manufacturers expressed concern regarding the proposed tests. Thus tests 4.4.1.2–4.4.1.4 and all tests in 4.4.3 are outside the specified limits of sensors S4 and S6.

4.4.1 Climatic parameters

Climatic tests were performed in accordance with IEC standards on dry heat, cold, damp heat and change of temperature.

4.4.1.1 Cold, IEC 68-2-1, Test Ad

* A functional test was performed in the chamber after stabilization at the standard conditions for testing.

* With the equipment switched off, the temperature was decreased to the specified low level, which was then kept for the specified duration.

* Immediately before the end of exposure, the equipment was switched on, and a functional test was carried out.

* After exposure, and after stabilization at the standard conditions, a final functional test was carried out.

Temperature: +5 °C, duration: 16 hours.

4.4.1.2 Dry heat, IEC 68-2-2, Test Bd

* A functional test was performed in the chamber after stabilization at the standard conditions for testing.

* The temperature was increased. A functional test was performed at an intermediate temperature, after stabilization for 2 hours.

* With the equipment still in the switched on state, the temperature was increased to the specified level, which was then kept for the specified duration.

* After exposure, and after stabilization at the standard conditions, a final functional test was carried out.

Temperature: 55 °C, duration: 72 hours.
A functional test at an intermediate temperature: 40 °C.

4.4.1.3 Damp heat, IEC 68-2-3, steady state, Test Ca

- After a functional test at the standard conditions, the equipment was placed in the test chamber in its unpacked, switched-off, ready-for-use state.
- After preconditioning, the specified exposure was commenced.
- Immediately before the end of exposure, the equipment was switched on, a functional test was performed, and the equipment was switched off.
- A final functional test was performed after recovery at standard conditions for testing.

Temperature: 40 °C, humidity: 93 % RH.
Duration: 21 days.

4.4.1.4 Change of temperature, IEC 68-2-14, Test Nb

- Initial measurements and visual examination were carried out.
- The specimen was introduced into the test chamber in its ready for use state, with the electrical connections necessary for checking the operation.
- The specimen was brought into its operating stand-by condition.
- The temperature cycling between temperatures T_A and T_B was started and carried out as described in IEC 68-2-14.
- The stand-by operating condition of the specimen was monitored continuously.
- Other operational checks or measurements, as full power operation, transmission measurements etc. were to be performed at both of the temperatures T_A and T_B immediately after the temperature stability in the chamber had been reached. These checks were to be repeated during two test cycles.
- After completing all five test cycles the specimen was to remain in the standard atmospheric recovery conditions for at least four hours.
- The final measurements and visual examination were carried out.

Low temperature T_A: +5 °C
High temperature T_B: + 40 °C
Rate of change of temperature: 5 K/min
Number of cycles: 5
Exposure time: 3 h
Recovery time: > 4 h

In addition humidity sensors were to be checked functionally after the following test:

- Store the sensor at -10 °C with the power switched off for 24 h
- Change the ambient conditions to +20 °C and a relative humidity of 80 % in less than 10 minutes. Switch on the power supply and record the output during 1 h.

4.4.2 Mechanical parameters

Mechanical tests were performed in accordance with IEC standards on random vibration.

4.4.2.1 Random vibration, IEC 68-2-36, Test Fdb

- The equipment was mounted on the vibrator using its normal means of mounting, e.g. flanges and screws. Any special brackets etc. were to be included. It was considered important also that external cables and connections were included and fastened to simulate conditions during use. If a special mechanical interface for mounting was required, a corresponding fixture was produced.
- A functional check was performed before exposure to the test conditions.
- With the equipment switched on, the level was increased to the specified level, which was applied for the specified duration.
- During the last minutes of exposure, a functional check was carried out.
- Steps 1, 3, and 4 were repeated for each of the two remaining perpendicular axes of the equipment.
- A functional check was performed after the vibrational tests.

ASD 10-20 Hz: 0.05 g^2/Hz
ASD 20-500 Hz: -3 dB/octave
Total rms acceleration: 1.9 g
Duration/axis: 90 minutes

4.4.3 Electrical parameters

Electrical tests were performed in accordance with IEC standards on conducted bursts, electrostatic discharge, electromagnetic radiation and surge voltage immunity.

4.4.3.1 Conducted transient bursts, IEC 801-4

- Equipment under test, auxiliary peripherals, the transient generator and cables were all placed 10 cm above a common ground plane.
- Signal cables were connected to the peripherals or to impedances simulating these. Cables were coiled up in a "number 8" fashion to limit the effective length to 1 meter.
- A common mode-coupling box/low pass filter, as specified, was inserted into the power supply leads, and the test generator was connected.
- The functional test was performed.
- In each functional mode of the equipment, transients were injected for at least 2 minutes with each polarity.
- The coupling box was left in the supply leads with a short circuit substituted for the generator.
- Each group of signal cables, running parallel in actual use, was now in turn exposed to transients using capacitive coupling boxes for each group (at least 2 minutes of each polarity for each group). All exposures were repeated for each specified functional mode of the equipment.
- Exposures could be stopped and resumed to prevent synchronization with functional cycles.

Amplitude 4 kV. Both polarities.

4.4.3.2 Electrostatic discharge, IEC 801-2

- A functional test was performed before exposure.
- The test object was placed on an insulated support 0.1 m above an earth reference plane and was to be operating in a functional mode.
- The test generator, charged to the specified voltage, was to be approached to points on the test object normally accessible to the operator.
- Ten discharges were to be applied on each preselected point.
- The test was to be repeated for each functional mode.

Level 3; 8 kV.

4.4.3.3 Radiated electromagnetic field, IEC 801-3

- A functional test was performed before exposure to radiation.
- The test object was placed on an insulated table and electrically connected according to the installation instructions
- The test object was to be operating in a functional mode.
- The test object was then exposed to electromagnetic radiation of the prescribed severity with the frequency changing from 27 to 500 MHz while the correct function was checked continuously.
- When disturbances occured, the frequency was recorded.
- The test was repeated for each functional mode.

Level 3; 10 V/m, 27-500 MHz.

4.4.3.4 Surge voltage immunity ("thunder"), IEC 801-5 DP

Draft proposal of an IEC standard.
Level 3; 2 kV.

4.5 Final test

The sensor output was checked in accordance with table 4.1 in chapter 4.3.

4.6 Field testing of DCV sensors

The test procedure consisted of four main parts including

- Performance of new sensors
- A building status control
- Exposure to ambient conditions
- Renewed performance control

4.6.1 Sampling and preparation

Sampling and preparation were carried out in accordance with the first part of chapter 4.1 (excluding the reference conditions).

4.6.2 Performance of new sensors

The performance of new sensors was determined in accordance with chapter 4.3.

4.6.3 A building status control

Prior to mounting the sensors to be tested, the building was to be checked concerning the type of activities, ventilation, and the opinion of the staff regarding air quality. The project was intended to record values of the respective indicators in buildings functioning in a normal way and without a DCV system.

A suitable method of checking the ventilation system is described in reference 2 "Functional control of ventilation installations" prepared by ASS (the National Board of Occupational Safety and Health), SP (the Swedish National Testing Institute), and the factory inspectorates of Sweden.

4.6.4 Exposure to ambient conditions

The sensors were to be installed in a conference room in an office building, preferably with large windows. The output of each sensor was to be monitored continuously for a period of one year using a data acquisition system. Room temperature and occupancy were also intended to be recorded.

4.6.5 Renewed performance control

The performance of the sensors was checked again according to chapter 4.3.2 after one year of exposure.

As a result of the measurements it was intended to make a comparison of which "indicators" have a good correlation with the usage pattern of the building and the contamination of the air as well as how large the discrepancy could be between different types of sensors and how stable the sensors are in the long term. Furthermore, a hint could be obtained as to the normal values of the "indicators". These normal values could then be used as reference levels for laboratory tests using extreme conditions.

5 Results

The test program, which was described in the previous chapter, provided the results for one specimen of each sensor type as presented in this chapter. Tables and diagrams are used for this purpose and the results for all sensors are presented under the heading of each specific part of the test program. Sensor S14 includes both a VOC sensing element and a humidity sensor. When necessary these elements are distinguished by the designations S14A (RH) and S14B (VOC) respectively.

5.1 Warming up time

Due to reasons presented below warming-up times were only measured for the humidity sensors.

5.1.1 VOC-sensors

Table 5.1. Warming up time for the VOC-sensors.

	S1	**S2**	**S3**	**S4**	**S14B**
Measured value (s)	-	-	-	-	-
Manufacturer's value (s)	*	-	>300	60	>24 h

* Depends on the time the sensor has been disconnected

The warming up times for these sensors were not measured due to difficulties in maintaining a stable level of concentration regarding volatile organic compounds for such a long time as 24 hours. It is also necessary to mention that the sensor element requires a fairly long "burn-in time" after disconnection of the power supply. The manufacturer of sensor S1 has provided values according to table 5.2 below.

Table 5.2. Warming up time for sensor S1 according to the manufacturer.

Time of disconnection	**Warming-up time**
< 1 h	12 h
< 1 day	2 days
1-3 days	1 week
> 3 days	< 20 days

5.1.2 CO_2-sensors

The warming-up times for the CO_2-sensors were not tested since the calibration facility in that case would require a carefully controlled supply of CO_2 during 24 hours. This presents practical and economic difficulties due to the amount of manual control involved and the large quantities of reference gas required. For the time being this type of measurement is not possible without a member of staff continuously supervising the equipment.

Table 5.3. Warming up time for the CO_2-sensors.

	S5	S6
Measured value (s)	-	-
Manufacturer's value (s)	30	300

Even if a regular test was not carried out some experience was gained of the warming-up times by chance. For the purpose of the field trials all of the CO_2-sensors were to be calibrated simultaneously. At the onset of the calibration procedure three specimens of sensor S5 had been connected for a long time and one specimen had been disconnected for about six months. When the sensors were connected, and the signals recorded in room air, the three connected sensors showed reasonable values (~350 ppm) whereas the previously disconnected sensor gave an indication of ~800 ppm. The high value, however, gradually decreased back to a normal value, but this seemed to take more than several days.

5.1.3 Humidity sensors

Table 5.4. Warming up time for the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (s)	0	0	4000	2000	800	3500	2700	2000	2700
Manufacturer's value (s)	<10	<1	-	-	<3	150	150	-	300*

* According to the manufacturer this is not a measured value.

5.2 Determination of the sensor characteristic curve

The output signal from the sensors were recorded at different levels specified for each sensor type in the test program (see table 4.1.). All sensors were exposed to the specified gas concentrations simultaneously. Based on these characteristic curves values of zero drift, linearity and hysteresis could be deduced. On the following pages in this chapter the characteristic curves for all sensors will be shown.

5.2.1 VOC-sensors

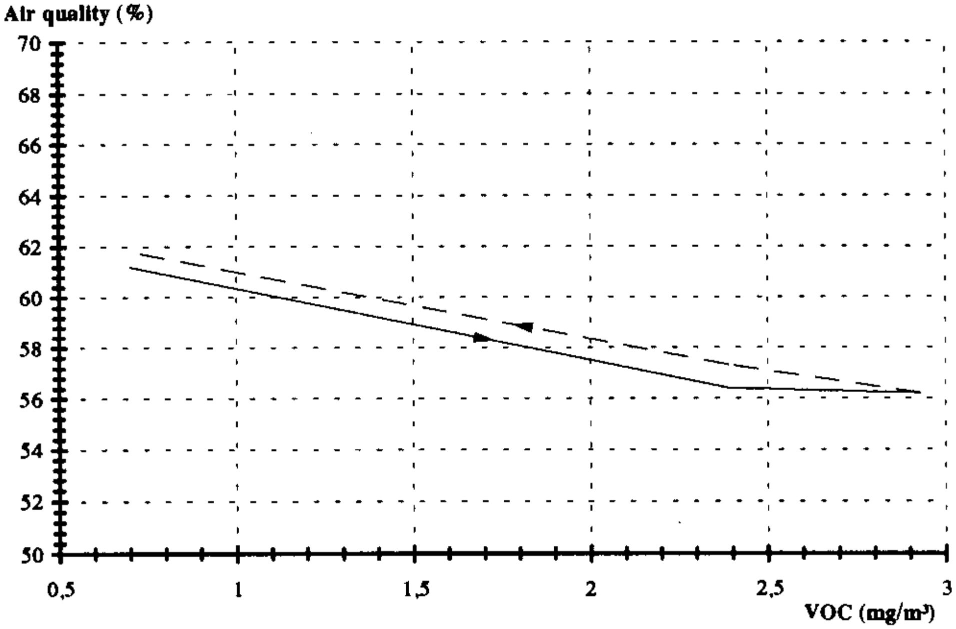


Figure 5.1. Characteristic curve for sensor S1.

Diagrams are not included for sensors S2 and S3 since the output signals were not influenced at all by the changes in VOC-concentration. Thus their characteristic curves will only be straight horizontal lines.

It may be noted that all three curves (figures 5.1-5.3) show a characteristic "notch" at a concentration of 2.4 mg/m^3. This may be a result of the test method but is more likely a characteristic of the sensing elements (all made by the same manufacturer). Concentrations are given as mean values and were checked all the time by means of Tenax sampling tubes with subsequent gas and mass chromatographic analysis.

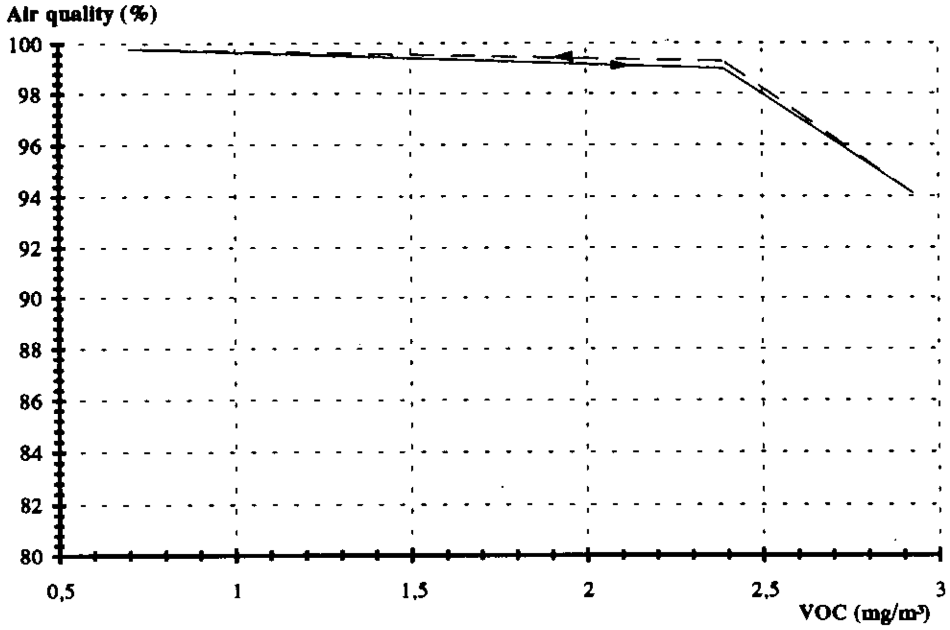


Figure 5.2. Characteristic curve for sensor S4 .

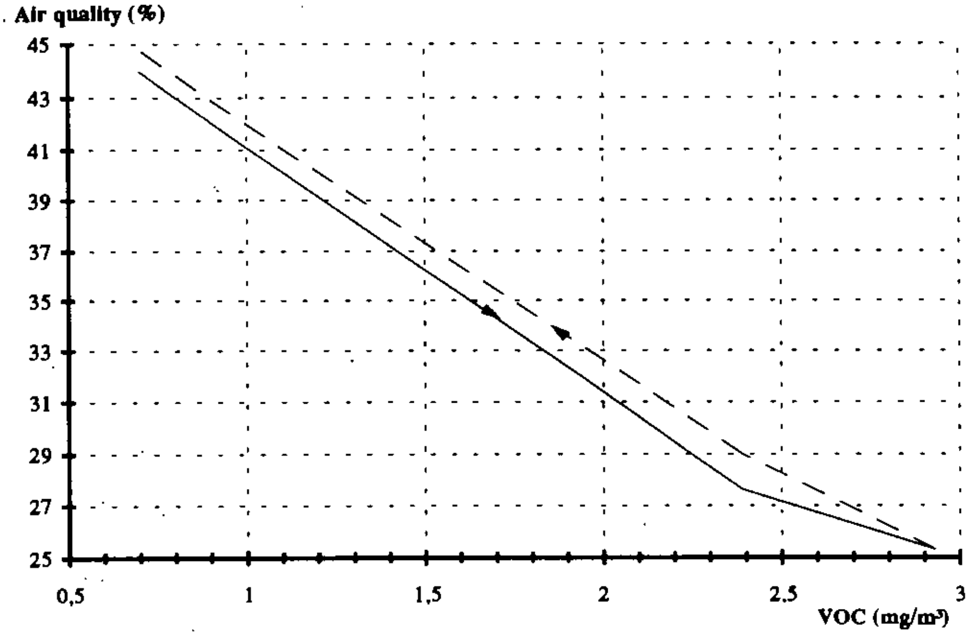


Figure 5.3. Characteristic curve for the VOC-sensor in sensor S14B.

5.2.2 CO_2-sensors

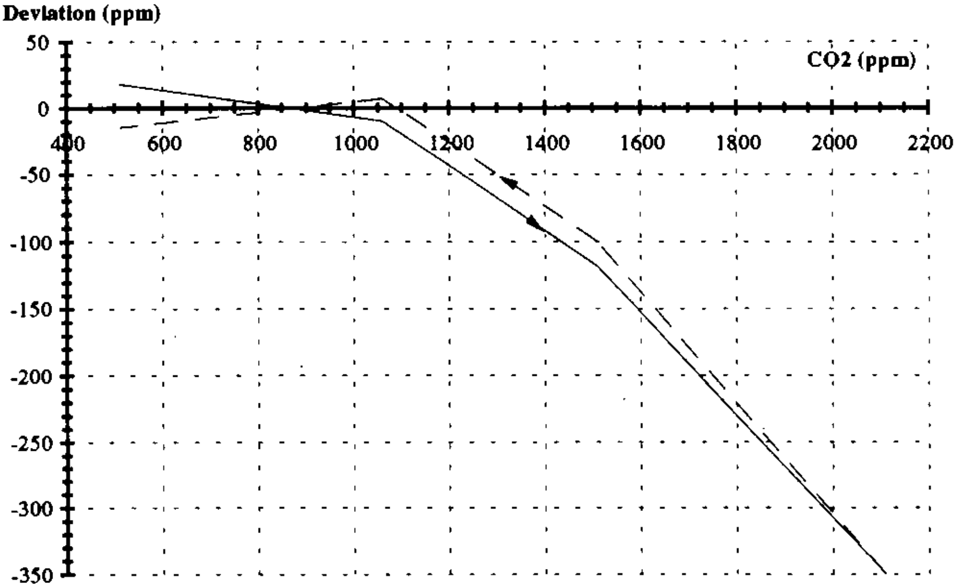


Figure 5.4. Characteristic curve for sensor S5.

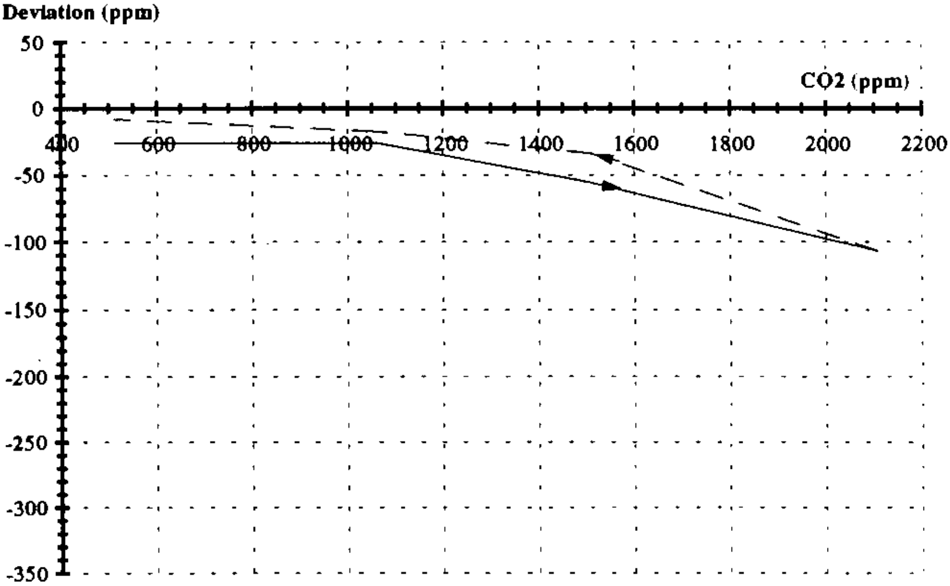


Figure 5.5. Characteristic curve for sensor S6.

5.2.3 Humidity sensors

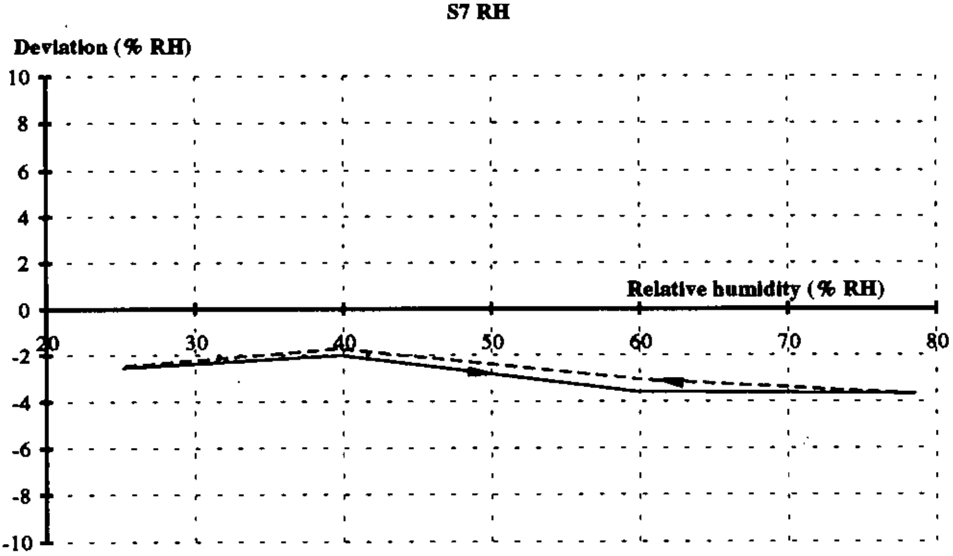


Figure 5.6. Characteristic curve for sensor S7.

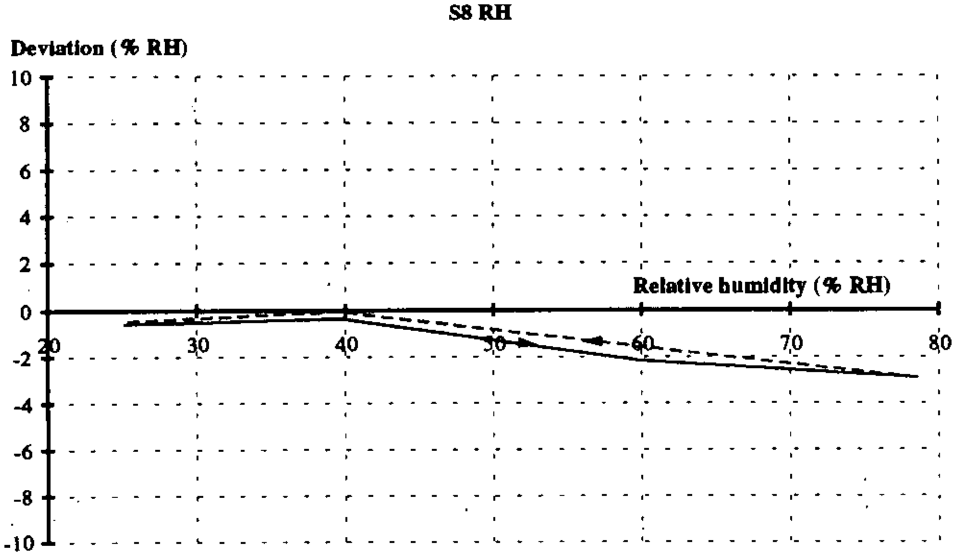


Figure 5.7. Characteristic curve for sensor S8.

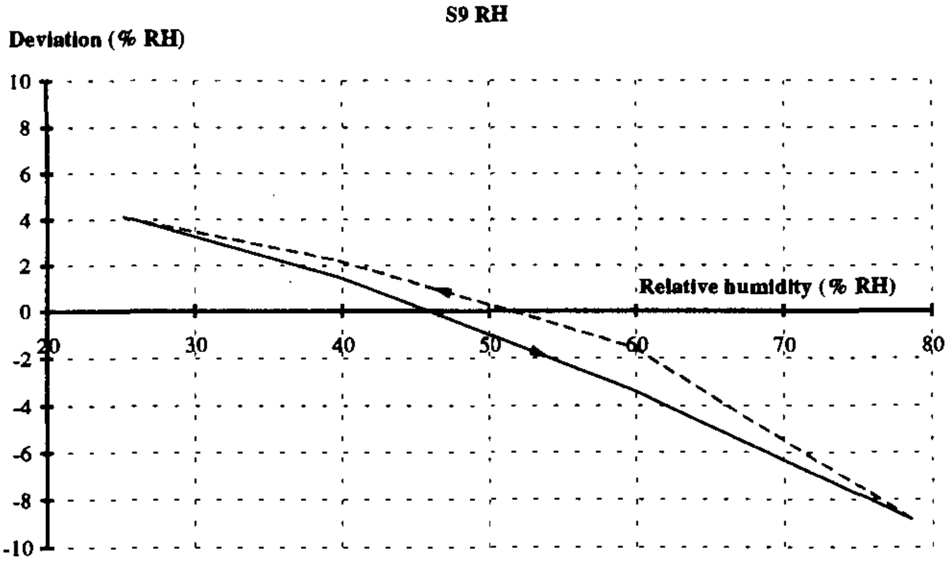


Figure 5.8. Characteristic curve for sensor S9.

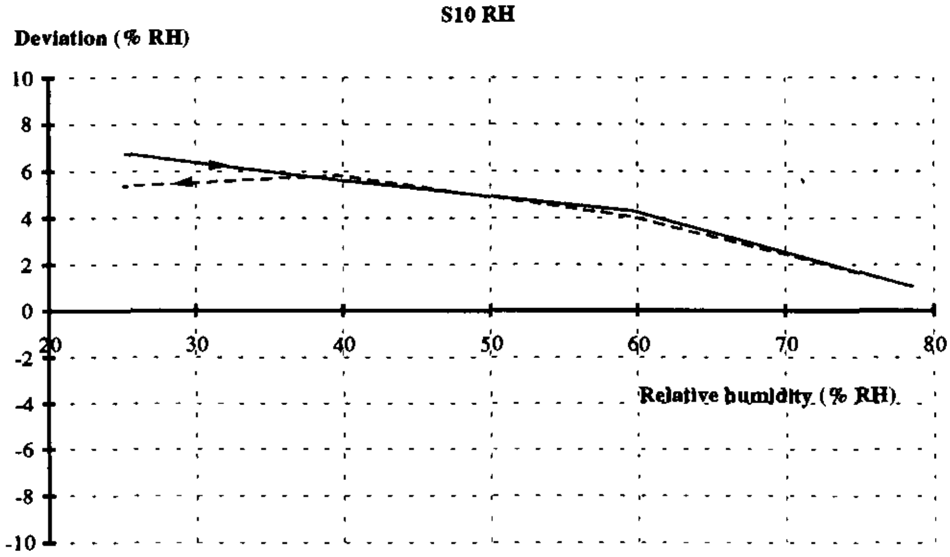


Figure 5.9. Characteristic curve for sensor S10.

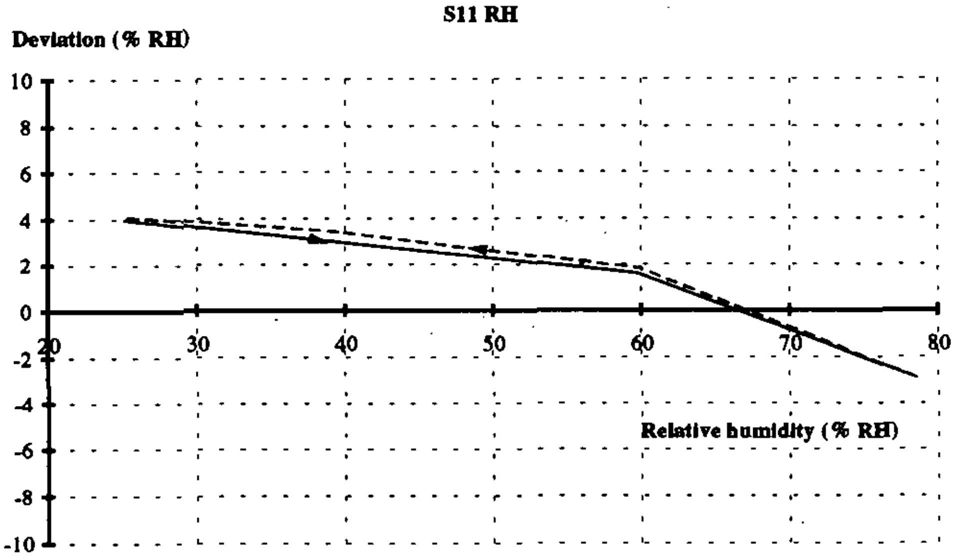


Figure 5.10. Characteristic curve for sensor S11.

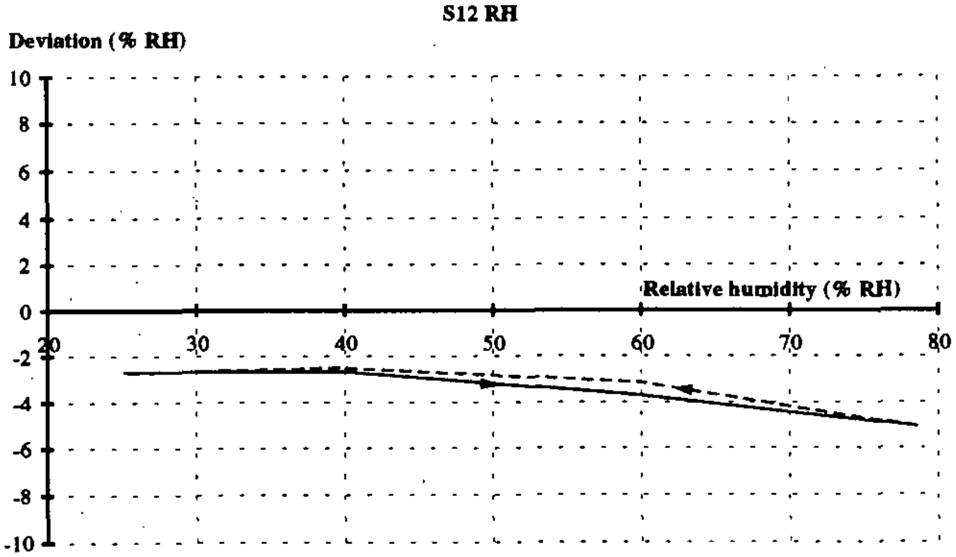


Figure 5.11. Characteristic curve for sensor S12.

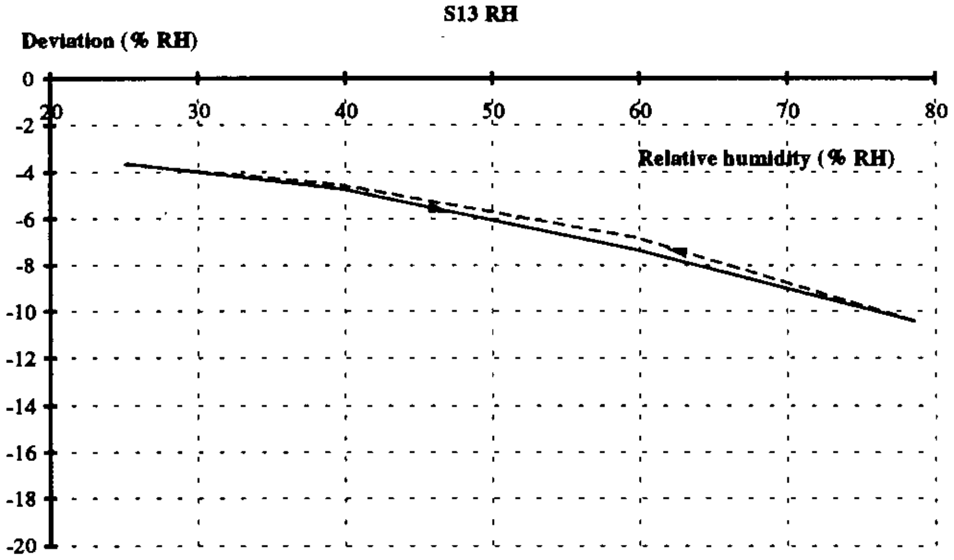


Figure 5.12. Characteristic curve for sensor S13.

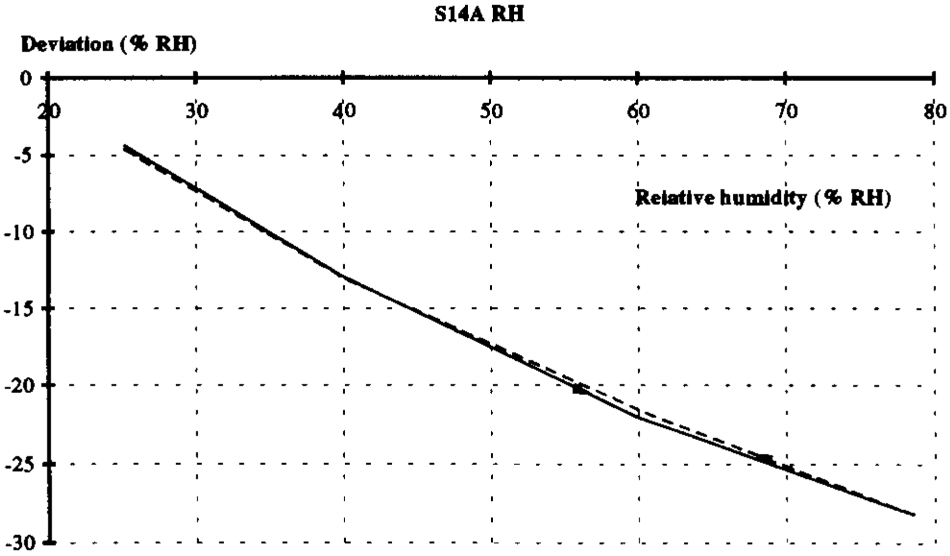


Figure 5.13. Characteristic curve for the RH-sensor in sensor S14, i.e. S14A.

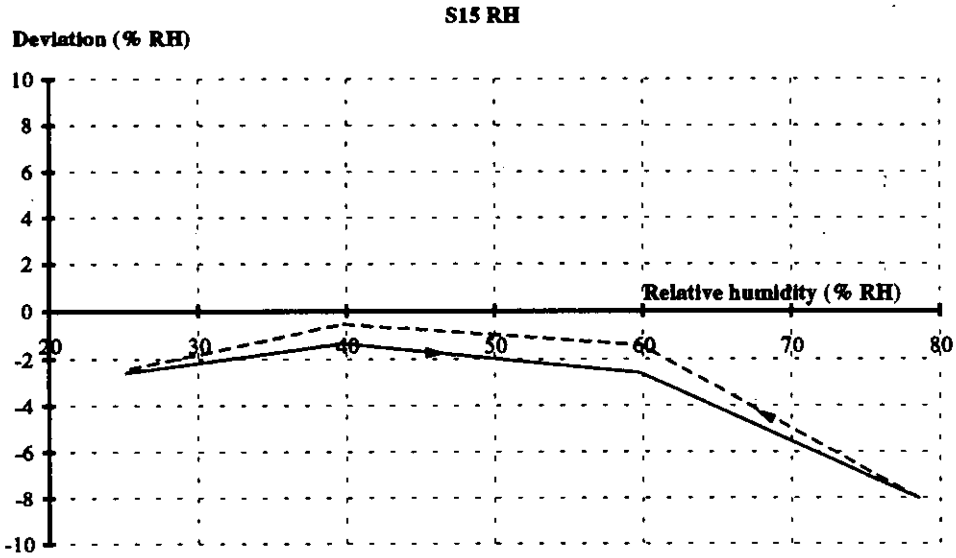


Figure 5.14. Characteristic curve for sensor S15.

5.3 Linearity

The deviations in linearity for the different sensors are presented in Tables 5.1 - 5.3. In those cases where the manufacturer has mentioned a value for the measured parameter this value is also indicated.

5.3.1 VOC-sensors

Table 5.5. Linearity deviation for the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (% AQ)	1	-	-	3.5	2.2
Manufacturer's value (% AQ)	-	-	-	-	-

5.3.2 CO_2-sensors

Table 5.6. Linearity deviation for the CO_2-sensors.

	S5	S6
Measured value (ppm CO_2)	98	26
Manufacturer's value (ppm CO_2)	<40	<100

5.3.3 Humidity sensors

Table 5.7. Linearity deviation for the RH-sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (% RH)	1.2	1.2	2.7	1.2*	2.3	1.1	1.2	2.2	4.7
Manufacturer's value (% RH)	<1	<1	-	-	<2.5	<0.7	<0.7	-	<5

*Some other specimens of this sensor type showed substantially larger deviations (see figure 5.39).

5.4 Hysteresis

The hysteresis measured for the different sensors, and the corresponding values from the manufacturers, are shown in tables 5.7 - 5.9. As can be seen from figures 5.1-5.14 hysteresis as a general rule is positive due to adsorption/desorption effects (the output is higher for decreasing concentrations than it is for increasing concentrations).

5.4.1 VOC-sensors

Table 5.8. Hysteresis for the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (% AQ)	0.9	-	-	0.3	1.4
Manufacturer's value (% AQ)	-	-	-	-	-

5.4.2 CO_2-sensors

Table 5.9. Hysteresis for the CO_2-sensors.

	S5	S6
Measured value (ppm CO_2)	18	21
Manufacturer's value (ppm CO_2)	-	0

5.4.3 Humidity sensors

Table 5.10. Hysteresis for the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (% RH)	0.7	0.8	2.0	0.2*	0.4	0.8	0.7	0.6	1.4
Manufacturer's value (% RH)	<0.5	<0.5	-	-	<0.5	<0.5	<0.5	<3	<3

*Other specimens of this sensor type did not perform as well. One specimen had a hysteresis as large as 15 %RH (see figure 5.39).

5.5 Sensitivity

Sensitivity is defined in accordance with 4.3.2.3 as the ratio of the change in output signal and the change in input signal.

5.5.1 VOC-sensors

Table 5.11. Sensitivity for the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (V/(mg/m³))	0.28	-	-	0.046	0.0098
Manufacturer's value (V/(mg/m³))	*	-	-	-	**

* The manufacturer claims that the sensor gives an output signal of 5 V when exposed to 1000 ppm of CH_4 at 21 °C and 50 % RH. The data sheet supplied with the sensor states that the same conditions yield an output signal of 3.5 V.

**35 ppm of CO in air gives an output signal of 0.7 V according to the data sheet.

5.5.2 CO_2-sensors

Table 5.12. Sensitivity for the CO_2-sensors.

	S5	S6
Measured value (V/ppm CO_2)	0.0038	0.0047
Manufacturer's value (V/ppm CO_2)	0.005	0.005

5.5.3 Humidity sensors

Table 5.13. Sensitivity for the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (unit/% RH)	0.15 (mA)	0.0091 (V)	0.076 (V)	0.078 (V)	0.15 (mA)	0.15 (mA)	0.14 (mA)	0.0054 (V)	0.094 (V)
Manufacturer's value (unit/% RH)	0.16 (mA)	0.01 (V)	0.1 (V)	* (V)	0.16 (mA)	0.16 (mA)	0.16 (mA)	0.01 (V)	0.1 (V)

*The output of sensor S10 gives the absolute humidity and the corresponding sensitivity, according to the data sheet, is 0.526V/(g moisture/kg dry air).

5.6 Repeatability

5.6.1 VOC-sensors

The repeatability could not be measured for the VOC-sensors. The reason for this was that the concentration of the gas mixture could not easily be held sufficiently constant due to variations in the outdoor air. Furthermore the diffusion rates of the pure compounds from the supply tubes were hard to control.

Table 5.14. Repeatability of the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (% AQ)	-	-	-	-	-
Manufacturer's value (% AQ)	-	-	-	-	-

5.6.2 CO_2-sensors

Table 5.15. Repeatability of the CO_2-sensors.

	S5	S6
Measured value (ppm CO_2)	8	9
Manufacturer's value (ppm CO_2)	40	14

5.6.3 Humidity sensors

Table 5.16. Repeatability of the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (% RH)	0.3	0.3	1.1	0.5	0.6	0.3	0.2	0.2	0.8
Manufacturer's value (% RH)	<0.5	<0.5	-	-	<1	<0.6	<0.6	-	-

5.7 Stability

5.7.1 VOC-sensors

Table 5.17. Stability for the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (% AQ)	-	-	-	-	-
Manufacturer's value (% AQ)	-	-	-	-	-

5.7.2 CO_2-sensors

Table 5.18.Stability for the CO_2-sensors.

	S5	S6
Measured value (ppm CO_2)	-	-
Manufacturer's value (ppm CO_2)	-	-

5.7.3 Humidity sensors

Table 5.19. Stability for the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Measured value (% RH)	0.3	0.2	0.2	0.2	0.7	0.3	0.3	0.4	0.1
Manufacturer's value (% RH)	<1	<1	-	-	<2	<1	<1	-	-

5.8 Rise time

5.8.1 VOC-sensors

Table 5.20.Rise time for the VOC-sensors.

	S1	S2	S3	S4	S14B
Measured value (s)	-	-	-	-	-
Manufacturer's value (s)	-	-	-	τ_L<30, $\tau_{0.63}$<60	-

τ_L = lag time, $\tau_{0.63}$ = time constant (63 %)

5.8.2 CO_2-sensors

Table 5.21. Rise time for the CO_2-sensors.

	S5	S6
Measured value (s)	-	-
Manufacturer's value (s)	$\tau_{0.63}$ <600	τ_d <60, $\tau_{0.63}$ <300, $\tau_{0.9}$ <480

$\tau_{0.9}$ = rise time (90 %)

5.8.3 Humidity sensors

To examine the rise and fall times of the humidity sensors the same calibration facility was used as for determination of the characteristic curves. At first the sensors were mounted in the calibration tank and a specified humidity level was fixed in this tank. The signals were recorded and then the pump was turned off and the air ceased to circulate. The humidity level in the saturator tank was then changed and, when this level had stabilized, the pump was switched on again. The sensors now changed their output signals and these signals were recorded until a stable level was reached. The rise time corresponds to the time required for the output signal to change its value by 90 percent of the total change between the two steady-state conditions. Measured rise times below 100 s have a high degree of uncertainty because the sampling frequency that was used with the measuring system was 20 s or 30 s. The time constant of the calibration facility is in the range of 0-37 s depending on whether the purging air flow through the calibration tank has a displacement or fully mixed character. The correspnding rise time (0-90%) will be approximately 2.3 times the value of the time constant.

Table 5.22. Rise time and fall time for the humidity sensors.

	S7	S8	S9	S10	S11	S12	S13	S14A	S15
Rise time, (s)	60	80	500	4400	80	100	100	100	260
Fall time, (s)	60	60	680	1080	100	60	80	220	320
Manufacturer's value (s)	$\tau_{0.9}$ =15	$\tau_{0.9}$ =15	160	$\tau_{0.63}<180$, $\tau_d<18$	$\tau_{0.63}<1$, $\tau_{0.9}<2$	$\tau_{0.63}$ <10	$\tau_{0.63}$ <10	-	180 * <300 **

* for a step of 10-43 % RH, ** for a step of 43-90 % RH.

5.9 Cross-sensitivity

The sensitivity of the sensors to various influence quantities was tested by varying each influence quantity, one at a time, according to table 4.2. The following minor changes were made to table 4.2 during the actual test:

*	Temperature:	14, 21 and 28 °C instead of 10, 20 and 30 °C
*	Supply voltage:	U_n V ± 10 % for sensors S1 - S6 (instead of U_n V ± 20 %)
*	Pressure levels:	(101+5.3, 101-1.7) kPa instead of (101 ± 4) kPa
*	VOC-level:	(0+1.4) mg/m^3 instead of (0+1.0) mg/m^3

The cross-sensitivity is given for each influence factor as the ratio between the total change in output and the total change in input. Test results are indicated in table 5.23 and these results are expressed as the change in output relative to the nominal operating point. The response to tobacco smoke is only indicated qualitatively by "yes" or "no".

VOC-sensors were also tested concerning their reactions to variations in the composition of the VOC-cocktail. At the nominal rating point of 1.0 mg/m^3 the sensors were tested by using the same total concentration with only one of the three constituents at a time. No significant influence by this variation was detected for any of the sensors.

Table 5.23. Results from the cross-sensitivity test.

Sensor no.	Voltage (unit/ V)	Frequency (unit/ Hz)	Temperature (unit/ K)	Rel. humidity (unit/ % RH)	Air pressure (unit/ hPa)	CO_2 (unit/ ppm CO2)	VOC (unit/ mg/ m^3)	Cig. smoke (yes or no)
S1 VOC (%AQ)	0.2	0.1	0.1	0.2	-*	-*	-	yes
S2 VOC (%AQ)	-*	-*	-*	-*	-*	-*	-	yes?
S3 VOC (%AQ)	-*	-*	-*	-*	-*	-*	-	yes
S4 VOC (%AQ)	0.8	0.3	1.5	0.7	-*	-*	-	yes
S5 CO2 (ppm)	3.2	-18	7.1	2.6	0.1	-	-*	yes
S6 CO2 (ppm)	-11	-0.2	4.6	0.1	0.4	-	-*	yes
S7 RH (%RH)	0.0	0.0	0.1	-	0.0	0.0	0.0	no
S8 RH (%RH)	0.0	0.0	0.1	-	0.0	0.0	0.0	no
S9 RH (%RH)	0.1	0.0	0.2	-	0.0	0.0	0.1	no
S10 RH (%RH)	0.0	0.0	0.4	-	0.0	0.0	0.0	no
S11 RH (%RH)	0.1	0.0	0.1	-	0.0	0.0	0.1	no
S12 RH (%RH)	0.0	0.0	0.0	-	0.0	0.0	0.0	no
S13 RH (%RH)	0.0	0.0	-0.1	-	0.0	0.0	0.0	no
S14 (%RH) /(%AQ)	0.0 /0.0	0 /0.3	0.1 /0.0	- /0.0	0 /-	0.0 /-	0.1 /-	no / yes
S15 RH (%RH)	4.9**	0.0	0.3	-	0.0	0.0	0.1	no

• The response of the sensor was too small to be significant or the results were inconclusive.

**This sensor has a nominal supply voltage of 15 V. The indicated result is obtained when the voltage is lowered to 12.03 V. At a voltage of 12.5 V the result is 0.0 %RH.

5.10 Tobacco smoke

To investigate the influence of tobacco smoke on the output signals of the VOC-sensors a number of experiments were performed in a conference room at the department of energy technology, SP. The conference room is sized to accomodate 18 people and is equipped with its own balanced ventilation system including speed controlled fans for both supply and exhaust. The sensors were installed in the exhaust air outlet device. The floor area of the room is 43 m^2 and the corresponding volume is 115 m^3.

The Swedish Building Code calls for a minimum outside air supply rate of 5 dm^3/s per person in a non smoking area and a minimum rate of 10 dm^3/s per person where smoking may occur. In the utilized conference room this would correspond to outside air flows of 325 and 650 m^3/h respectively. For the purpose of the smoke tests it was decided to fix the ventilation rates at the respective minimum values and to vary the number of cigarettes being smoked for each flowrate. Tests were also conducted with the maximum capacity of the ventilation system, in this case 970 m^3/h. The full test program is presented in table 5.24 below.

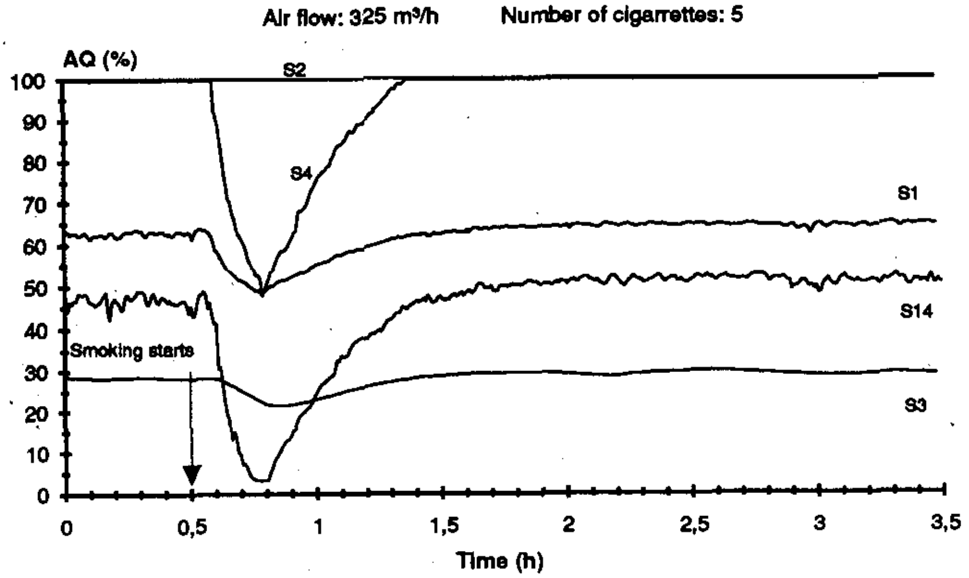
Table 5.24. Test program to evaluate the response of VOC-sensors to tobacco smoke.

Test no.	Ventilation flowrate (m^3/h)	Number of cigarettes	Smoking process
1	325	5	All smoked on one occasion.
2	325	10	All smoked on one occasion.
3	650	5	All smoked on one occasion.
4	650	10	All smoked on one occasion.
5	910	5	All smoked on one occasion.
6	910	10	All smoked on one occasion.
7	910	1	Continuously during 45 min.
8	910	5	Continuously during 2 h 40 min.
9	970	30	All smoked on one occasion.
10	970	30	Continuously during 40 min.

In order to have a reproducible test procedure cigarettes of one specific brand were smoked by an artificial smoker rented from the Swedish Tobacco Company. In this way air was always drawn through the cigarettes with the same suction flow rate. Results from the tests are presented in diagrams 5.15 - 5.25 below.

In the diagrams the outputs of the CO_2-sensors have also been incluced. Sensor S0 is a CO_2-sensor of the same make as sensor S5 and is used for control puposes in the ventilation system. As can be seen in the diagrams even the CO_2-sensors seem to react on tobacco smoke, which was rather unexpeced. So far no conclusive explanation to this phenomenon has been deduced. No people were present in the conference room during the smoke tests except for tests number 7, 8 and 10. During these tests, with continuous smoking, the feed mechanism of the artificial smoker had to be supervised from time to time by a member of staff.

5.10.1 Sensor output during smoking - 325 m³/h of outside air flow



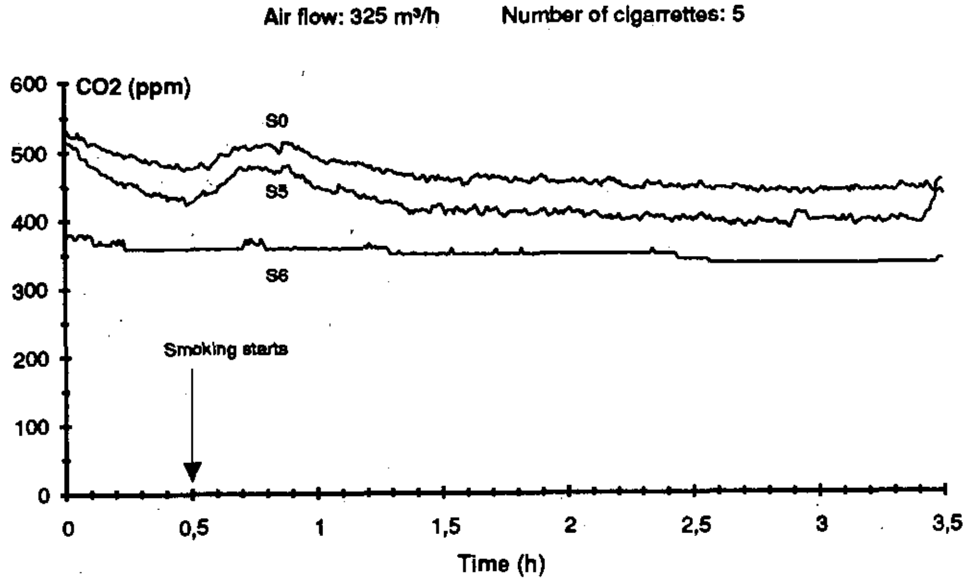
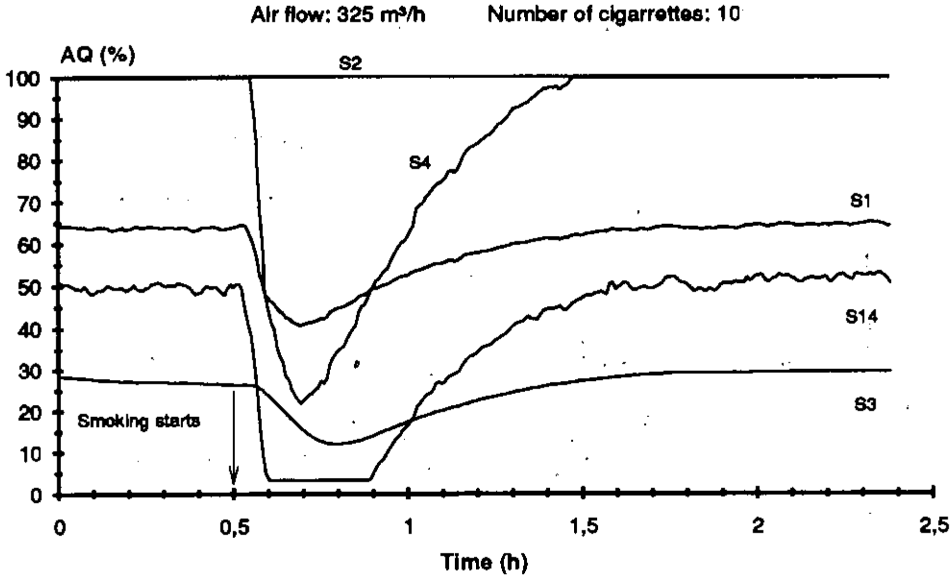


Figure 5.15. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 325 m^3/h and 5 cigarettes were smoked simultaneously on one occasion.



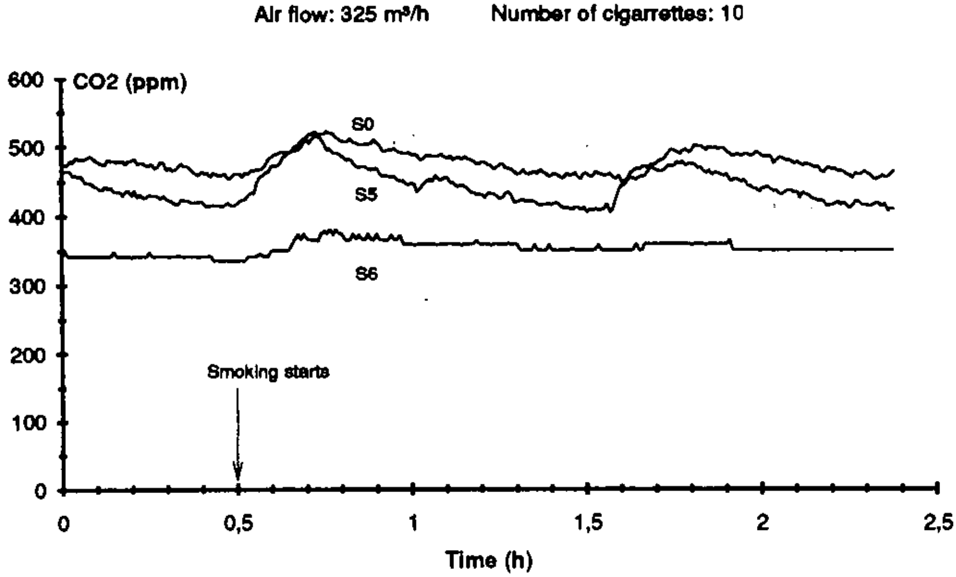
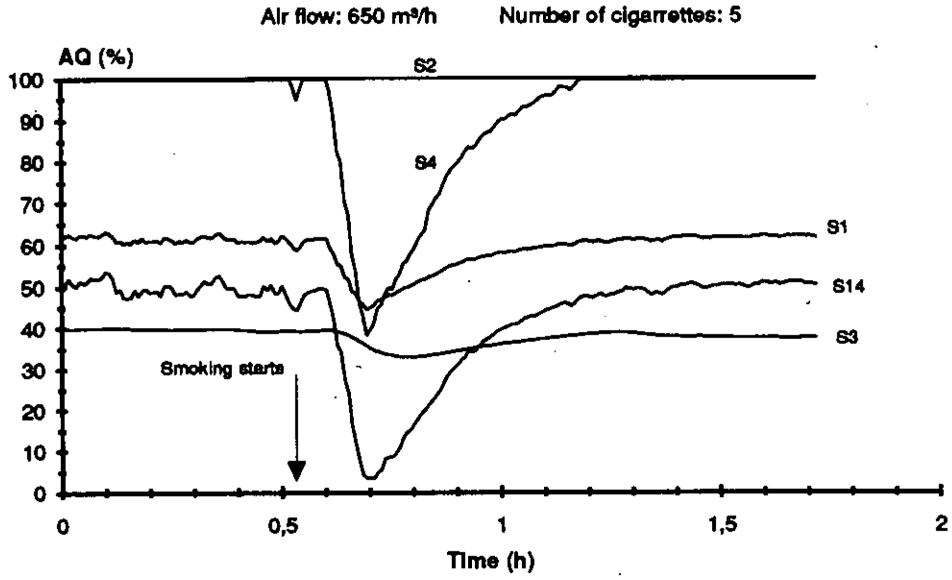


Figure 5.16. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 325 m^3/h and 10 cigarettes were smoked simultaneously on one occasion.

5.10.2 Sensor output during smoking - 650 m³/h of outside air flow



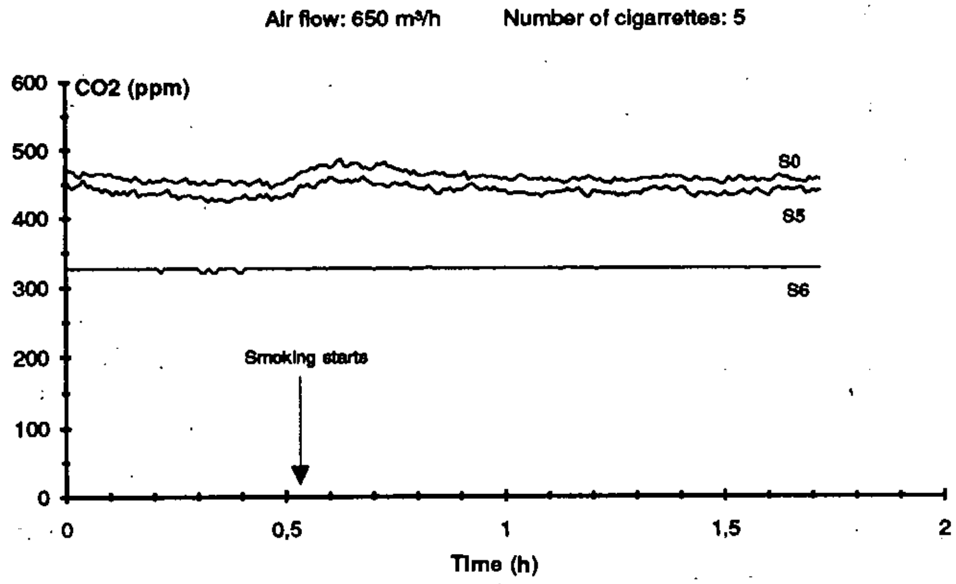
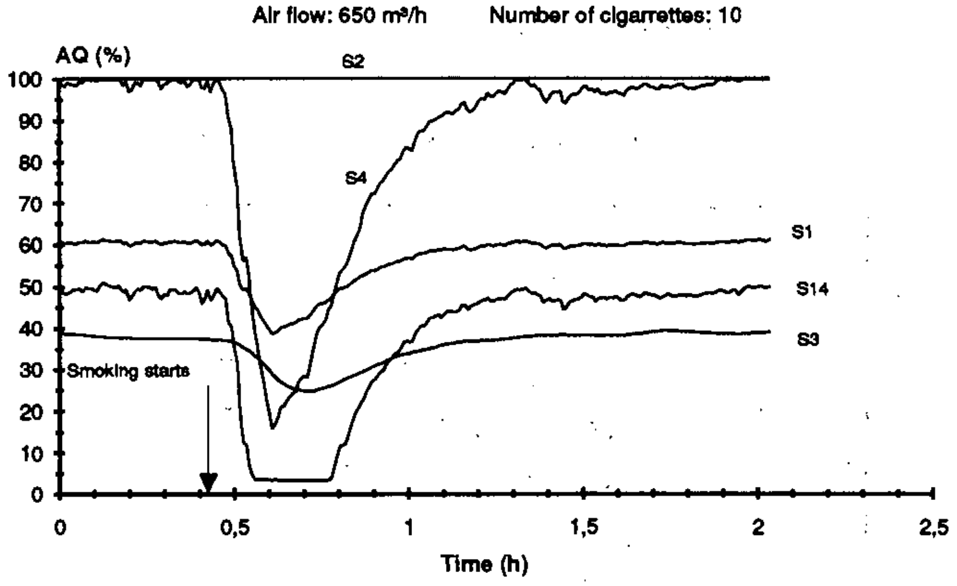


Figure 5.17. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 650 m^3/h and 5 cigarettes were smoked simultaneously on one occasion.



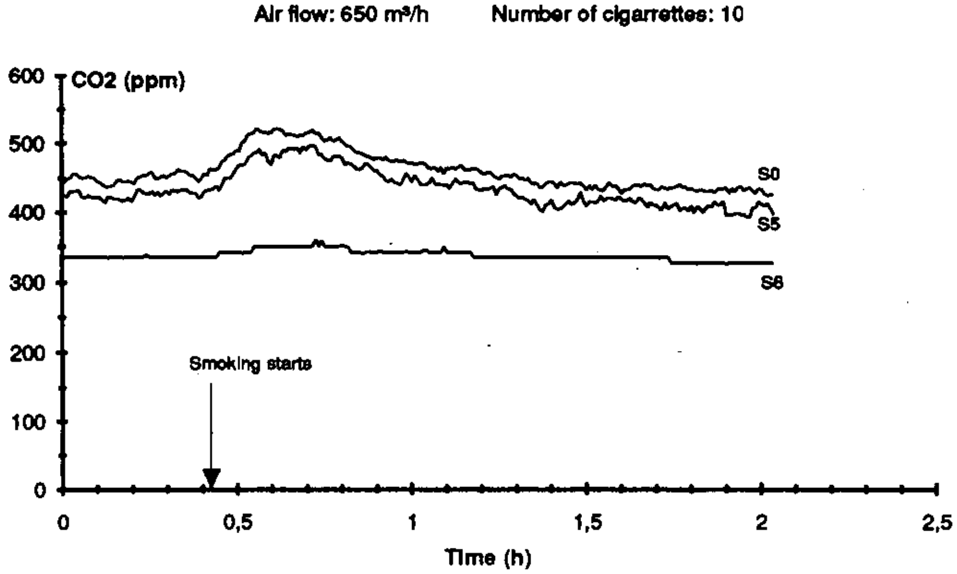
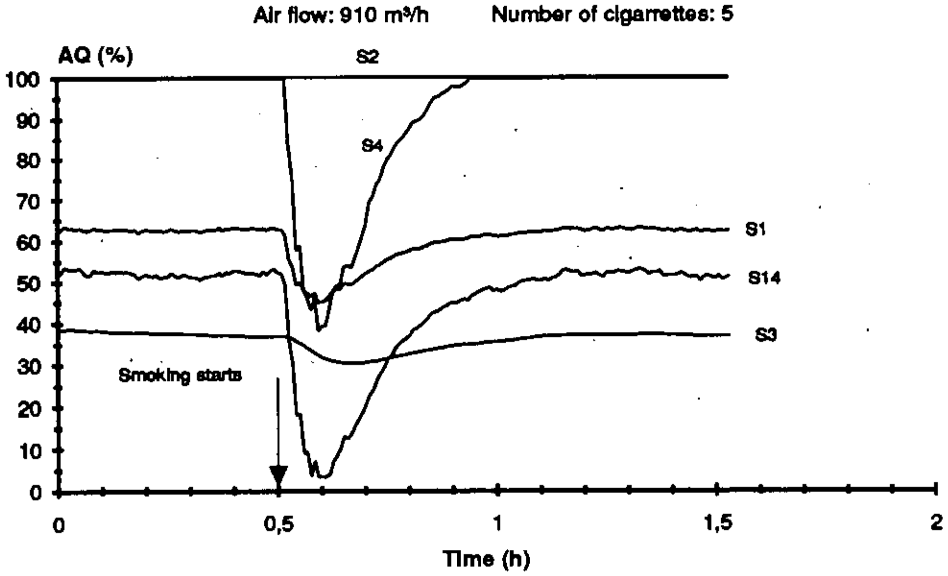


Figure 5.18. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 650 m^3/h and 10 cigarettes were smoked simultaneously on one occasion.

5.10.3 Sensor output during smoking - 910 m³/h of outside air flow



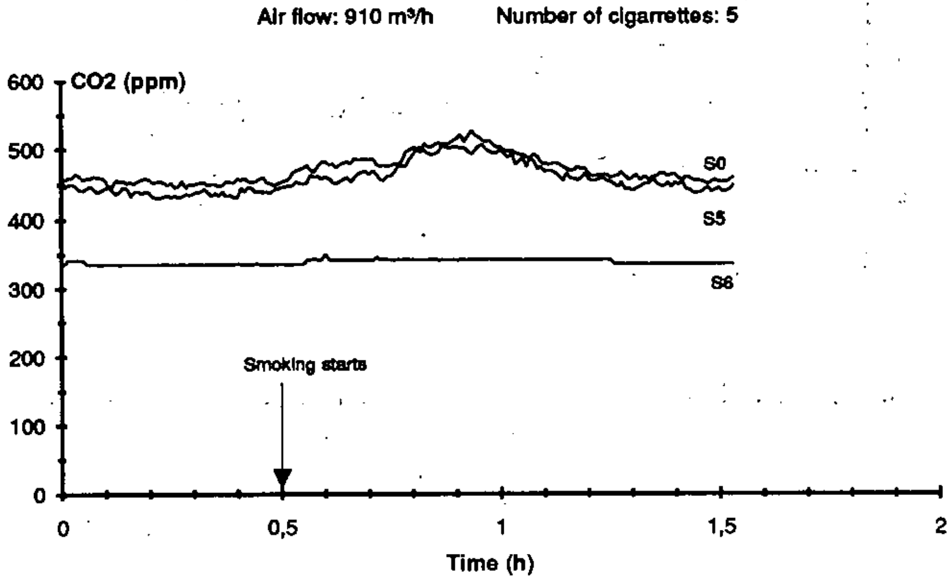
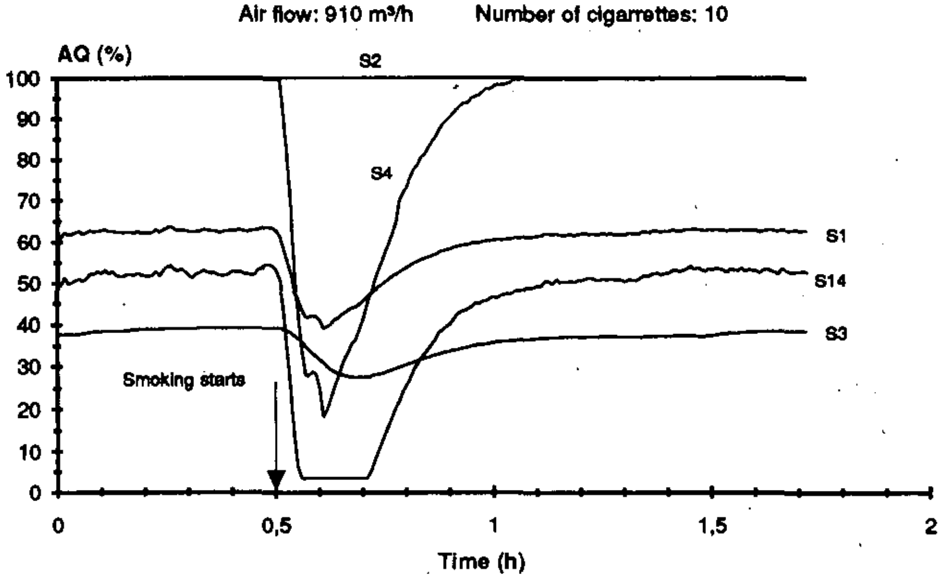


Figure 5.19. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 910 m^3/h and 5 cigarettes were smoked simultaneously on one occasion.



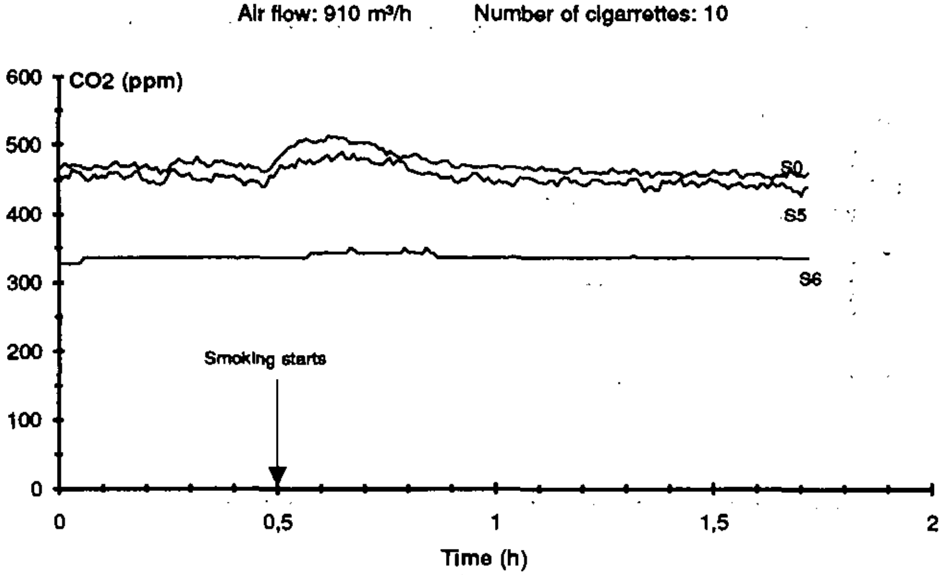
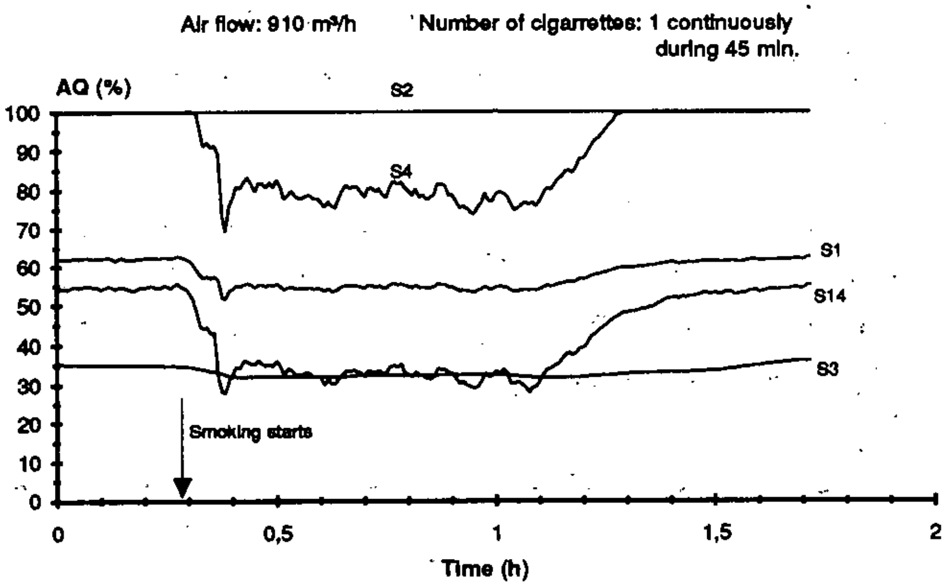


Figure 5.20. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 910 m^3/h and 10 cigarettes were smoked simultaneously on one occasion.



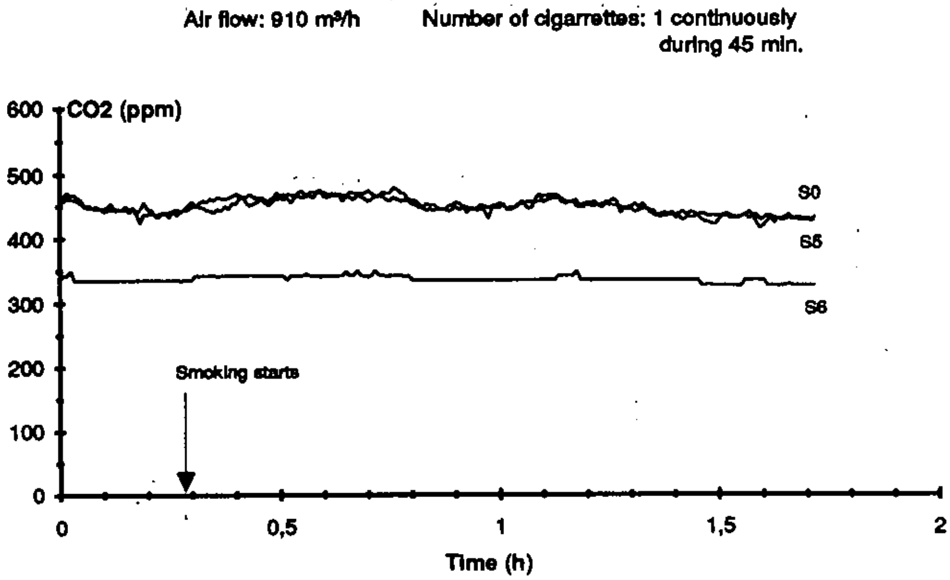


Figure 5.21. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 910 m^3/h and 1 cigarette was smoked continuously during 45 minutes.

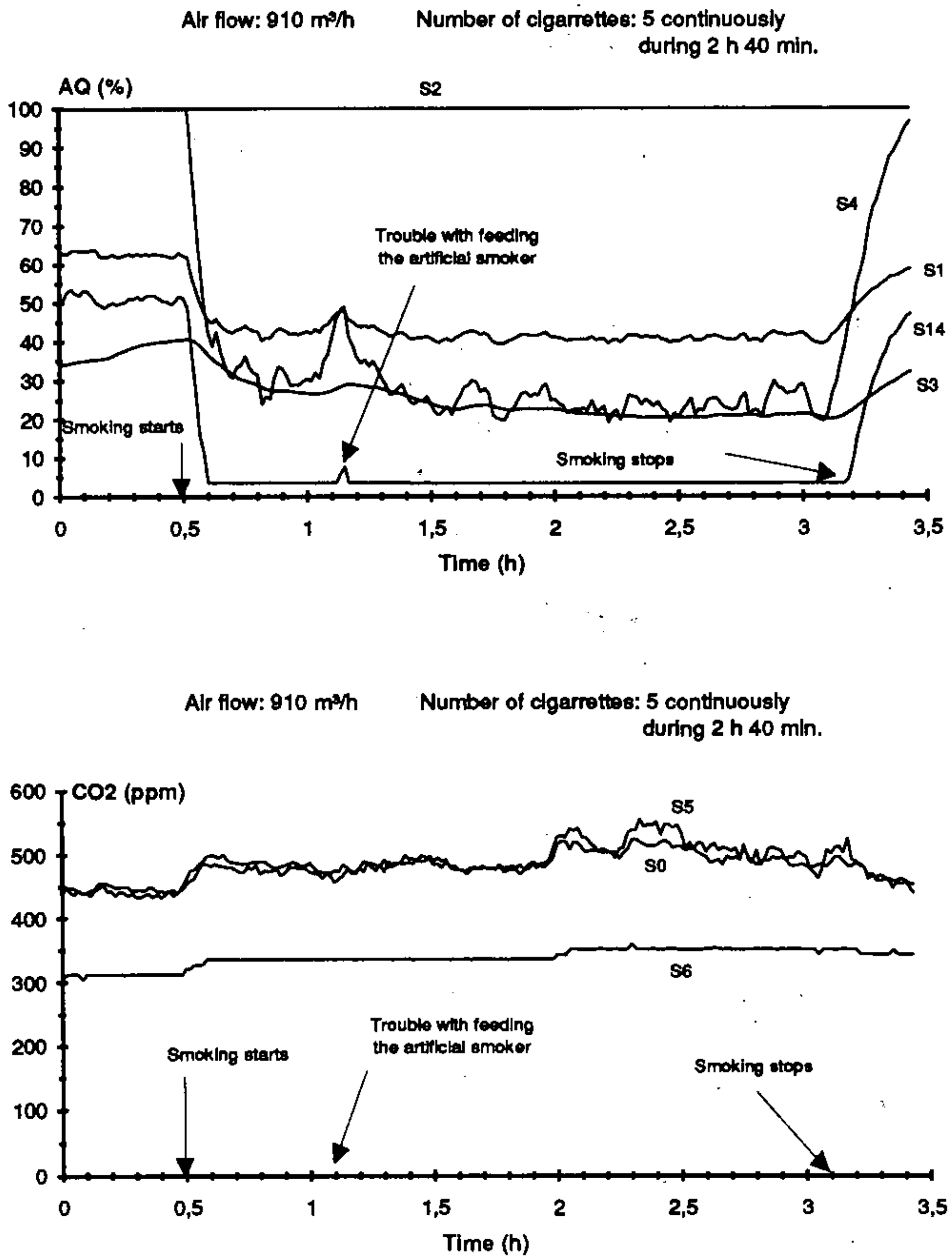
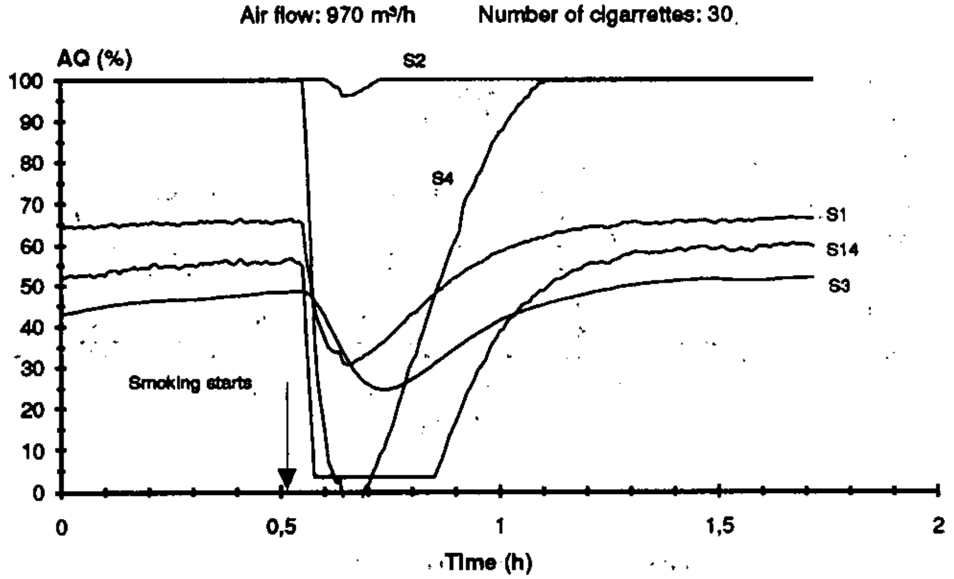


Figure 5.22. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 910 m^3/h and 5 cigarettes were smoked continuously during 2 h 40 minutes.

5.10.4 Sensor output during smoking - 970 m³/h of outside air flow



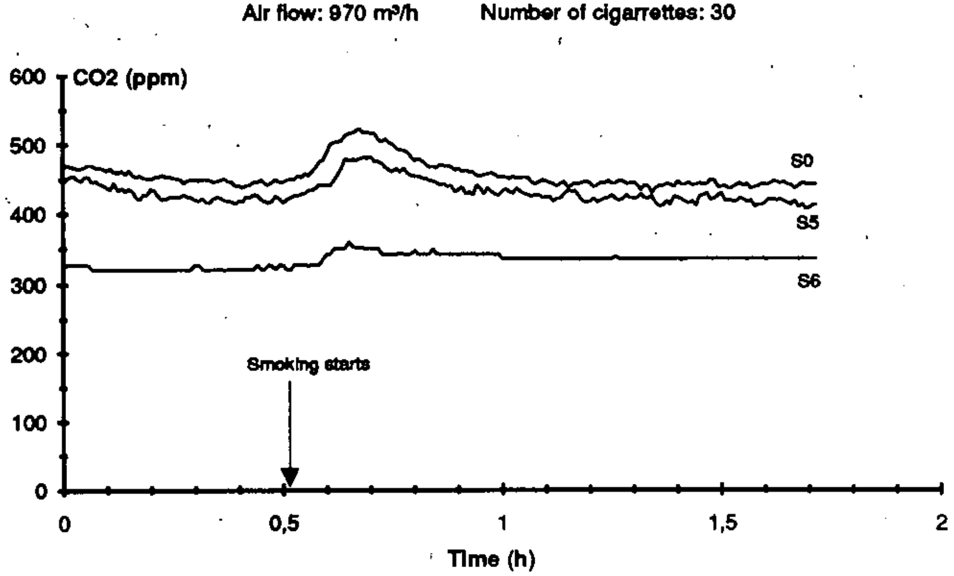


Figure 5.23. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 970 m³/h and 30 cigarettes were smoked simultaneously on one occasion.

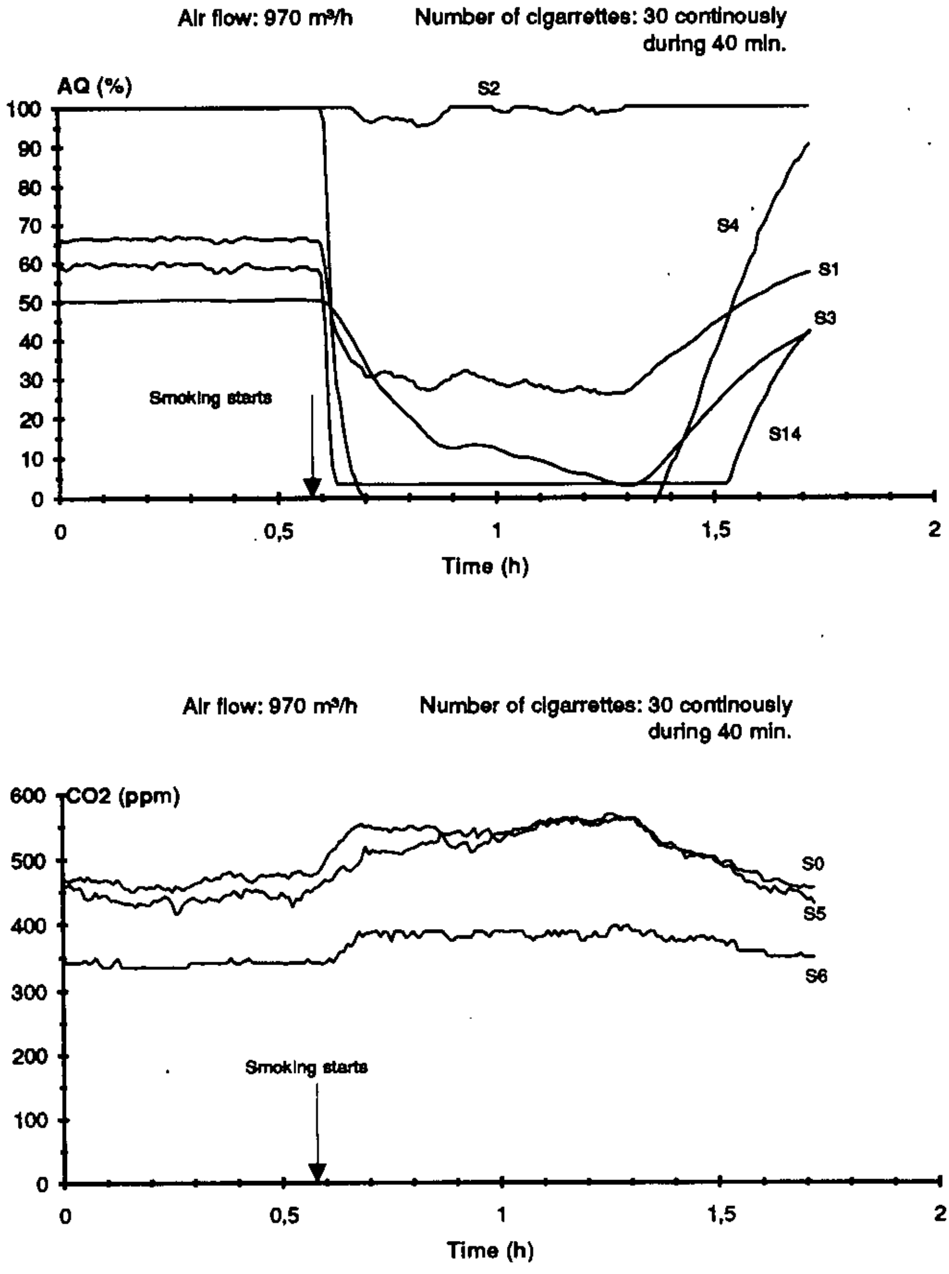


Figure 5.24. Output of VOC- and CO_2-sensors during tests with tobacco smoke. The ventilation flowrate was 970 m^3/h and 30 cigarettes were smoked continuously during 40 minutes.

5.11 Environmental tests

Environmental tests were performed according to the test program described in chapter 4. The purpose of the tests was to check the resistance of a sensor to possible environmentally extreme situations within its field of application. These tests were conducted at the electrotechnical laboratory of SP (ref. 4). For some of the tests a simple functional control was carried out either before, during and/or after a change in the test conditions. Where this control is indicated it consisted of a simple measurement of the output signal of the sensor by means of an electric multimeter. Since the sensors react to the ambient conditions the read-out is only an indication of whether the sensor is working or not. Sensors will for instance react to the breath from a member of staff in the proximity of the sensor (humidity, carbon dioxide and a number of hydrocarbons).

5.11.1 Climatic parameters

Climatic tests were performed in accordance with IEC standards on dry heat, cold, damp heat and change of temperature. Results and some comments are presented below.

5.11.1.1 Cold, IEC 68-2-1, Test Ab

The sensors were placed in the test chamber with their power supplies disconnected. The test chamber was initially kept at room temperature. The temperature was then decreased at a rate of 1 K/minute to the set value +5 °C. This temperature was kept constant during a period of 16 h after reaching stable conditions. Thereafter the temperature was increased back to the normal room temperature at a rate of 1 K/minute. Functional tests were performed in the chamber before, during (after stabilization at +5 °C) and after the test. Test results are shown in table 5.25 below.

Excepting the functional tests the power supplies were disconnected during the test. Forced convection air circulation was used in the chamber during the entire test.

This test is often applied to consumer electronics and other electronic equipment used in an ordinary indoor environment. The effect on the sensors was miniscule and none of the sensors failed during this test. Concerning the actual temperature sensitivity of the output signal reference is made to table 5.23 regarding temperature as an influence parameter.

Table 5.25. Results from the cold test (IEC 68-2-1 Ab).
Temperature: +5 °C Duration: 16 h

Sensor	Output signal (V)			Comments
	Before (+22 °C)	During (+5 °C)	After (+22 °C)	
S1 (VOC)	-	6.11	5.72	OK
S2 (VOC)	-	-0.01	0.01	OK
S3 (VOC)	-	0.06	0.06	OK
S4 (VOC)	-	0.02	0.02	OK
S5 (CO_2)	-	2.38	0.36	OK
S6 (CO_2)	-	1.25	0.46	OK
S7 (RH)	-	4.80	4.45	OK
S8 (RH)	-	0.35	0.31	OK
S9 (RH)	-	4.06	3.18	OK
S10 RH)	-	2.48	0.81	OK
S11 (RH)	-	4.98	4.83	OK
S12 (RH)	-	4.66	4.56	OK
S13 (RH)	-	4.50	4.41	OK
S14A (RH)	-	0.42	0.25	OK
S14B (VOC)	-	0.96	0.51	OK
S15 (RH)	-	3.47	2.20	OK

5.11.1.2 Dry heat, IEC 68-2-2, Test Bd

The next step in the test program was to expose the sensors to dry heat. For this purpose the sensors were placed in a test chamber with their power supplies disconnected. At the onset of the test the chamber was kept at ordinary room temperature. Thereafter the temperature was raised at a rate of 1 K/minute until the set value of +40 °C was reached. Having obtained steady state conditions the functional tests were conducted. The temperature was then further raised to +55 °C. This temperature was kept constant for a duration of 72 h after achieving stable conditions. Finally the temperature was lowered back to the normal room temperature at a rate of 1 K/minute.

Functional tests were performed in the chamber both prior to the test and subsequently after the test. Forced convection air circulation was used in the chamber for the entire duration of the test. In table 5.26 below the test results are displayed. Again there was little effect of the test and all sensors continued to function. As before the temperature sensitivity of the actual output signal is referred to table 5.23.

Table 5.26. Results from the dry heat test (IEC 68-2-2 Bb).
Temperature: +55 °C Duration: 21 days.
(Functional and intermediate checks at +40 °C)

Sensor	Output signal (V)			Comments
	Before (+22 °C)	During (+55 °C)	After (+22 °C)	
S1 (VOC)	5.35	7.12	6.59	OK
S2 (VOC)	4.80	0.63	-0.01	OK
S3 (VOC)	0.06	0.06	0.06	OK
S4 (VOC)	2.85	2.18	0.02	OK
S5 (CO_2)	2.19	1.55	1.87	OK
S6 (CO_2)	1.32	1.82	1.82	OK
S7 (RH)	4.57	2.45	5.17	OK
S8 (RH)	0.33	0.07	0.36	OK
S9 (RH)	3.88	0.03	3.62	OK
S10 RH)	3.39	7.61	4.58	Output goes up when RH goes down!
S11 (RH)	4.87	2.55	5.19	OK
S12 (RH)	4.47	2.11	4.9	OK
S13 (RH)	4.33	2.09	4.76	OK
S14A (RH)	0.31	0.12	0.28	OK
S14B (VOC)	0.97	0.87	0.61	OK
S15 (RH)	3.22	0.89	3.38	OK

5.11.1.3 Damp heat, IEC 68-2-3, steady state, test Ca

To evaluate the ability of sensors to withstand damp heat a test according to IEC 68-2-3, test Ca, was selected. Prior to introducing the test specimens into a test chamber they were preheated to a temperature exceeding the dew point temperature of the test conditions. This was done to avoid condensation of water on the sufaces of the sensors.

The sensors were then brought into the test chamber in their switched-off, ready for use, states. At this instant the chamber was already kept at the set point temperature (+40 °C) and humidity (93 % RH) according to the test standard and the specified severity. The time of exposure to the test conditions was 21 days.

After conclusion of the test the sensors were exposed to a reconditioning atmosphere during which the relative humidity was reduced from 93% to 75 % within 0.5 h. Finally the temperature was adjusted from 40 °C back to an ordinary room temperature of 22 °C within 0.5 h. Functional tests were conducted before, at the end of, and after the test program.

Table 5.27. Results from the damp heat test (IEC 68-2, steady state, test Ca). Temperature: 40 °C, humidity: 93 % RH. Duration: 21 days.

Sensor	**Output signal (V)**			**Comments**
	Before (+22 °C)	During (+40 °C, 93 %RH)	After (+22 °C)	
S1 (VOC)	6.29	9.13	8.27	OK
S2 (VOC)	-0.01	-0.01	-0.01	OK
S3 (VOC)	0.06	0.06	0.06	OK
S4 (VOC)	0.02	0.02	0.02	OK
S5 (CO_2)	2.13	1.49	2.04	More affected than x-sensitivity of temperature and humidity would suggest
S6 (CO_2)	1.36	9.75	6.80	Strongly affected during the test
S7 (RH)	5.87	4.35	4.84	OK
S8 (RH)	0.47	0.38	0.37	OK
S9 (RH)	4.62	5.15	7.19	OK
S10 RH)	4.86	13.44	5.18	Extreme time lag/hysteresis
S11 (RH)	5.98	5.48	5.58	OK
S12 (RH)	5.83	7.16	5.03	OK
S13 (RH)	5.61	4.76	4.75	OK
S14A (RH)	0.49	0.38	0.51	OK
S14B (VOC)	0.59	0.98	0.97	OK
S15 (RH)	4.67	4.20	3.80	OK

None of the sensors showed any signs of significant deterioration due to this test. Concerning the actual sensitivity of the output signal reference is made to table 5.23 regarding humidity and temperature as influence parameters.

5.11.1.4 Change of temperature, IEC 68-2-14, Test Nb

The effect of a cyclic change in temperature was investigated in a climate chamber in accordance with IEC 68-2-14, test Nb. Initially the test chamber was kept at room temperature (22 °C) and the sensors were introduced in their switched-off, ready for use, states. The sensors were equipped with the electrical connections necessary for checking their operation. Functional tests and visual examinations were then carried out.

The sensors were brought into their operating stand-by conditions and the temperature cycling between temperatures T_A and T_B was then carried out as described in IEC 68-2-14. This implies a temperature decrease to $T_A = +5$ °C at a rate of 3 K/minute. This temperature is kept for 3 h after which it is raised to $T_B = +55$ °C, again at a rate of 3 K/minute. This temperature is also kept for 3 h before reverting to the low temperature condition. Forced convection air circulation was used in the chamber throughout the test.

During the test, which comprised five full temperature cycles, the stand-by operating conditions of the specimens were continuously monitored.

Operational checks were performed at both of the temperatures T_A and T_B immediately after the temperature stability in the chamber had been reached. These checks were made during the two final test cycles. To conclude this part of the test program the sensors were again checked after the chamber had been brought back to and kept at standard atmospheric recovery conditions for more than four hours.

Results from the checks are shown in table 5.28 below. None of the sensors was permanently affected by this test.

To check the possibility of humidity sensors to withstand condensation of moisture a special test was planned. This test included a functional check after storing the sensor at -10 °C with the power switched off for 24 h and then changing the ambient conditions to +20 °C with a relative humidity of 80 % in less than 10 minutes. Mainly due to time considerations this test had to be excluded from test procedure.

Table 5.28. Results from the change of temperature test (IEC 68-2-14, test Nb).
Low temperature T_A: +5 °C *High temperature T_B: + 40 °C*
Exposure time: 3 h *Recovery time: > 4 h*
Rate of change of temperature: 5 °C/min *Number of cycles: 5*

Sensor	**Output signal (V)**						**Comments**
	Cycle 1			**Cycle 2**			
	Before (22 °C)	During (5 °C)	During (40 °C)	During (5 °C)	During (40 °C)	After (22 °C)	
S1 (VOC)	9.50	8.17	8.37	6.72	7.56	5.31	OK
S2 (VOC)	-0.01	-0.01	-0.01	-0.01	-0.01	2.29	OK
S3 (VOC)	0.06	0.06	0.06	0.06	0.06	0.06	OK
S4 (VOC)	0.02	0.02	0.02	0.02	0.02	4.53	OK
S5 (CO_2)	2.71	1.34	2.16	1.84	2.35	2.59	OK
S6 (CO_2)	6.70	10.01	4.59	2.33	4.36	4.25	OK
S7 (RH)	4.57	4.45	2.86	5.51	2.78	5.90	OK
S8 (RH)	0.38	0.33	0.12	0.45	0.11	0.49	OK
S9 (RH)	4.02	2.60	1.15	5.66	0.88	5.11	OK
S10 RH)	2.62	4.18	13.43	1.32	13.46	8.40	Extreme time lag results in the output being totally out of phase with the temperature change
S11 (RH)	5.23	5.08	3.11	6.16	5.98	6.55	OK
S12 (RH)	4.47	4.58	2.40	5.75	2.27	5.87	OK
S13 (RH)	4.30	4.49	2.14	5.64	2.08	5.61	OK
S14A (RH)	0.46	0.47	0.19	0.58	0.17	0.41	OK
S14B (VOC)	0.65	0.43	0.60	0.69	0.78	0.98	OK
S15 (RH)	3.00	2.15	0.53	5.44	0.53	5.42	OK

5.11.2 Mechanical parameters

Mechanical tests were performed in accordance with IEC standards on random vibration.

5.11.2.1 Random vibration, IEC 68-2-36, Test Fdb

The sensors were mounted on the vibrator using the normal means of mounting. External cables and connections were included and fastened to simulate conditions during use.

Before commencing the test the sensors were electrically connected in their ready for use states and functional checks were performed before exposure to the test conditions. With the equipment switched on, the level of vibration was increased to the specified level, which was applied for the specified duration of 90 minutes. The functional checks were repeated before and after vibrational tests in axis directions 1 and 3. The test results are presented in table 5.29 below. One CO_2-sensor (S5) and two humidity sensors (S12 and S14) broke during this test.

Table 5.29. Results from the vibration test (IEC 68-2-36 Fdb).

ASD 10-20 Hz: 0.5 g^2/Hz *Total rms acceleration: 1.9 g*
ASD 20-500 Hz: -3 dB/octave *Duration/axis: 90 minutes*

Sensor	**Output signal (V)**				**Comments**
	Direction 1		**Direction 2**		(***B*** = broken sensor)
	Before	After	Before	After	
S1 (VOC)	8.3	8.38	8.67	8.98	OK
S2 (VOC)	0.01	0.01	0.01	0.01	OK
S3 (VOC)	0.06	0.06	0.06	0.06	OK
S4 (VOC)	0.02	0.02	0.02	0.02	OK
S5 (CO_2)	2.4	***B*** (0)	***B*** (0)	***B*** (0)	***B***. One capacitor (4700 pF) came loose, the sensor ceased to function
S6 (CO_2)	6.54	3.33	10.28	10.28	A plastic window covering the LED display loosened. Function of the sensor was not affected.
S7 (RH)	6.02	5.09	3.89	3.72	The sensor probe loosened, was refastened and the test continued
S8 (RH)	0.51	0.39	0.26	0.24	OK
S9 (RH)	4.98	3.91	3.12	2.55	OK
S10 RH)	2.58	2.36	1.76	1.82	OK
S11 (RH)	6.1	5.42	4.53	4.13	OK
S12 (RH)	5.83	4.83	3.7	7.7	***B***
S13 (RH)	5.63	4.68	3.66	3.5	OK
S14A (RH)	0.3	0.31	0.23	0.2	***B***
S14B (VOC)	0.42	0.52	0.96	0.37	***B***
S15 (RH)	3.48	3.09	1.82	1.48	OK

5.11.3 Electrical parameters

Electrical tests were performed in accordance with IEC standards on conducted bursts, electrostatic discharge, electromagnetic radiation and surge voltage immunity.

5.11.3.1 Conducted transient bursts, IEC 801-4

The sensors, the transient generator and the connecting cables were all placed 10 cm above a common ground plane. Signal cables were coiled up in a "number 8" fashion, to limit the effective length to 1 meter, and connected to the peripherals or to impedances simulating these. A common mode coupling-box/low pass filter, as specified, was inserted into the power supply leads, and the test generator was connected. The sensors were connected to their power supplies and remained connected for the duration of the test.

Table 5.30. Results from conducted transient bursts (IEC 801-4).
Amplitude: 4 kV (both polarities).

Sensor	**Output signal (V)**				**Comments**
	Before	During positive pulse	During negative pulse	After	(***B*** = broken sensor)
S1 (VOC)	8.39	8.45	8.45	8.39	OK
S2 (VOC)	-0.01	1.2±0.8	0.6±0.3	0.01	OK but affected
S3 (VOC)	0.06	0.04±0.04	0.2±0.1	0.06	OK but affected
S4 (VOC)	0.02	-0.05±0,05	0.3±0.2	0.02	OK but affected
S5 (CO_2)	***B***	***B***	***B***	***B***	***B*** (before the test)
S6 (CO_2)	10.28	40±20	40±20	10.28, ***B***	***B***. Directly after the test the output was 0.3 V. Afterwards it rose to 10.28 V
S7 (RH)	3.92	3.9±0.2	3.2±0.3	3.92	OK
S8 (RH)	0.28	0±0.2	0.75±0.25	0.28	OK
S9 (RH)	2.9	3.3±0.5	3.3±0.5	2.9	OK
S10 RH)	1.76	1.72±0.03	1.72±0.03	-0.01	Brief large variations down to -3 V
S11 (RH)	4.53	7±2	6±1	4.51	OK but affected
S12 (RH)	***B***	***B***	***B***	***B***	***B*** (before the test)
S13 (RH)	3.8	25±10	10±5	3.85	OK but affected
S14A (RH)	***B***	***B***	***B***	***B***	***B*** (before the test)
S14B (VOC)	***B***	***B***	***B***	***B***	***B*** (before the test)
S15 (RH)	1.0	-10±10	10±10	1.0	OK

Functional tests of the sensors were performed before injecting transients for at least 2 minutes with each polarity. After this test the coupling box was left in the supply leads with a short circuit substituted for the generator. Each group of signal cables, running parallel in actual use, was then successively exposed to transients using capacitive coupling boxes for each group. At least 2 minutes of each polarity was used for each group. Functional tests were carried out before, during both postive and negative exposures, and finally after completion of the test. Results of these tests are given in table 5.30 above. Sensors S6 and S10 were irretrievably damaged by this test. According to the manufacturer of S6 items 4.4.1.2 - 4.4.1.4 and all of 4.4.3 were out of bounds for this sensor. Still S6 endured all the climatic tests but failed during the conducted transients.

5.11.3.2 Electrostatic discharge, IEC 801-2

Simulation of electrostatic discharges were made according to IEC 801-2. Functional tests of the sensors were performed before and after exposing them to the electrostatic discharges. For the purpose of the test the sensors were placed on an insulated support 0.1 m above an earth reference plane. The sensors were connected to their power supplies and kept operating in a functional mode during all of the discharge testing activities.

Table 5.31. Results from the electrostatic discharge test (IEC 801-2).
Level: 3 Amplitude: 8kV

Sensor	Output signal (V)		Comments
	Before	After	(*B* = broken sensor)
S1 (VOC)	8.34	8.35	OK
S2 (VOC)	-0.01	-0.01	OK
S3 (VOC)	0.06	0.06	OK (possibly already disfunctioning)
S4 (VOC)	0.02	0.02	OK
S5 (CO_2)	*B*	*B*	*B* (before the test)
S6 (CO_2)	*B*	*B*	*B* (before the test)
S7 (RH)	3.77	3.78	OK
S8 (RH)	0.25	0.25	OK
S9 (RH)	2.96	2.96	*B* (after the test)
S10 RH)	*B*	*B*	*B* (before the test)
S11 (RH)	4.20	4.16	OK
S12 (RH)	*B*	*B*	*B* (before the test)
S13 (RH)	3.43	1.87	*B* (during the test; discharges against the actual sensor part dropped the output to 1.87 V)
S14A (RH)	*B*	*B*	*B* (before the test)
S14B (VOC)	*B*	*B*	*B* (before the test)
S15 (RH)	1.40	1.48	OK

The test generator, charged to the specified voltage, was approached to points on the test object normally accessible to the operator. Ten discharges were applied on each preselected point. Results and comments are presented in table 5.31 above.

During the electrostatic discharges there was little change in the output signals of the sensors. However, two more sensors (S9 and S13) failed during this test leaving only eight sensors for the continued evaluation.

5.11.3.3 Radiated electromagnetic field, IEC 801-3

Functional tests of the sensors were performed before exposing them to radiated electromagnetic fields. Each sensor was then placed on an insulated table and electrically connected according to the installation instructions. The sensors remained connected and operating in their respective functional modes for the duration of the test.

The connecting cables of the sensors were then exposed to electromagnetic radiation of the prescribed severity with the frequency changing from 25 to 225 MHz (low frequency) and 200 to 500 MHz (high frequency) respectively. During the tests the connecting cables of the sensors were installed horizontally for 1 m whereafter the cables were directed vertically down to an earthing plane. The output signals of the sensors were recorded continuously and, whenever disturbances occured, the frequencies were recorded. Finally the sensors were checked after completion of the test. Results and comments are given below in tables 5.32 and 5.33 for the low and high frequency ranges respectively. During these tests monitoring of the sensor outputs was carried out by staff from the department of energy technology.

The results from the tests with radiation clearly indicate that this type of interference is a potential source of trouble. Even though the behaviour of individual sensors was quite different in detail all of the sensors changed their outputs by several orders of magnitude at specific frequencies or frequency ranges.

Table 5.32. Results from the test with radiated electromagnetic fields, low frequency (IEC 801-3).
Level: 3 *Strength: 10 V/m* *Frequency range: 25-225 MHz.*

Sensor	**Output signal (V), 25 < f < 225 MHz**			**Comments**
	Before	During	After	(***B*** = broken sensor)
S1 (VOC)	8.7	8.7 - 10^6	8.7	Extremely strong interference in the intervals 25-26, 30-31, 34-36 MHz
S2 (VOC)	-0.02	-0.02 - 10^6	-0.02	Extremely strong interference in the intervals 25-27, 33-36, 94-98 and 103-108 MHz
S3 (VOC)	0.06	0.06	0.06	No interference (the sensor is probably already disfunctioning prior to this test)
S4 (VOC)	0.02	0.02 - 0.08	0.02	Strong interference in the intervals 64-66, 92-98, 134-147, and 180-190 MHz
S5 (CO_2)	***B***	***B***	***B***	***B*** (before the test)
S6 (CO_2)	***B***	***B***	***B***	***B*** (before the test)
S7 (RH)	3.16	3.16 - 3.18	3.18	OK. No interference
S8 (RH)	0.16	0.00 - 0.17	0.16	Strong resonance in the intervals 55-63 and 88-155 MHz
S9 (RH)	1.93	0.93 - 2.11	1.64	Moderately strong resonance in the interval 55-82 MHz
S10 RH)	***B***	***B***	***B***	***B*** (before the test)
S11 (RH)		1.7 - 10.1		Strong resonance over the entire frequency range
S12 (RH)	***B***	***B***	***B***	***B*** (before the test)
S13 (RH)	***B***	***B***	***B***	***B*** (before the test)
S14A (RH)	***B***	***B***	***B***	***B*** (before the test)
S14B (VOC)	***B***	***B***	***B***	***B*** (before the test)
S15 (RH)	-	0.20 - 5.52	-	Strong resonance over most of the frequency range

Table 5.33. Results from the test with radiated electromagnetic fields, high frequency (IEC 801-3).
Level: 3 *Strength: 10 V/m* *Frequency range: 200-500MHz.*

Sensor	**Output signal (V), 200 < f < 500 MHz**			**Comments**
	Before	During	After	(***B*** = broken sensor)
S1 (VOC)	-	5.8 - 10^6	-	Extremely strong interference in the intervals 210-220, 225, 240-245, 269-270, 273-275, 297-301 and 485-500 MHz
S2 (VOC)	-0.02	-0.02 - -10^6	-0.02	Extremely strong interference in the intervals 200-203, 208-229, 231-240 and 263-278 MHz
S3 (VOC)	0.06	0.06	0.06	No interference (the sensor is probably already disfunctioning prior to this test)
S4 (VOC)	0.02	0.02 - 0.28	0.02	Strong interference in the intervals 200-202 and 210-230 MHz
S5 (CO_2)	***B***	***B***	***B***	***B*** (before the test)
S6 (CO_2)	***B***	***B***	***B***	***B*** (before the test)
S7 (RH)	3.01	1.12 - 3.21	3.21	Moderate interference in the interval 200-240 MHz
S8 (RH)	0.13	0.08 - 0.17	0.17	Strong resonance in the interval 350-360 MHz
S9 (RH)	1.68	1.65 - 1.84	1.70	Moderately strong resonance in the intervals 210-230 and 420-500 MHz
S10 RH)	***B***	***B***	***B***	***B*** (before the test)
S11 (RH)		1.70 - 3.60		Strong resonance over most of the frequency range
S12 (RH)	***B***	***B***	***B***	***B*** (before the test)
S13 (RH)	***B***	***B***	***B***	***B*** (before the test)
S14A (RH)	***B***	***B***	***B***	***B*** (before the test)
S14B (VOC)	***B***	***B***	***B***	***B*** (before the test)
S15 (RH)	-	0.46 - 6.97	-	Strong resonance over most of the frequency range

5.11.3.4 Surge voltage immunity ("thunder"), IEC 801-5 DP

The final electrical test was a simulated strike of lightning. The test was carried out according to IEC 801-5 with the exception of the generator performance data. The surge voltage generator used, instead of conforming with IEC 801-5, conformed with the national Swedish standard SS 436 15 03. The source impedance used was 40 ohm.

The test consisted of the application of five positive and five negative pulses to each sensor. During these tests the sensors remained connected to their power supplies operating in their respective functional modes. Functional tests were performed on the sensors before, during and after the test with results being presented in table 5.34 below. As a result of this final test three more sensors (S2, S4 and S15) were irrevocably damaged. The manufacturer of S4, however, cautioned that tests according to 4.4.1.2 - 4.4.1.4 and all of 4.4.3 would be outside the tolerable range of this sensor.

When the characteristic curves of the surviving sensors were to be recaptured it turned out that yet another sensor (S11) had been permanently changed and was no longer useable. Thus as a final result of all the envionmental testing there was a total of three surviving sensors.

Table 5.34. Results from the surge voltage immunity test, "thunder" (IEC 801-5 DP).
Level: 3 *Amplitude: 2 kV*

Sensor	Output signal (V)		Comments
	Before	After	(***B*** = broken sensor)
S1 (VOC)	8.25	8.60	OK
S2 (VOC)	-0.01	***B***	***B*** (during the test)
S3 (VOC)	***B***	***B***	***B*** (before the test)
S4 (VOC)	0.80	***B***	***B*** (during the test)
S5 (CO_2)	***B***	***B***	***B*** (before the test)
S6 (CO_2)	***B***	***B***	***B*** (before the test)
S7 (RH)	3.58	3.58	OK
S8 (RH)	0.21	0.21	OK
S9 (RH)	***B***	***B***	***B*** (before the test)
S10 RH)	***B***	***B***	***B*** (before the test)
S11 (RH)	4.20	4.16, ***B***	***B*** (during the test)
S12 (RH)	***B***	***B***	***B*** (before the test)
S13 (RH)	***B***	***B***	***B*** (before the test)
S14A (RH)	***B***	***B***	***B*** (before the test)
S14B (VOC)	***B***	***B***	***B*** (before the test)
S15 (RH)	5.00	***B***	***B*** (during the test)

5.11.4 Summarized results from the environmental tests

The outcome of the environmental tests are summarized in diagrams for each individual sensor in the proceeding paragraphs. In these diagrams the output signals have been converted to the unit of the measurand, i.e. AQ, CO_2 and RH. When looking at the output signals of the sensors it must be remembered that all of the sensors are sensitive to the presence of human beings, e.g. members of the testing staff. The diagrams will, however, indicate whether the sensor is operating with a reasonable output (N.B. the scale of the y-axis in the diagrams has been limited and during some of the tests the output of the sensor greatly exceeds this value).

5.11.4.1 VOC-sensors

The climatic tests, i.e. cold, dry heat, damp heat and cyclic changes, seemed not to affect any of the VOC-sensors appreciably. Some changes in output may be due to emissions inside the test chamber or the presence of testing staff. All VOC-sensors also endured the random vibration test without any problems.

The electrical tests proved to be slightly more of a problem. Sensors S3, S4 and S5 were affected during the transient bursts whereas sensor S1 was not affected at all. Electrostatic discharges left all of the VOC-sensors unaffected with the possible exception of S3. Radiated electromagnetic fields, on the other hand, caused very severe interference with sensors S1 and S2 and quite strong interference with sensor S4. Sensor S3 was not influenced but on the other hand this sensor was probably broken after one of the previous tests (the sensor seemed not to respond to anything at all). The final "thunder" test proved to be too much for sensors S2 and S4 (the manufacturer of S4 had cautioned in advance that this type of test was outside the tolerable level of the sensor). Sensors S1, S4 and S14 were the sensors with the best characteristic curves for control purposes and sensor S1 was the sensor that best endured the environmental tests.

Output of VOC-sensors during environmental tests

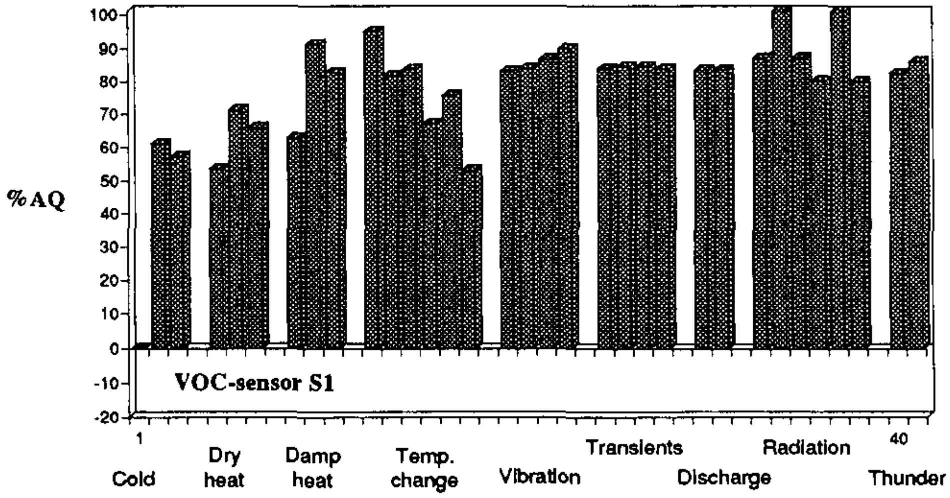


Figure 5.25. The output signal of VOC-sensor S1 during the environmental tests.

Output of VOC-sensors during environmental tests

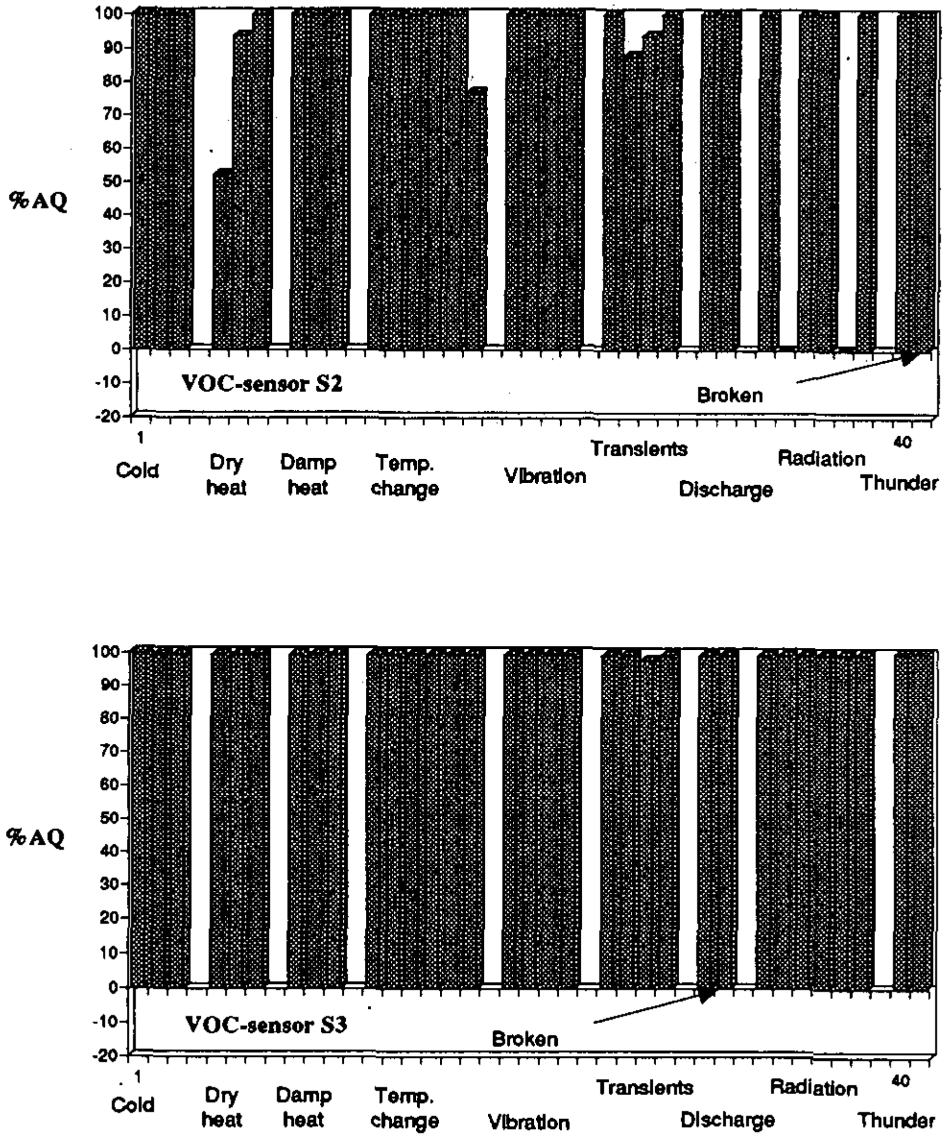
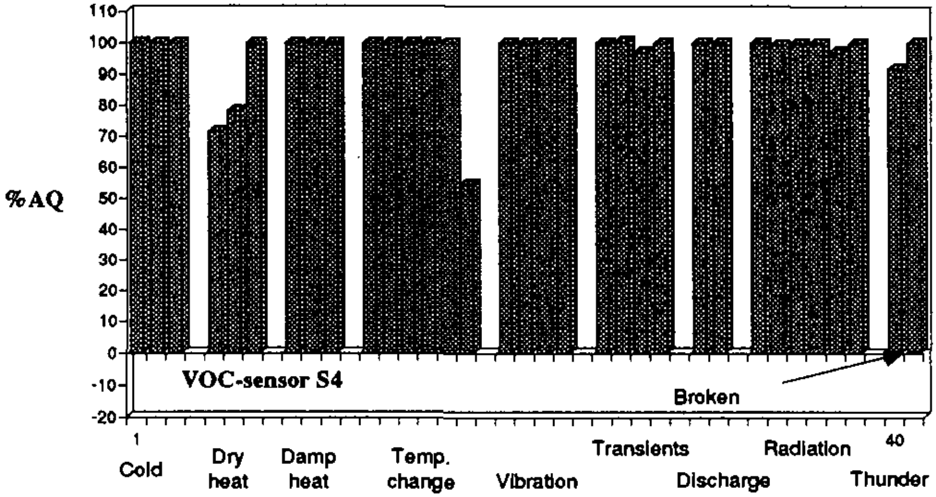


Figure 5.26. The output signals of VOC-sensors S2 and S3 during the environmental tests.

Output of VOC-sensors during environmental tests



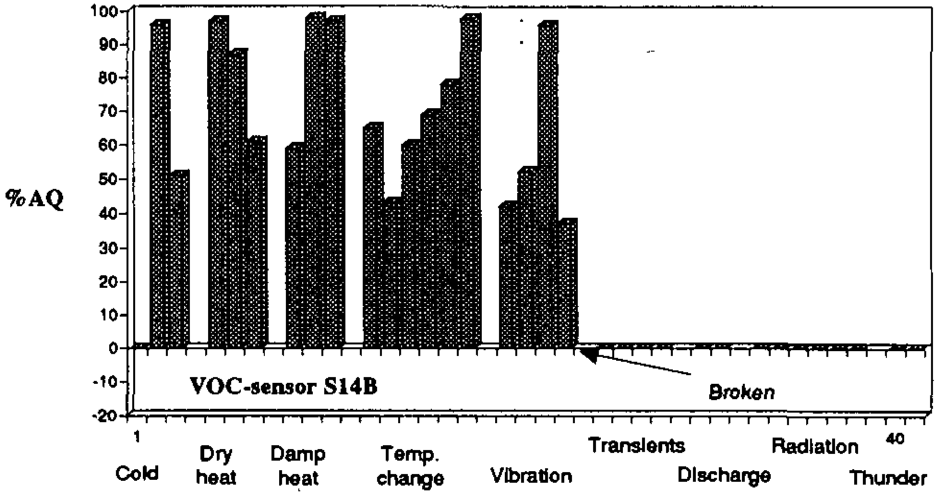


Figure 5.27. The output signals of VOC-sensors S4 and S14B during the environmental tests.

5.11.4.2 Carbon dioxide sensors

Except for the possible influence by the presence of testing staff tests with cold and dry heat had little or no effect on the carbon dioxide sensors. The test with damp heat did not affect sensor S5 whereas sensor S6, as it seems, was permanently influenced by this test. The output increased dramatically during the test and never recovered back to its normal value. According to the manufacturer of S6 this test is outside the specifications of the sensor. During cyclic temperature changes the outputs of both sensors seem to follow the temperature variations. S5 is less influenced than S6 even though results from the cross-sensitivity tests would predict the opposite result.

Output of CO_2-sensors during environmental tests

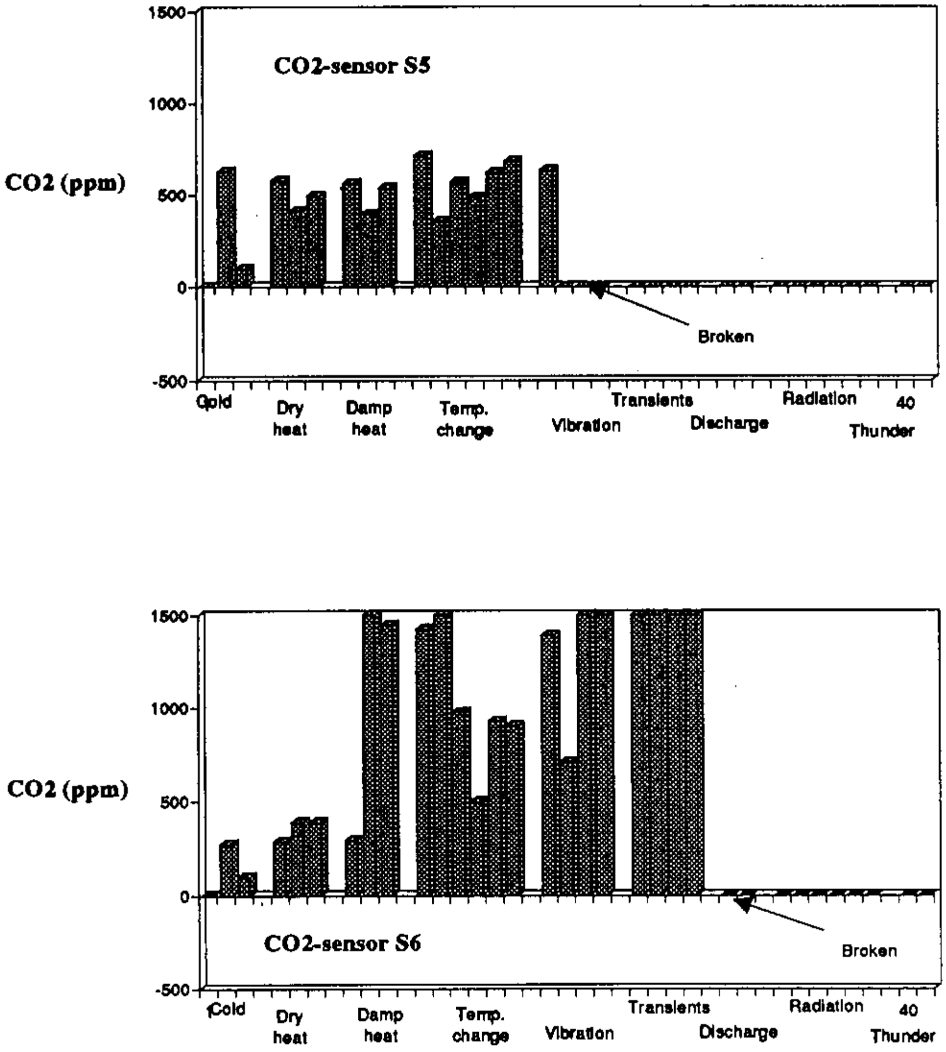


Figure 5.28. The output signals of carbon dioxide sensors S5 and S6 during the environmental tests.

Random vibration caused sensor S5 to fail due to a broken capacitor. On sensor S6 a plastic cover over the LED display fell off but the operation of the sensor was unaffected. The first of the electrical tests, i.e. conducted transient bursts, proved to be too much for the remaining carbon dioxide sensor. During this test the sensor changed its output from 10.3 V to 40 V and then slowly ceased to function altogether.

5.11.4.3 Humidity sensors

Exposure to cold caused no problems for any of the humidity sensors. The relative humidity is directly influenced by the temperature and indeed all humidity sensors, except for S10, lowered their outputs during the dry heat test. S10 indicated a value around 76 % while the other sensors indicated 10-30 %. S10 also showed a substantial temperature dependence during the cross-sensitivity tests (S10 measures absolute humidity but the result is recalculated to an RH output).

Even the damp heat test was no problem for any sensor except S10, which again was greatly influenced. Measurements were taken after the humidity had changed back to the ambient level and S10 still indicated a value of 134 % RH! The final of the climatic tests, the change of temperature test, resulted in the same situation as the previous tests. The only sensor having any problems was sensor S10. Even though the cycle periodic time was more than three hours the sensor response was totally out of phase with the temperature changes. This indicates extreme time lag and/or hysteresis. This also confirms the previous results for the characteristic curve of this sensor.

Sensors S12 and S14 broke during or after the tests with random vibration. The sensor probe of S7 loosened but was easily refastened. All the rest of the sensors were unaffected.

Conducted transient bursts caused sensor S10 to fail permanently. Sensors S11, S13 and S15 were greatly affected during the actual bursts but quickly recovered back to their normal outputs. The output of S15 changed from 1 V to -10 V and that of S13 changed from 3.8 V to 25 V. S7, S8 and S9, on the other hand, showed little influence by the bursts. The electrostatic discharges made the output of sensor S13 drop from 3.4 V to 1.9 V and after the test it never recovered again. Sensor S9 also failed after this test while sensors S7, S8, S11 and S15 showed no signs of distress what so ever.

Electromagnetic interference greatly influenced the outputs of all sensors in some frequency range or ranges. The only sensor to graduate from this test with honours was sensor S7. In the frequency range 25-200 MHz it showed no signs of interference at all and only in the range 200-240 MHz a moderate influence was detected. All other sensors displayed extreme levels of interference. During the final "thunder" test yet another sensor, S15, failed never to recover again.

After the tests were concluded the manufacturer of S11 claims to have solved the problem of electromagnetic interference. For this purpose a special plug is fitted to the input connector of the sensor.

Output of humidity sensors during environmental tests

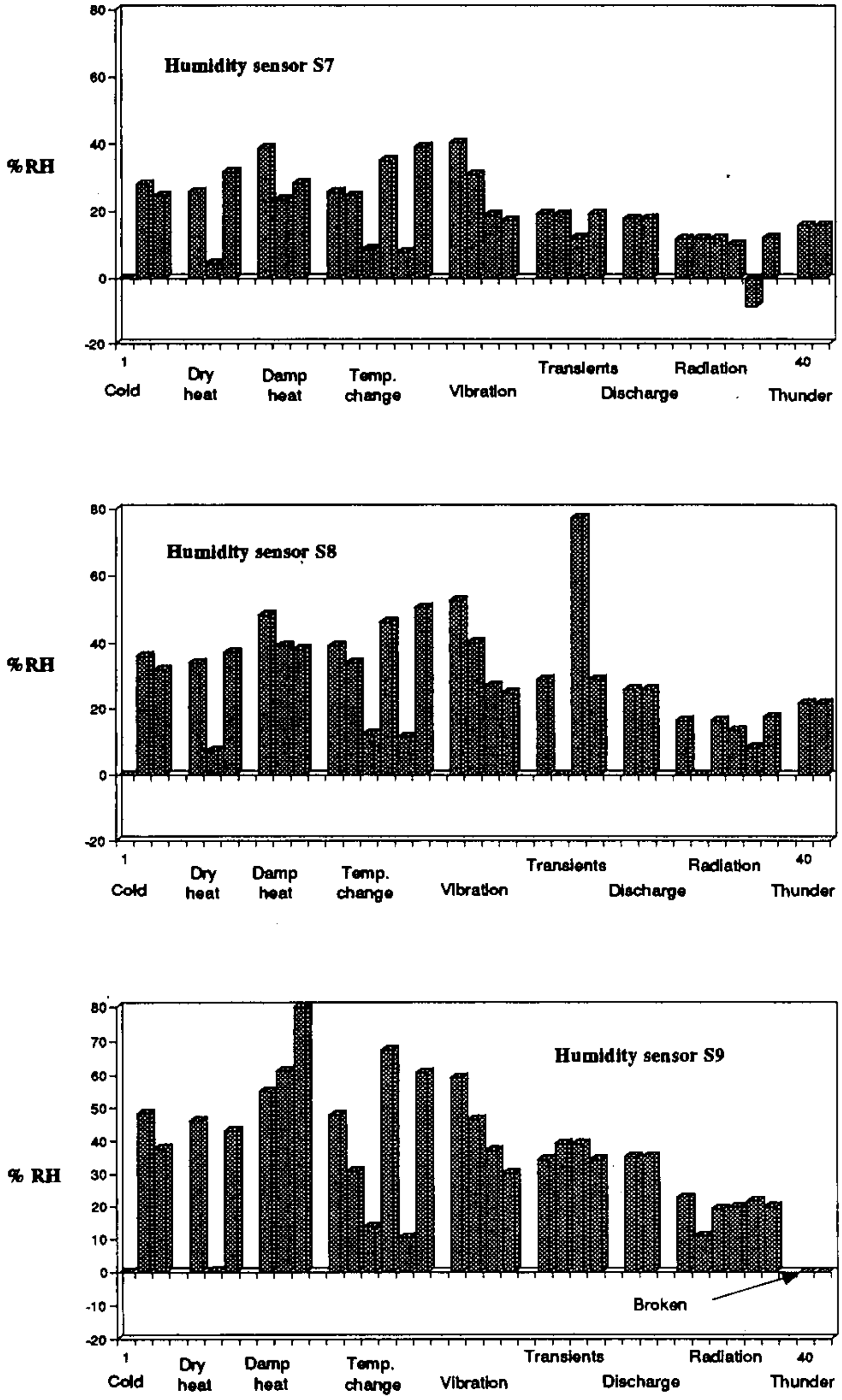
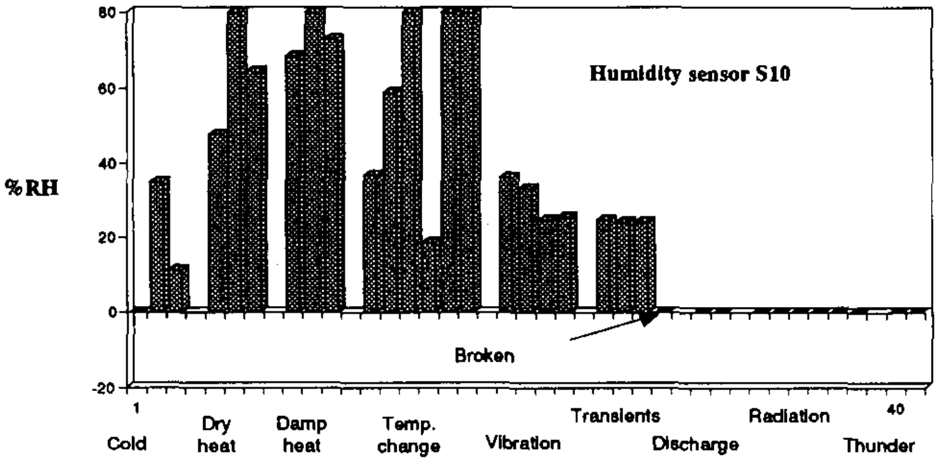
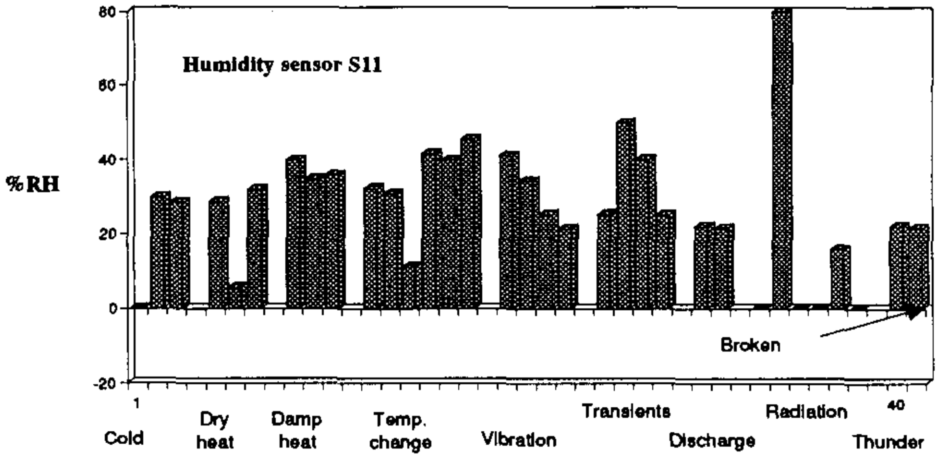


Figure 5.29. The output signals of humidity sensors S7, S8 and S9 during the environmental tests.

Output of humidity sensors during environmental tests





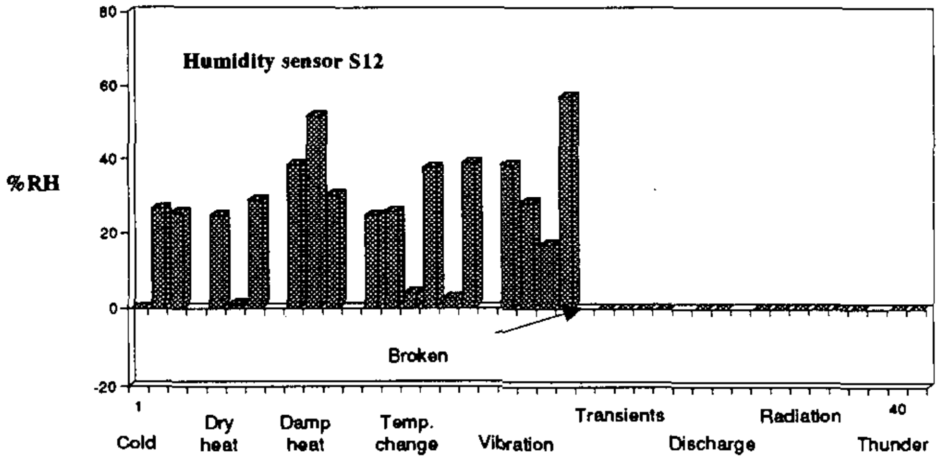


Figure 5.30. The output signals of humidity sensors S10, S11 and S12 during the environmental tests.

Output of humidity sensors during environmental tests

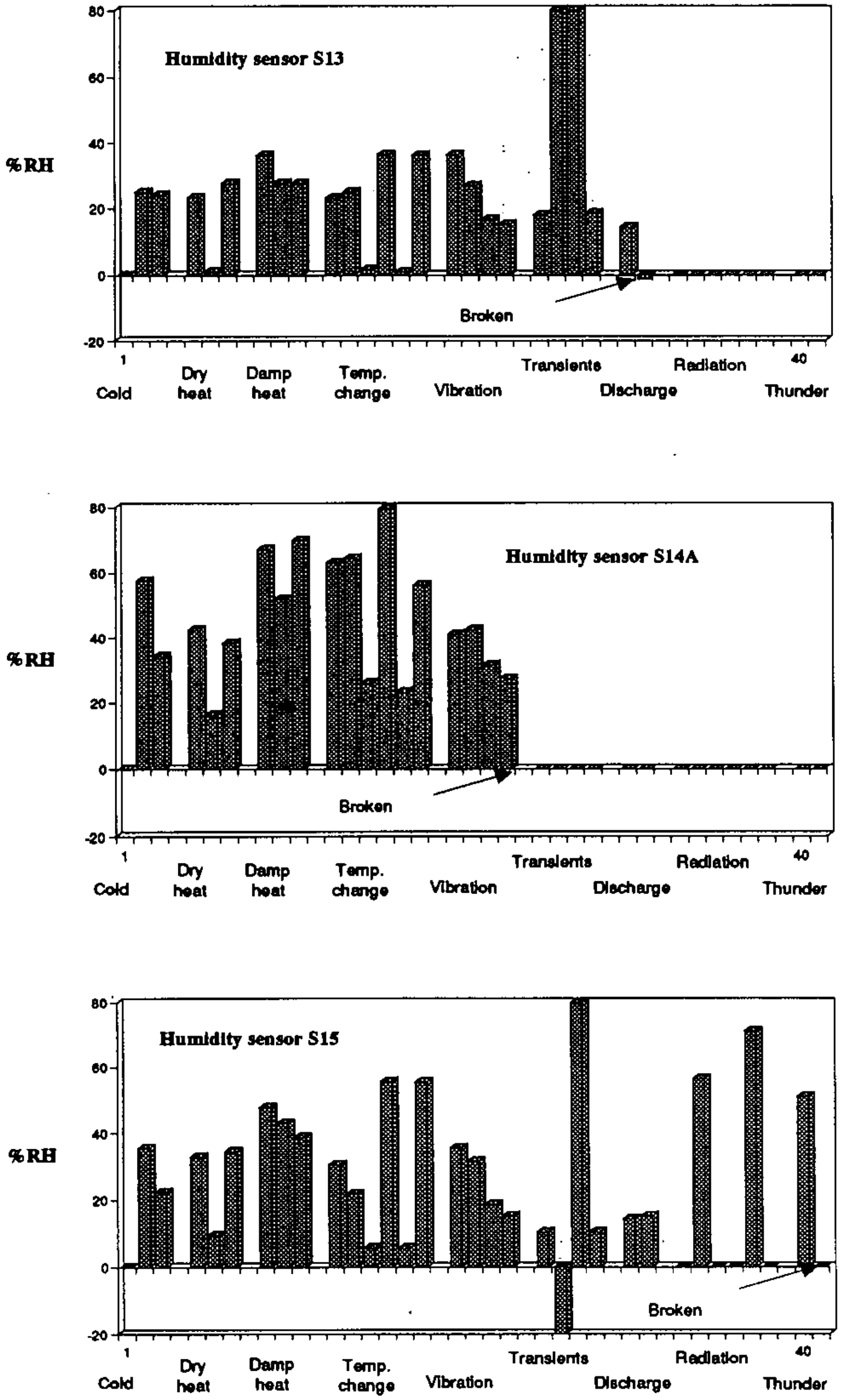


Figure 5.31. The output signals of humidity sensors S13, S14A and S15 during the environmental tests.

5.12 Final test

The outputs of the sensors were checked in accordance with table 4.1 in chapter 4.3. Only three sensors survived the environmental tests (S1, S7 and S8). The VOC-sensor S1 was only checked as to whether it was working or not after the test program. The humidity sensors S7 and S8 were thoroughly evaluated in accordance with the test program and their respective characteristic curves are presented i figures 5.32-5.33. As a comparison the original characteristic curves of the new sensors are also included (dashed lines).

Characteristic curve for S7 RH before and after environmental tests

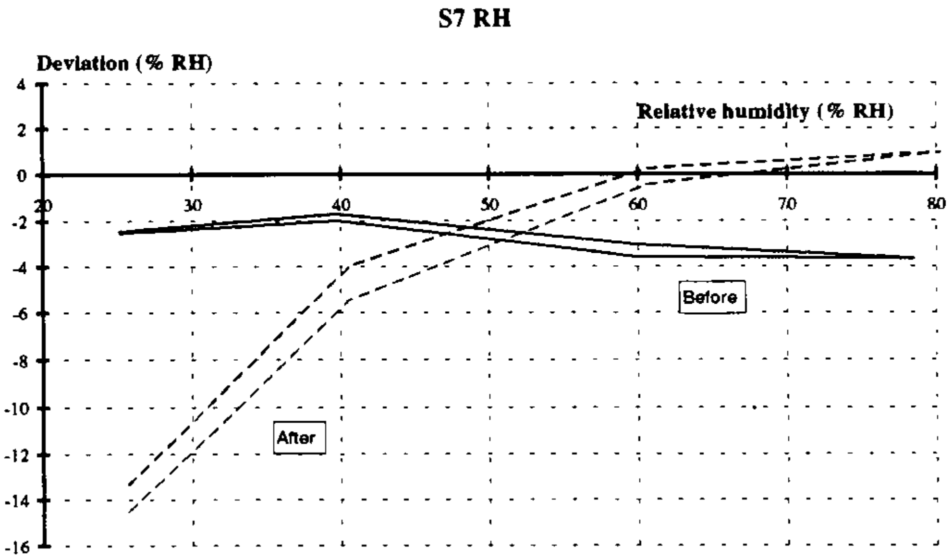


Figure 5.32. The characteristic curve of sensor S7 before and after the environmental test program (continous and dashed curves respectively).

Sensor S7 has passed the environmental test program with honours. This sensor retains its quality concerning a low level of hysteresis. There is, however, an increased linearity error and most importantly the characteristic curve has shifted considerably in the lower humidity range, possibly due to some sort of zero point off-set voltage.

Characteristic curve for S8 RH before and after environmental tests

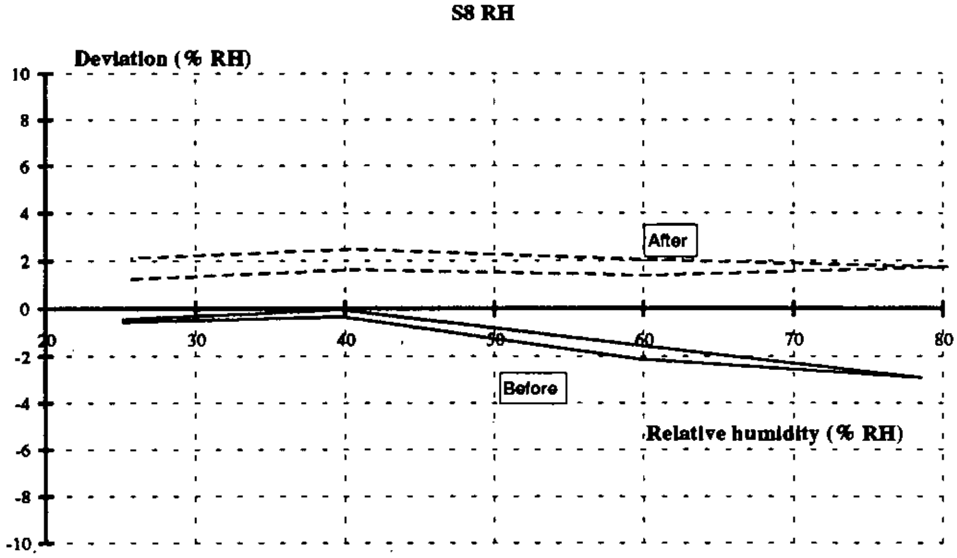


Figure 5.33. The characteristic curve of sensor S8 before and after the environmental test program (continous and dashed curves respectively).

From the diagram in figure 5.33 it is clearly seen that sensor S8 has faired extremely well during the the environmental test program. There is only a slight shift of a few percent RH of the entire curve and performance, in terms of linearity and hysteresis, is still excellent.

5.13 Field testing of DCV sensors

To evaluate the effect of time and exposure to real world operating conditions two sets of sensors, identical to those evaluated in the laboratory test program, were installed in two different office buildings. One site of installation was a conference room at the department of energy technology, SP, Borås. The other site of installation was a cell type office room in an office building in Malmö.

The test procedure consisted of the following four main parts,

- performance of new sensors
- a building status control
- exposure to ambient conditions
- renewed performance control

5.13.1 Sampling and preparation

Sampling and preparation was carried out in accordance with the first part of chapter 4.1. The sensors were in most cases delivered by the manufacturers at the same time as the set up of sensors used in the laboratory test program. Since the process of gathering enough sensors for the test program turned out to be an extremely drawn out procedure delivery dates of the sensors varied substantially. This is indicated in table 5.35, where delivery dates of the sensors are stated. Comments concerning the state of the sensors when unpacked are also given in this table.

Table 5.35. Delivery dates and appearance of sensors on arrival at SP.

Sensor no.	Date of arrival	Comments	Date of arrival	Comments
S1 (VOC)	891016	4 sensors, OK	-	-
S2 (VOC)	891207	4 sensors, OK	-	-
S3 (VOC)	891127	4 sensors, OK	-	-
S4 (VOC)	891130	Only 2 sensors, OK	-	-
S5 (CO_2)	891103	4 sensors, OK	-	-
S6 (CO_2)	900327	Only 2 sensors, OK	-	-
S7 (RH)	891130	2 sensors, OK	900307	2 sensors, OK
S8 (RH)	891130	2 sensors, OK	900307	2 sensors, OK
S9 (RH)	900126	4 sensors, OK	-	-
S10 RH)	891207	4 sensors, OK	-	-
S11 (RH)	890703	4 sensors, OK	-	-
S12 (RH)	891122	4 sensors, OK	-	-
S13 (RH)	891122	4 sensors, OK	-	-
S14A (RH)	900608	4 sensors, OK	-	-
S14B (VOC)	900608	4 sensors, OK	-	-
S15 (RH)	900702	3 sensors	900723	1 sensor

5.13.2 Performance of new sensors

The performance characteristics of the sensors were determined in accordance with chapter 4.3 prior to their installation in the chosen office buildings. The results from these measurements will not be presented in this report but in 5.13.5 the deviations between initial calibrations and the results after 11 months of exposure to office atmospheres are displayed in diagrams.

5.13.3 A building status control

Prior to mounting the sensors to be tested, the building was checked concerning the type of activities, ventilation, and the opinion of the staff regarding air quality. The method used to check the ventilation system is described in reference 2, "Functional control of ventilation installations", prepared by ASS (the National Board of Occupational Safety and Health), SP (the Swedish National Testing Institute), and the factory inspectorates of Sweden.

The conference room at the department of energy technology, SP, is located centrally inside the building and is entirely without windows. Air quality is deemed satisfactory by most people. During the period of investigation the ordinary CAV-type ventilation system was replaced by a DCV-system, which could be controlled by a selection of CO_2-, VOC- or humidity sensors. Flow rates, air tightness of ducts and walls and the operation of the control system were all checked before the beginning of the test. Cleaning of the premises is performed on a weekly basis.

The cell type office rooms in Malmö were thoroughly investigated before installation of the sensors. Each office has its own VAV-controller (regulated by the room temperature) and a fresh air supply normally ranging between 50 - 60 dm^3/s during office hours. The supply air system operates with outside air only. This air is well filtered and supplied at a constant temperature of +17 °C. Despite a sophisicated ventilation system and well proven building materials people have been constantly complaining about the the quality of the indoor climate. Numerous air tests have not provided any conclusive information as to the real nature of the air quality problems in this building.

5.13.4 Exposure to ambient conditions

The sensors were installed in the conference room in Borås and in the office room in Malmö during January 1991. Indoor temperatures have ranged between 20 - 25 °C and the relative humidity between 20 - 50 % RH. After a period of eleven months the sensors were returned to the laboratory for a renewed performance control.

5.13.5 Renewed performance control

The performance of the sensors was checked again according to chapter 4.3.2 after eleven months of exposure. The results are presented in diagrams below. In the diagrams the initial characteristic curve is represented by a full line whereas the curve after exposure is represented by a dashed line.

5.13.5.1 VOC-sensors

The VOC-sensors were only checked as to whether they were still functioning or not. Results from these checks are shown in table 5.36 below.

Table 5.36. Results of functional checks of the VOC-sensors after the field trials.

Sensor	Sensor location during the field trials		
	Conference room	**Office**	**Calibration room**
S1	OK	OK	OK
S2	OK	OK	OK
S3	OK	OK	OK
S4	OK	- *	- *
S14B	OK	OK	OK

* Only one sensor was delivered for the field tests, and this sensor was installed in the conference room.

5.13.5.2 CO$_2$-sensors

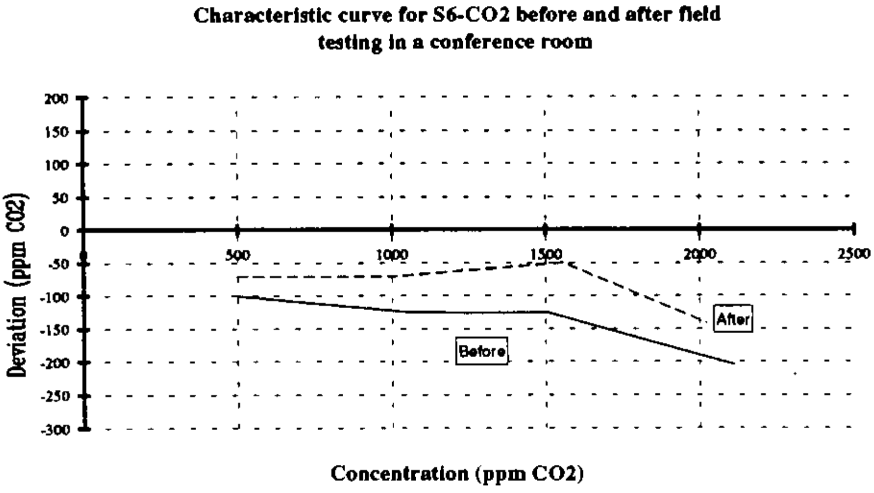
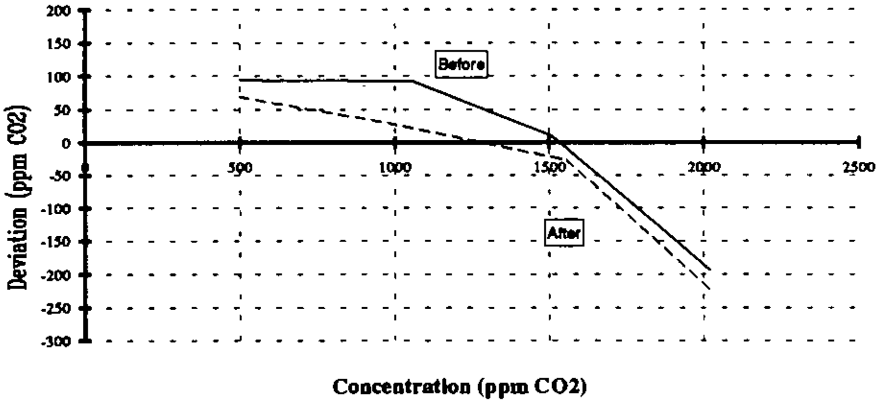
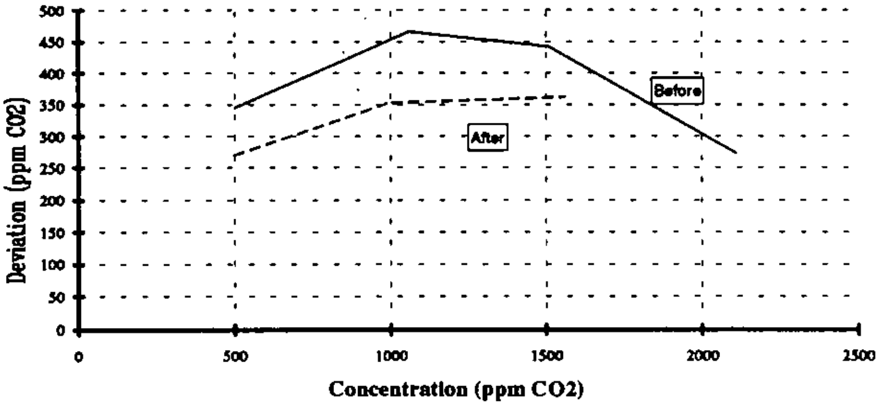


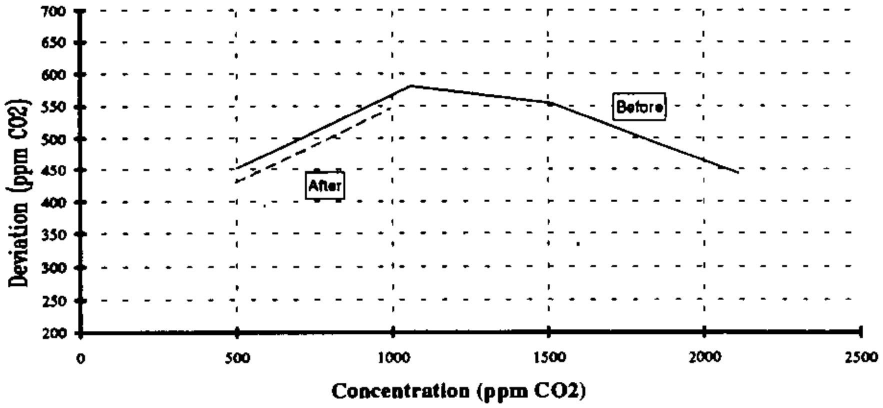
Figure 5.34. The characteristic curve of one sensor of the type S6 before and after 11 months of installation. Only one was delivered and this was installed in a conference room.



Characteristic curve for S5-CO2 before and after field testing in a conference room



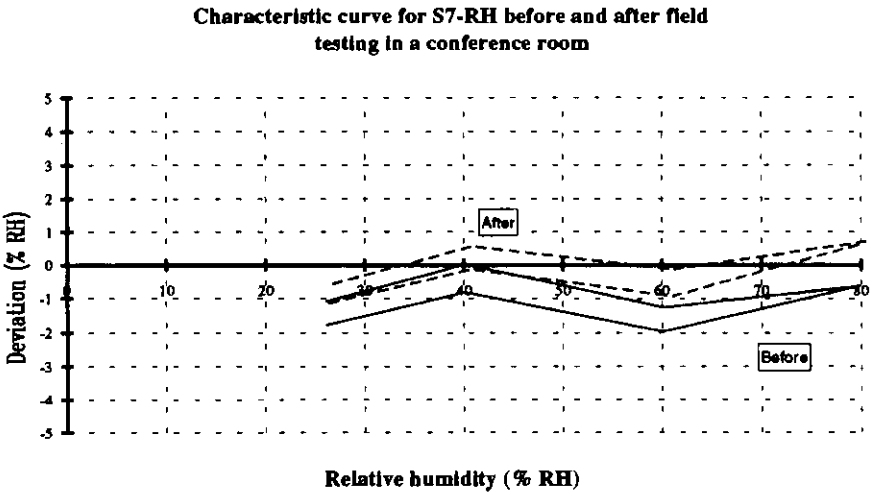
Characteristic curve for S5-CO2 before and after field testing in an office building

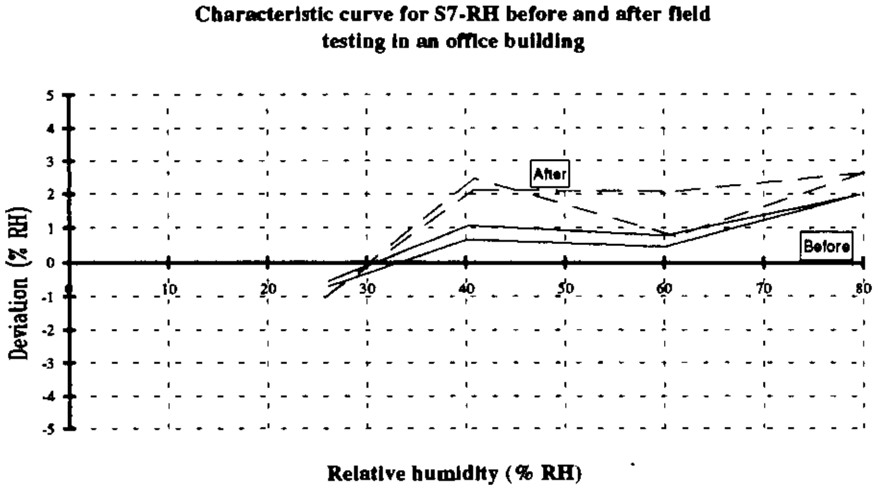


Characteristic curve for S5-CO2 before and after field testing in a calibration room

Figure 5.35. Characteristic curves of sensors of the type S5 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively. The dashed curve disappears outside the format of the bottom diagram.

5.13.5.3 Humidity sensors





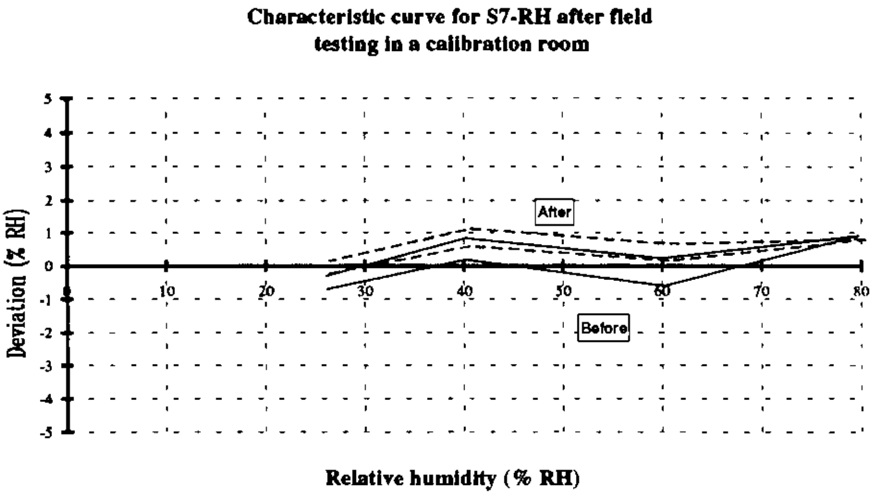
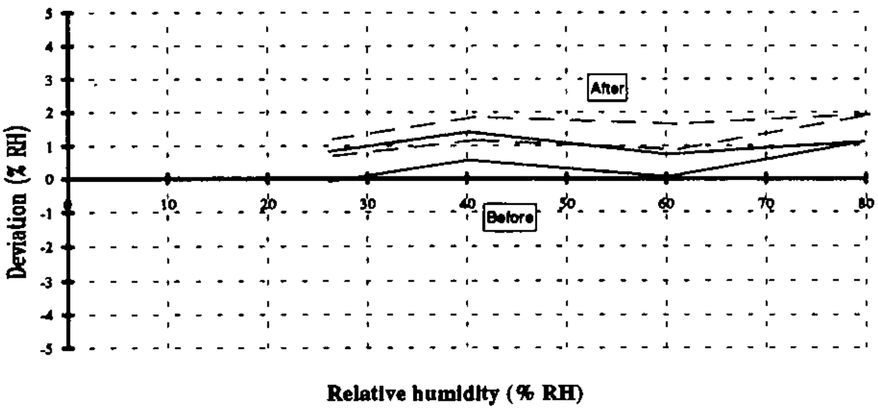
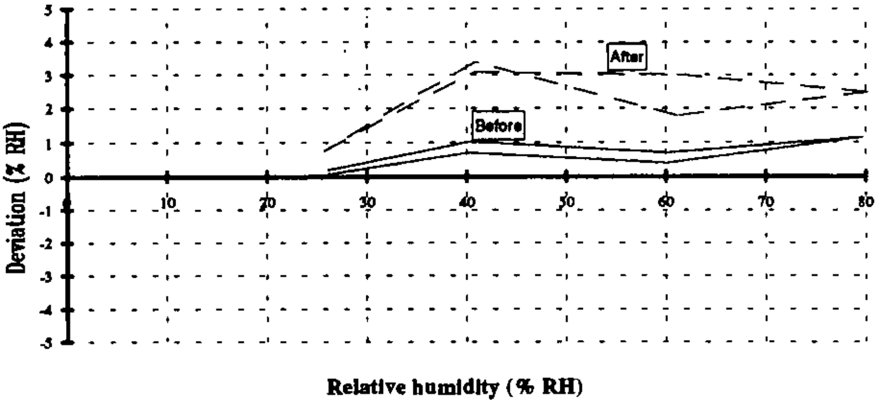


Figure 5.36. Characteristic curves of sensors of the type S7 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.

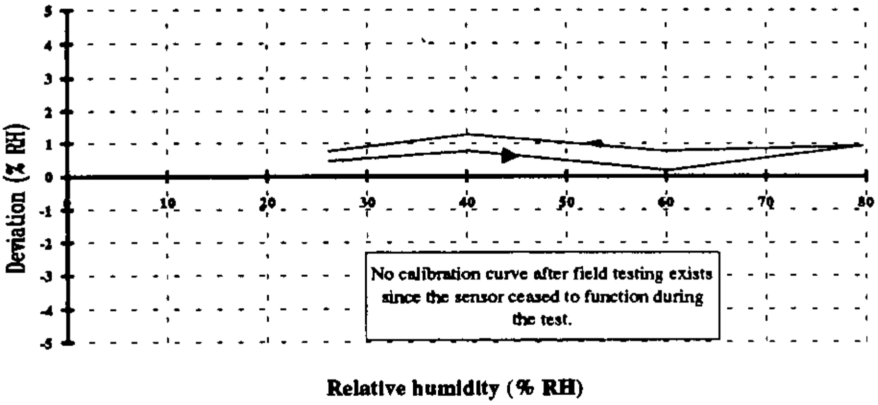
Characteristic curve for S8-RH before and after field testing in a conference room



Characteristic curve for S8-RH before and after field testing in an office building

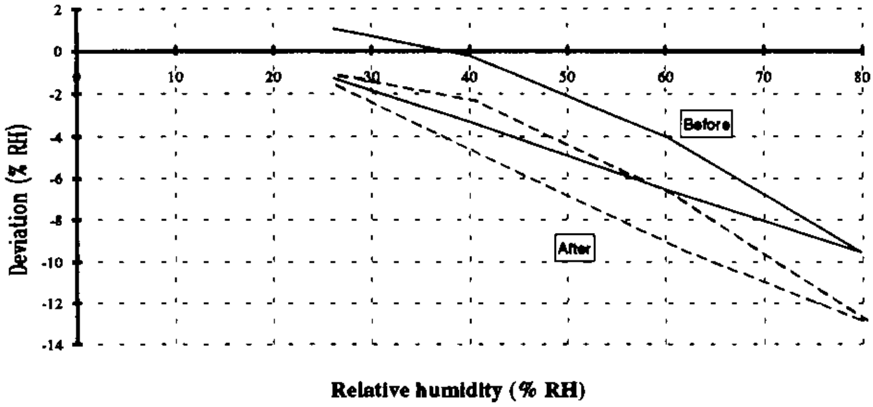


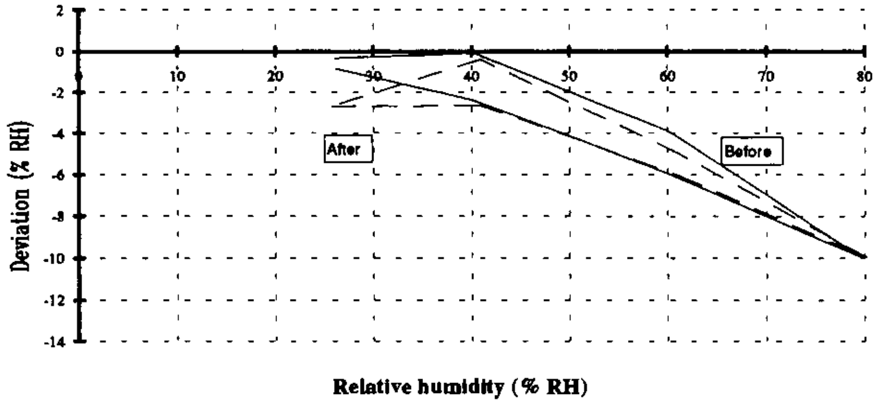
Characteristic curve for S8-RH before field testing in a calibration room



No calibration curve after field testing exists since the sensor ceased to function during the test.

Figure 5.37. Characteristic curves of sensors of the type S8 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.


Characteristic curve for S9-RH before and after field testing in a conference room


Characteristic curve for S9-RH before and after field testing in an office building

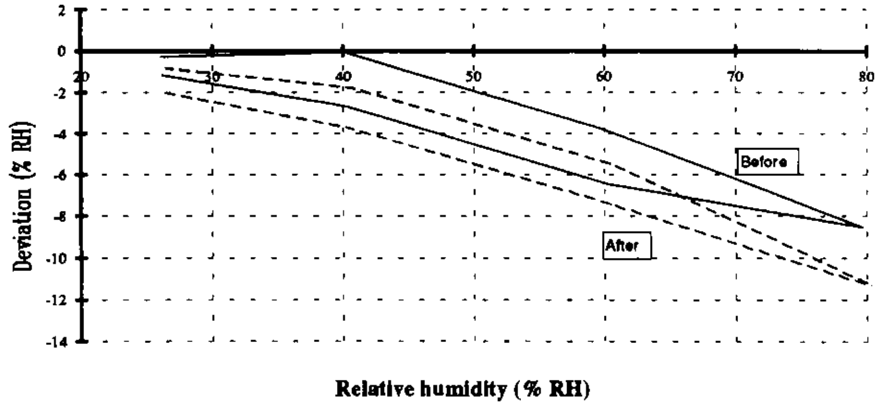
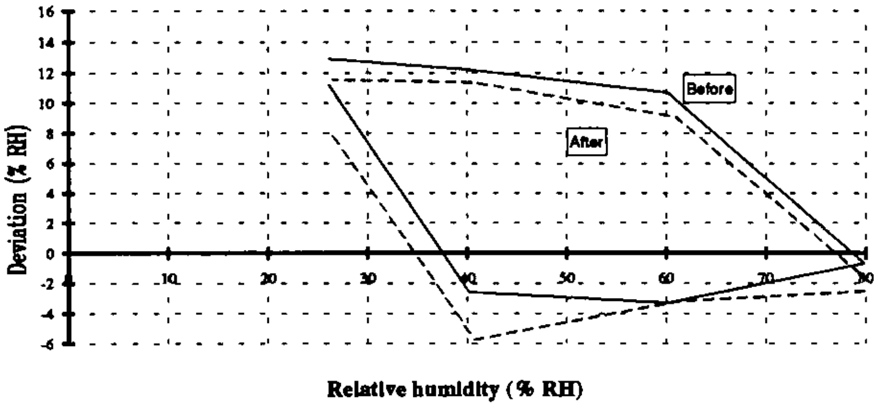
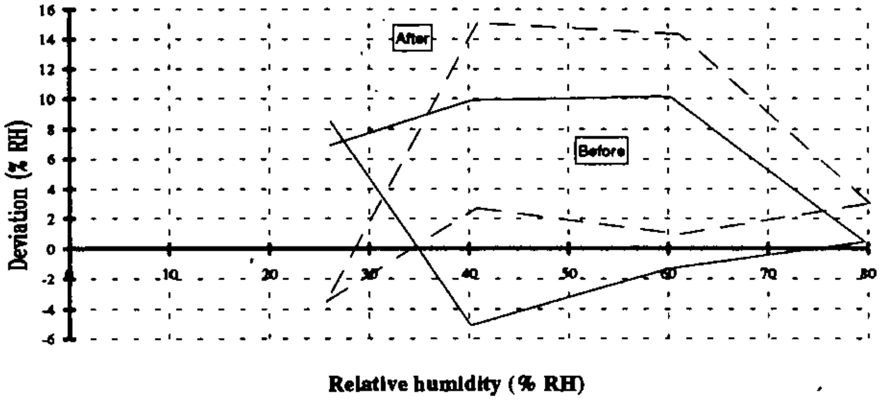

Characteristic curve for S9-RH before and after field testing in a calibration room

Figure 5.38. Characteristic curves of sensors of the type S9 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.

Characteristic curve for S10-RH before and after field testing in a conference room



Characteristic curve for S10-RH before and after field testing in an office building



Characteristic curve for S10-RH before and after field testing in a calibration room

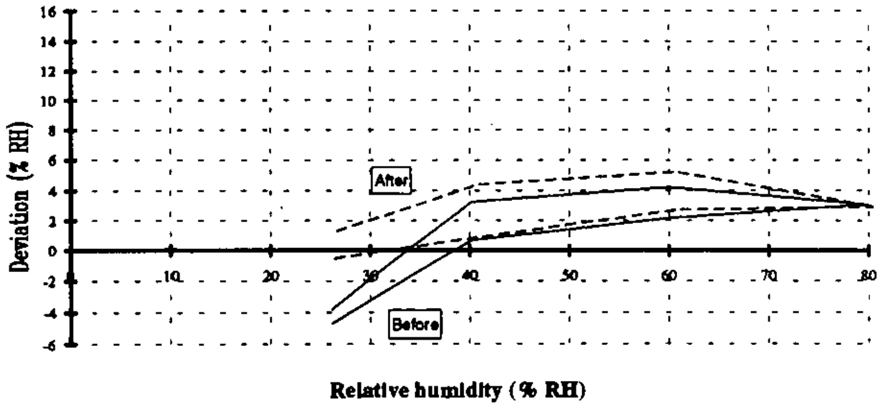
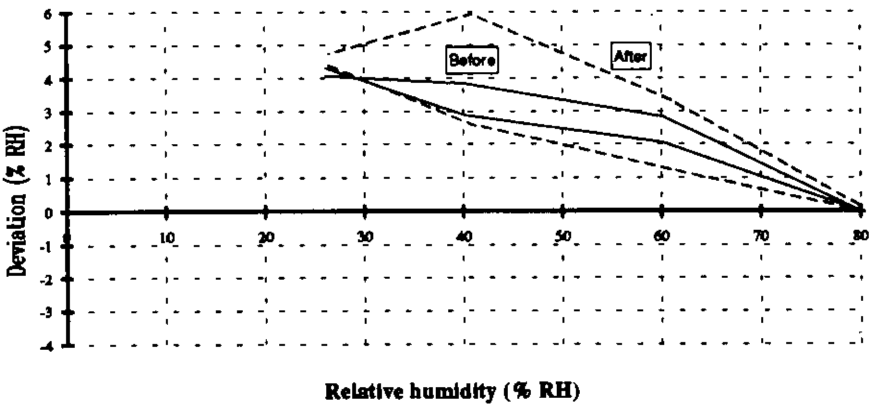
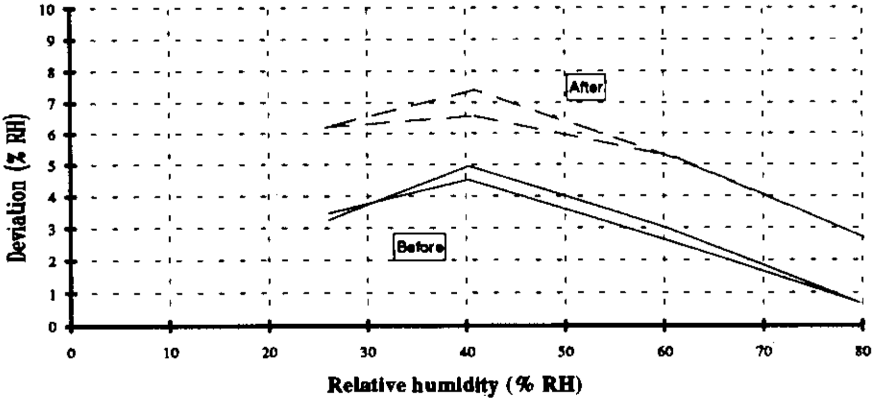


Figure 5.39. Characteristic curves of sensors of the type S10 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.


Characteristic curve for S11-RH before and after field testing in a conference room


Characteristic curve for S11-RH before and after field testing in an office building

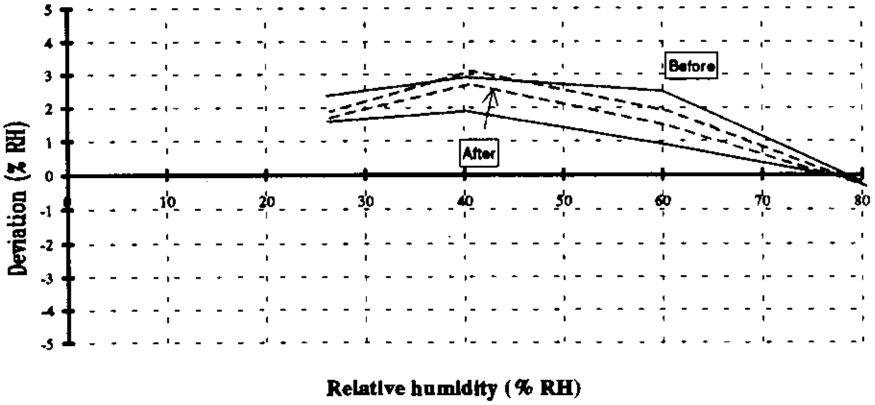
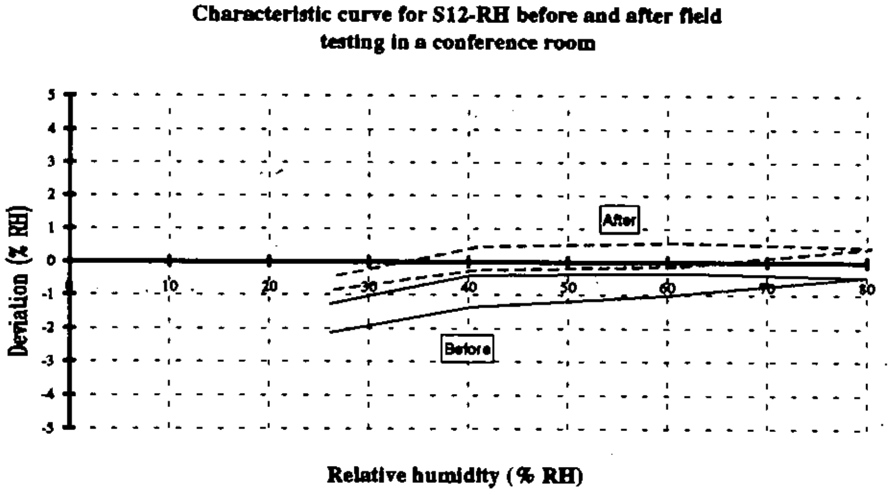
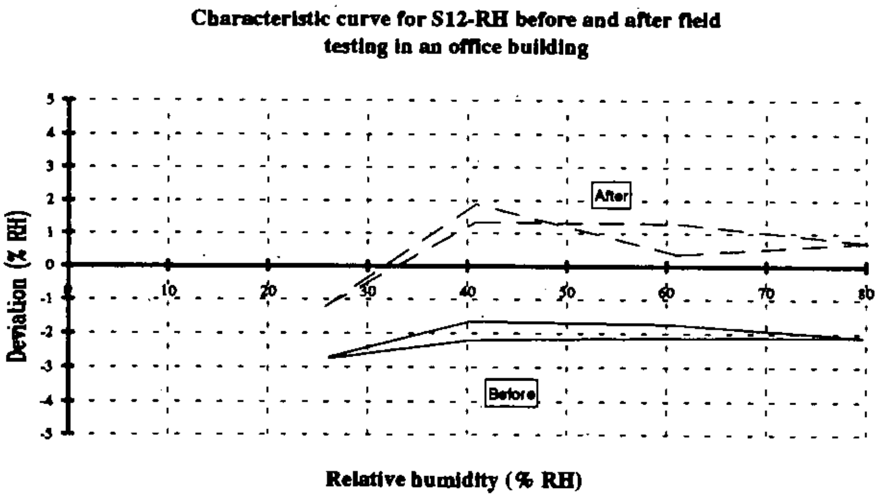

Characteristic curve for S11-RH before and after field testing in a calibration room

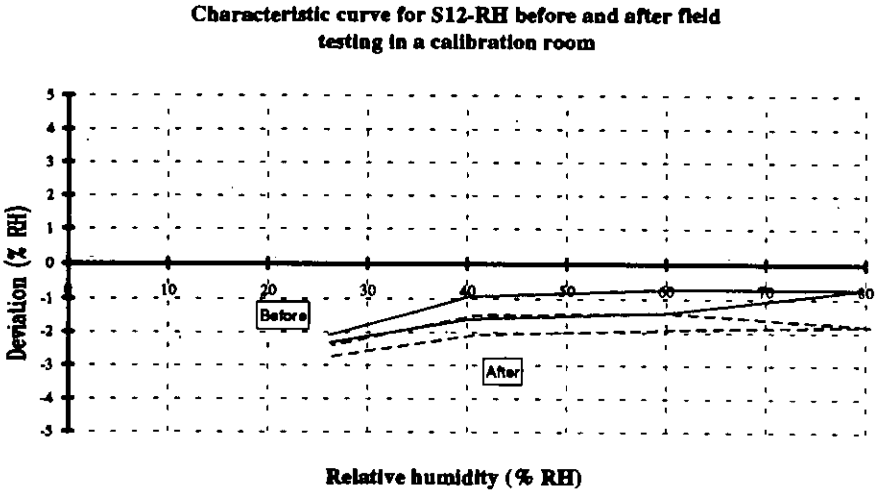
Figure 5.40. Characteristic curves of sensors of the type S11 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.



Characteristic curve for S12-RH before and after field testing in a conference room



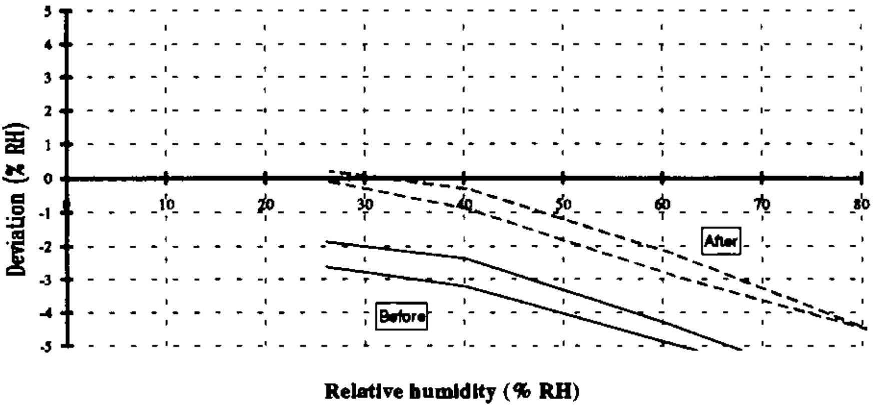
Characteristic curve for S12-RH before and after field testing in an office building



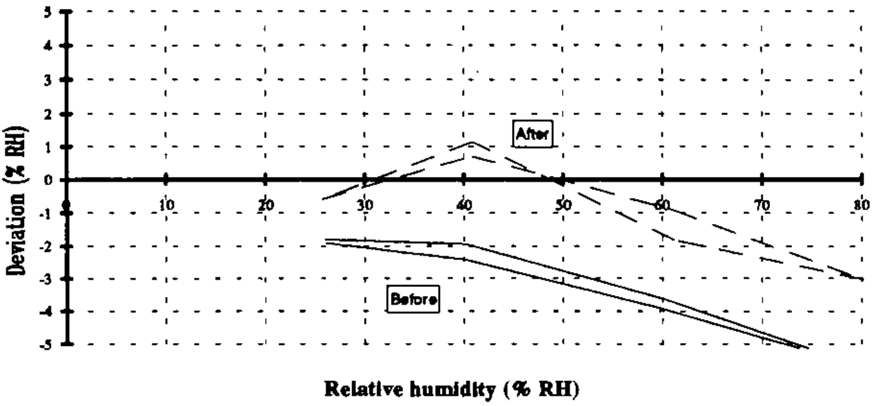
Characteristic curve for S12-RH before and after field testing in a calibration room

Figure 5.41. Characteristic curves of sensors of the type S12 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.

Characteristic curve for S13-RH before and after field testing in a conference room



Characteristic curve for S13-RH before and after field testing in an office building



Characteristic curve for S13-RH before and after field testing in a calibration room

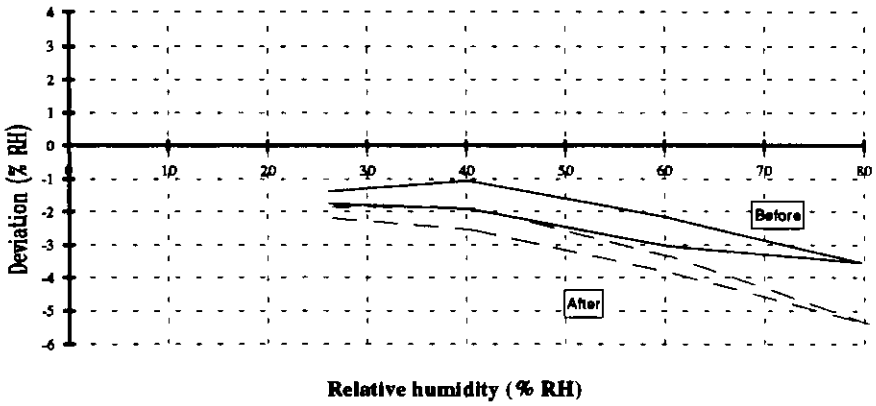
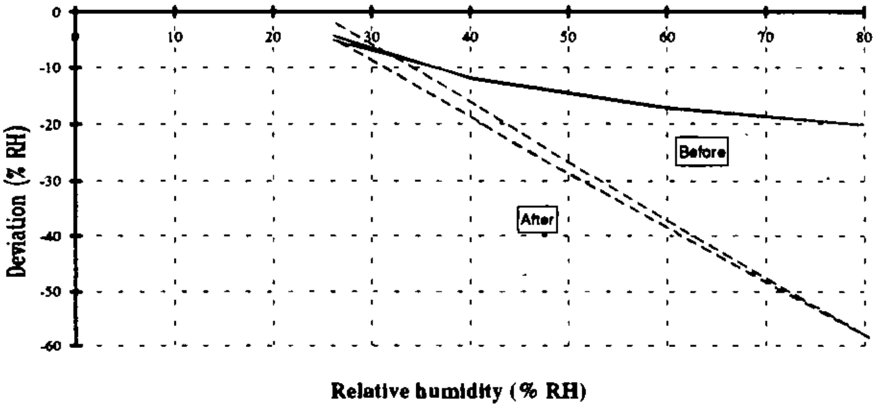
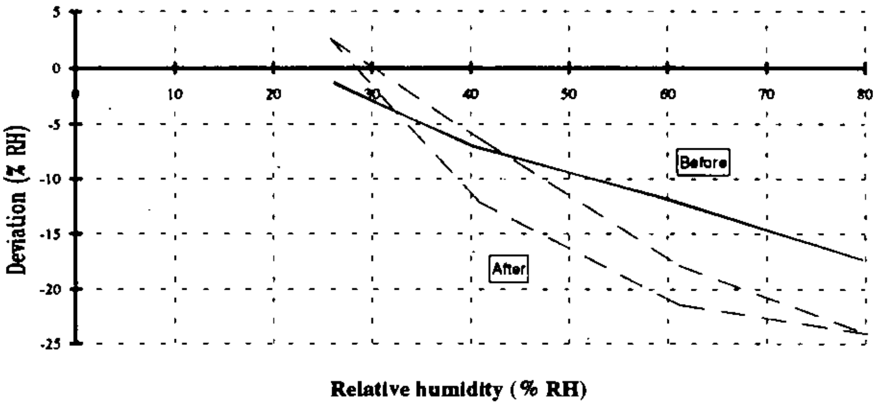


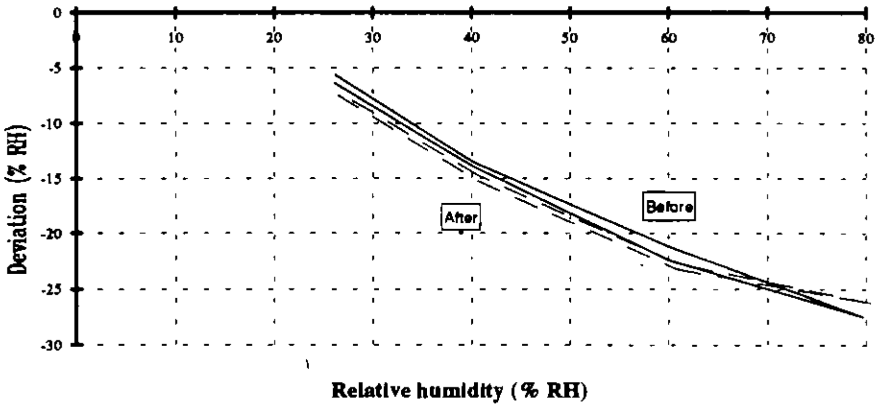
Figure 5.42. Characteristic curves of sensors of the type S13 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.



Characteristic curve for S14-RH before and after field testing in a conference room

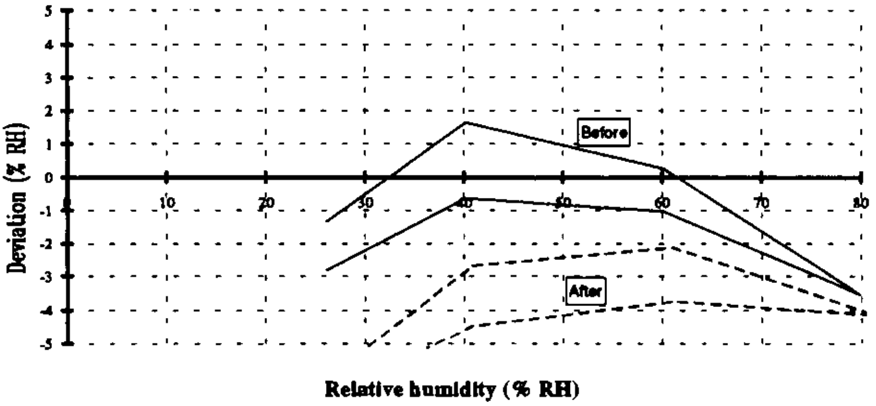


Characteristic curve for S14-RH before and after field testing in an office building

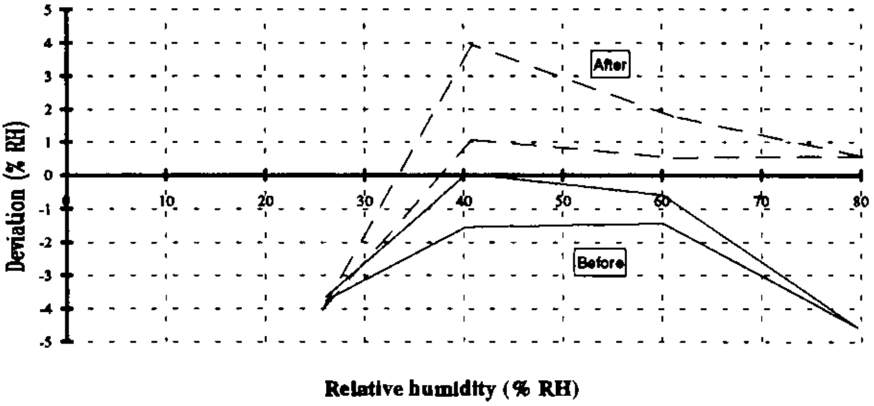


Characteristic curve for S14-RH before and after field testing in a calibration room

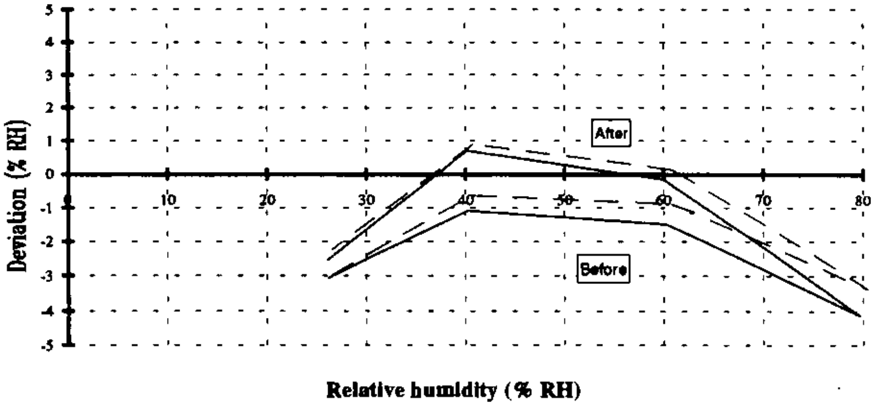
Figure 5.43. Characteristic curves of sensors of the type S14A before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.



Characteristic curve for S15-RH before and after field testing in a conference room



Characteristic curve for S15-RH before and after field testing in an office building



Characteristic curve for S15-RH before and after field testing in a calibration room

Figure 5.44. Characteristic curves of sensors of the type S15 before and after 11 months of installation. One was installed in a conference room, one in an office and one in a calibration room respectively.

6 Comments on the test results

To give an overall impression of the outcome of the test comments on the test results will be given for each of the three categories of sensors in this chapter.

6.1 VOC-sensors

VOC-sensors show a complex behaviour and present numerous pit falls for the designer of a laboratory test method. Since the sensors react to a very large number of substances it is difficult to distinguish between the measurand(s) of interest and external influence factors. Indeed, the unwanted influence factor in one DCV-application may well be the primary measurand in another application.

The problem of defining the VOC-sensor performance characteristics is clearly reflected in the data sheets and other information supplied by the manufacturers. There is in general precious little information concerning the sensor performance in terms of sensitivity, linearity, warming up time, stability, repeatability, cross-sensitivity, calibration procedures etc. The manufacturer of the sensing elements, on the other hand, provided ample information concerning most aspects of interest for the end user of the product. Deeming from the results of the tests the actual lay-out of the electronic circuitry supporting the sensing element has a major influence on the operation of the sensor and it is therefore not possible to use the information concerning the sensing element directly on a comlete sensor/controller unit.

6.1.1 Warming up time

The warming up times of these sensors are directly dependent on the time the power supply has been disconnected. This is clearly illustrated in table 5.2 where the manufacturer claims a variation in the warming up time between 12 h and 20 days due to power interrupts between 1 h and 3 days.

6.1.2 Sensor characteristic curve

Sensors S1 and S14B show a linear dependence of the output signal as a function of VOC-concentration. These sensors could provide proportional ventilation flowrate control bearing in mind the problem with pollution of the outside air. As shown in figure 6.1 the sensors will respond to e.g. exhaust fumes from cars. These fumes may enter a building through the outside air inlets. In this way the controller can be induced to increase the outside air flowrate, thus aggraving the problem instead of providing a remedy.

Sensor S4 has a very unlinear response with regard to the VOC-cocktail, and will probably operate more or less as an on-off regulator with this type of low concentration gas mixture. On the other hand, S4 shows a very good response concerning tobacco smoke.

The remaining two sensors, S2 and S3, hardly react to anything at all and will therefore be of little use for the purpose of controlling ventilation rates. Even tobacco smoke has little influence on these two sensors. After the tests were concluded the manufacturer of sensor S3 has announced that the production of this sensor will be discontinued.

As mentioned previously a special problem with the use of an open calibration system is that the quality of the outdoor air is beyond the control of the experimenter. Figure 6.1 clearly illustrates this problem. In connection with the determination of the characteristic curves of the VOC-sensors the supply air to the test set up is being fed with a constant level of 3.5 mg/m^3 of toluene. Initially the outputs of the sensors are constant but at a specific time, which corresponds to the end of the working day, the indicated air quality deteriorates. This is the result of people starting their cars to go home. This phenomenon, illustrated in figure 6.1, is also one of the reasons why warming up time, repeatability, stability, rise time etc. could not easily be measured for the VOC-sensors. Figure 6.1 is only included to illustrate the problem of using an open calibration system at times when the quality of the ambient air changes. The individual sensors are therefore not identified.

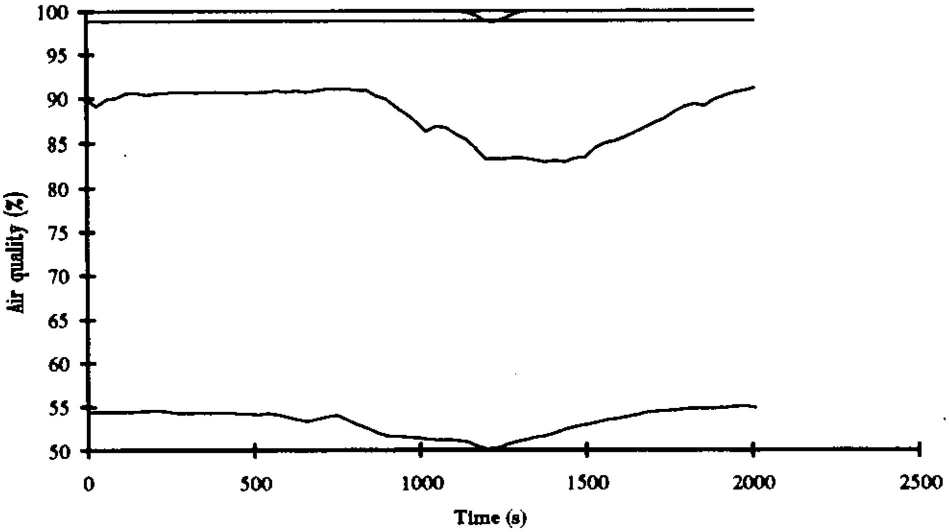


Figure 6.1. Output signals in terms of "percentage air quality" for sensors S1 - S4 and S14B as a function of time. The VOC-level was aimed at 3.5 mg/m^3 but the background level changes after 800 s.

6.1.3 Cross-sensitivity

Apart from sensors S2 and S3, which hardly respond to anything at all, all of the VOC-sensors have relatively high cross-sentitivities to a number of influence quantities. Normal variations in supply voltage will provide a change in output of the same order of magnitude as ordinary variations of VOC-concentration for sensors S1 and S4 whereas S14B is relatively unaffected by the supply voltage. This applies to frequency changes as well but on a much smaller scale.

Temperature affects all sensors to some extent and S4 to a great extent. Indeed this sensor operates more like a thermometer than as an AQ-sensor. This is also the case for humidity changes. Seasonal humidity variations will change the output of the AQ-sensors by more than the entire span of VOC variations would. In this respect sensor S14, however, has the benefit of an included humidity sensor. This makes it possible to distinguish between changes in humidity and changes in VOC-concentration. The influence of air pressure and CO_2 could not be tested since an open system had to be used for these sensors.

The manufacturer of sensor S1 is the only manufacturer to provide any information concerning cross-sensitivity. The data sheet in table 3.1 also indicates a sizeable dependence of the output due to temperature and humidity variations. On the other hand there seems to be no influence at all on the sensor output signal when the composition of the VOC-cocktail is varied, provided that the total conentration remains the same.

6.1.4 Tobacco smoke

Cigarette smoke made all of the VOC-sensors react, as indeed they should, smoke being one of the primary measurands for these sensors. In the presence of tobacco smoke S1, S4 and S14B behaved as could be expected, and these sensors would be possible to use for the control of air quality in an environment where smoking is expected. Sensor S3 gave a very small response and S2 hardly gave any sign of life at all. These two sensors would therefore be difficult to employ for any type of indoor AQ-control.

6.1.5 Environmental tests

Sensor S1 was the only VOC-sensor to survive the entire environmental test program. Two of the sensors, S2 and S4, did not cope with the final surge voltage immunity test ("thunder") whereas S14 broke during the test with random vibration. Since S3 has had almost the same output most of the time it is unclear at which stage of the test program it actually ceased to function. It was, however, considered inoperable after the electric discharge test. Looking at the diagrams in chapter 5.11.4.1 it is readily seen how the VOC-sensors act as thermometers and humidity sensors during the low and high temperature and damp heat tests.

6.1.6 Field trials

Due to the time consuming and problematic process of calibrating the VOC-sensors, these were only given a rough check-up after the field trials. All VOC-sensors seemed to be functioning properly and reacted in a similar manner after the field trials. The check-up could, for instance, be executed by a member of staff breathing on the sensor.

6.2 CO_2-sensors

CO_2-sensors have been used succesfully in numerous practical installations. Unfortunately only two manufacturers finally participated in the test program. Both of these sensors are accompanied by data sheets containing most of the required information. Remaining questions were answered promptly by the manufacturers.

6.2.1 Warming up time

The warming up times of these sensors were not measured directly. According to the manufacturers' data sheets warming up times vary between 30 - 300 s. Experience in using these sensors during the test program indicates that this time, at least for one of the sensors, may be of the order of several days before a correct output signal is obtained.

6.2.2 Sensor characteristic curve

Both CO_2-sensors display good measuring characteristics. Errors due to linearity, hysteresis and repeatability are generally within 20 - 30 ppm. This is also within, or close to, the limits given by the manufacturers. Sensor S5 had a significantly greater linearity deviation than S6 and was calibrated to provide correct values in the normal operating range of 500 - 1200 ppm (error < 20 ppm). The result is a calibration error of -300 ppm at the end of the measuring range (2000 ppm). This, however, is of little consequence for an intended DCV-application.

Rise times were not measured directly. The manufacturers state values in the range of 5 - 10 minutes for the simple time constant $\tau_{0.63}$. These values are fairly high and could lead to control problems in some cases.

6.2.3 Cross-sensitivity

None of the CO_2-sensors is particularly sensitive to the voltage of the power supply. A voltage drop of 10 % would change the output of sensor S6 corresponding to - 11 ppm and that of S5 by even less. This can be considered to be quite acceptable for practical installations. Both sensors are also slightly sensitive to the supply frequency, but for practical purposes the sensitivities are small enough to be neglected.

Temperature has an influence on both sensors. A change in temperature by 10 K will change the outputs equivalent to a change in CO_2-concentration by 50 - 70 ppm.

Humidity has a major influence on sensor S5 and very little effect on S6. Seasonal humidity variations affect the output of S5 corresponding to CO_2-variations of around 100 ppm. Air pressure, on the other hand, seemed to have little or none effect on the sensor outputs.

6.2.4 Tobacco smoke

Contrary to expectations the CO_2-sensors seemed to be influenced also by tobacco smoke. Since cigarette smoke contributes with very little carbon dioxide, and no people were present during the smoke tests, some other constituent in the smoke must affect the sensor. Changes in output were of the order of 100 ppm (see chapter 5.10).

6.2.5 Environmental tests

As was noted during the cross-sensitivity tests, temperature affects both sensors. When temperatures deviate from ordinary room temperatures, this effect is even more pronounced. During the low temperature test (+5 °C), which is within the stated operating range of the sensors, the outputs of both sensors drop from the normal values of 300 - 500 ppm down to an unrealistic value of less than 100 ppm (see chapter 5.11.4.2).

Dry heat does not seem to influence the sensors to quite the same extent. Damp heat, on the other hand, causes S6 to indicate close to 2000 ppm whereas S5 is more or less unaffected. The same situation appears during the temperature change tests.

Vibration caused sensor S5 to fail whereas S6 continued to show extremely high values also during this test. Conducted transient bursts also caused S6 to show extreme values. During the actual pulses the indicated CO_2-level varied between 4000 and 12000 ppm until finally the sensor ceased to function.

6.2.6 Field trials

The CO_2-sensors seem to fare rather well during the field trials. At 1000 ppm the deviation from the original result is between 0 and 100 ppm. Deviations exceeding 50 ppm may, however, prove too much for DCV purposes.

All specimens of sensor S5 retain their typical nonlinear characteristics. Furthermore one of the three field tested sensors has a similarly large calibration error at high CO_2-concentrations as the originally laboratory tested sensor. The other two sensors, on the other hand, are correctly calibrated at high concentrations but show excessively high values at medium conentrations instead.

6.3 Humidity sensors

Measurement of humidity by means of sensors with electric outputs is a time honoured and well proven technology. Experience from this test shows that substantial progress has been made during the past decade concerning most sensor aspects. Most of the sensors performed well and some of the sensors were excellent. Data sheets were adequate for some of the sensors and sadly lacking in vital information in other cases.

After the conclusion of the tests the manufacturer of sensors S9 and S10 announced that both sensors will be replaced by improved designs. S9 has already been replaced and S10 will be replaced during the autumn of 1992.

6.3.1 Warming up time

Sensors S7 and S8 had warming up times shorter than the sampling rate of the measuring system (a few seconds). This is in good agreement with data provided by the manufacturer of these two sensors.

The rest of the sensors had warming up times ranging from 800 - 4000 s, i.e. 0.2 - 1.1 h. Where pertinent data from the manufacturers exist for these sensors agreement is very poor. Measured values may be more than 20 times as large as the values claimed in data sheets.

6.3.2 Sensor characteristic curve

Three sensors, S7, S8 and S12, had errors due linearity, hysteresis and repeatability of less than 1 %RH. The total errors for these sensors were below 2 %RH within the entire tested measuring range. There is also good or reasonable agreement between measured values and claims according to the manufacturers of these sensors. Sensor S15 had a good total accuracy but displayed higher levels of linearity and hysteresis errors than the preceeding sensors.

Sensors S11, S13 and S14A also perform well concerning linearity, hysteresis and repeatability but these sensors all have calibration errors. S11 has a low humidity off-set whereas S13 and S14A suffer from low span factors (-6 and -20 %RH respectively at 80 %RH).

Finally sensors S9 and S10 have high values of the total errors as well as having high values of hysteresis. In the case of sensor S10 the hysteresis effect of one specimen is almost negligible whereas the effect for other specimens can amount to 15 % RH, which is extremely high (see figure 5.39).

All humidity sensors have good or excellent stability properties. Measured values range between 0.1 - 0.6 %RH and all values are well within the claims of the manufacturers.

The rise times of the humidity sensors were measured with a fairly small air velocity past the sensors. Even so sensors S7 and S8 had reasonable rise and fall times of approximately 1 minute (15 s according to the manufacturer). S11, S12, S13 and S14 had unsymmetric rise and fall times ranging from 1 - 3 minutes. S15 had unsymmetric rise and fall times of 4 - 5 minutes and S9 had corresponding times of 8 - 11 minutes. Finally S10 had a rise time of 73 minutes and a fall time of 18 minutes. The rise time of this sensor renders it virtually unusable for most control purposes. According to the manufacturer of S10 the rise time should be less than 3 minutes ($\tau_{0.63}$, no requirement concerning air velocity).

It is interesting to notice how the characteristic behaviour of the different types of sensors is repeated for individual specimens of each particular type. This is readily seen in the diagrams from the field trials presented in 6.3.6 and applies both to linearity and hysteresis deviations. One exception to this rule, however, is sensor S10 in which case one specimen has virtually no hysteresis whereas the other specimens display very high values. Hysteresis is always positive due the sorption/desorption process, i.e. the falling characteristic curve lies above the rising curve.

6.3.3 Cross-sensitivity

None of the humidity sensors was particularly sensitive to variations in the voltage or frequency of the power supply. Only sensor S15 displayed a drop in the output signal when the supply voltage dropped below a threshold value (17 % below the nominal supply voltage).

The temperature influence was insignificant for most sensors but sensor S10 was substantially more affected than the other sensors. This was also the experience during the environmental tests (see 6.3.5).

Air pressure, carbon dioxide, VOC and cigarette smoke had no significant effect on any of the sensors. S9 and S11, however, were very slightly affected by changes in VOC-concentration.

6.3.4 Tobacco smoke

There was no measurable influence of tobacco smoke on any of the humidity sensors.

6.3.5 Environmental tests

Results from environmental tests are summarized in 5.11.4.3. The only sensor to have any problems with the climatic tests was the sensor S10. The plastic strip design suffers from hysteresis and time lag when temperature and/or humidity changes.

The low temperature test did not seem to affect the humidity sensors appreciably although the output of S10 dropped more than that of the other sensors. Dry heat had a sizeable influence on sensor S10. Contrary to the response of the other sensors the output of S10 increased when the temperature increased (an increased temperature causes the relative humidity to decrease). This is due to a hysteresis/time lag effect that makes this sensor remember previous humidity conditions, which may have occurred many hours ago (in this case the low temperature test). This can also be noted during the damp heat test, where measurements are taken after a standard recovery period and the sensor output is still very high. To some extent this also applies to S9. The lag effect of S10 is most notable during the temperature change trials, where the output is constantly out of phase with the actual conditions, even though the temperature is kept constant for three hours during each cycle.

The vibration test made sensors S12 and S14 break. The output signals, however, seemed not to be affected during the actual test for any of the sensors.

Transient bursts did not affect sensors S7, S8 and S9 at all. S10 could indicate down to -30%RH during the pulses but returned back to normal after the test. S8, S11 and S13 were also affected by the transients but to a lesser extent.

Electric discharges put an end to continued operation of sensors S9 and S13. The remaining sensors seemed unaffected. Electromagnetic radiation had a strong influence on all sensors except sensor S7. In particular sensors S11 and S15 suffered from strong interference over broad frequency ranges. Both sensor S11 and sensor S15 were permanently damaged by the surge voltage immunity test.

The only problem common to most of the sensors was a strong influence on the output signals by radiated electromagnetic fields. There is obviously a call for EMC-testing of most types of sensors and indeed some manufacturers have undertaken precautions after the tests to avoid future problems.

6.3.6 Field trials

Most humidity sensors proved reliable and stable over time. The deviation between calibrations before and after exposure to an ordinary indoor environment was generally of the order of 1-2 %RH. One specimen of sensor S8 ceased to function during the field test and one speicmen of sensor S14 changed its output by -40 %RH!

It is interesting to notice that the characteristics of a particular sensor type are retained for individual specimens. It should also be noted that some manufacturers seem to have problems in calibrating their sensors. Notably sensor S14 has a calibration error of -20 %RH at a test condition of 80 %RH and S9 has a corresponding error of -10 %RH. S13 and S15 have calibration errors of approximately -5 %RH.

Sensor S11 indicates correctly at high humidity levels but has a calibration error of about +5 %RH at an ambient humidity of 40 %RH. The rest of the sensors, i.e. S7, S8, S10 and S12, seem to have been correctly calibrated.

7 Conclusion

It has been the ambition of this presentation to illuminate the performance characteristics of sensors used in DCV-systems. Humidity and carbon dioxide controlled systems are nowadays becoming common practice in various types of installations whereas the use of VOC-control still is in its infancy. Aspects of systems design and application are not part of this presentation but will be extensively covered in an IEA source book on DCV-systems.

All sensors endured the climatic tests reasonably well. Mechanical vibration on the other hand caused some of the sensors to break. Radiated electromagnetic fields affected all sensors and the electric shock due to a simulated strike of lightning proved too much for most of the sensors.

The environmental tests were decisive in the respect that only three out of fifteen sensors survived all of the tests. These results notwithstanding, the test conditions were chosen to represent environmentally favourable operating situations that e.g. household electronics may encounter. It must, however, be born in mind that laboratory tests are one thing, and the facts of real world situations may be quite a different cup of tea. Future in situ evaluations will hopefully provide further useful information in this respect.

Long term exposure to office environments proved that most sensors were sufficiently stable for practical purposes. After eleven months only one of the humidity sensors ceased to function. One of the humidity sensors, however, experienced an extreme change in its calibration curve (-40 %RH!)

7.1 VOC-sensors

With one exception manufacturers of VOC-sensors provided precious little information in their data sheets. All VOC-sensors, however, use sensing elements from the same Japanese manufacturer. This manufacturer could provide information in great detail concerning most aspects of interest. Even so performance of the sensor unit seems to be greatly affected by its electronic circuitry, and therefore information concerning the sensing element can not be used directly on the complete sensor unit.

A fundamental problem for this type of sensor is of course that the supplier, or indeed in most cases even the customer, will not know in advance what sort of substances the sensor is asked to react on. Thus calibration, and as a consequence the stated performance characteristics, causes a major problem. This still has to be resolved in a satisfactory manner.

Despite having sensing elements of similar types, originating from the same manufacturer, the mixed gas sensors show a mixed behaviour . Some react strongly on tobacco smoke, some slightly and one hardly at all. On the other hand, all of them seem quite sensitive to humidity. Tests with varying compositions of the chosen VOC-cocktail indicated little difference in the response to the individual components. These sensors have a complex warming up behaviour with the warming up time being strongly dependent on the duration of an interruption of the power supply. After a long interruption the warming up time may be of the order of several weeks or even up to a month.

Exposure to climatic variations show that the VOC-sensors react just as strongly to temperature and humidity changes as to changes in the VOC-concentration.

7.2 Carbon dioxide sensors

Both manufacturers of carbon dioxide sensors provided detailed and reasonably well specified information with regard to the perfomance characteristics of their sensors. A simple time constant ($\tau_{0.63}$) seems to be the preferred metod of presenting the dynamic behaviour of the sensor. Uncertainty, linearity and hysteresis are given in absolute units (ppm), as a percentage of full scale (FS) or as an unspecified percentage.

Carbon dioxide sensors show acceptable performance for control purposes in terms of accuracy with a deviation of less than 30 ppm at a level of 1000 ppm. Sensor calibration and/or adjustment is, however, a time consuming process. This is partly due to fairly long rise times (in the order of 10 minutes). Long rise times also imply a necessity of using heavily damped control loops to avoid instability problems. These sensors are also sensitive to humidity below a threshold carbon dioxide level. Cross-sensitivity to variations in voltage, temperature and tobacco-smoke have also been noted.

7.3 Humidity sensors

The test results indicate that capacitive humidity sensors are well suited for the control of humidity levels in buildings. The combined error of linearity, hysteresis and repeatability is normally below 5% RH at 20 °C. For some of the sensors the combined error is even less than 2 %RH. The cross-sensitivity to variations in the ambient temperature and power supply (voltage and frequency) are acceptable and the cross-sensitivity to hydrocarbons, carbon dioxide and tobacco smoke is negligible. A plastic strip humidity sensor on the other hand proved less suitable due to excessive hysteresis and linearity errors.

Most manufacturers supplied data sheets which were reasonably detailed or could otherwise provide the desired information on request. The method of presentation, however, varies considerably. Rise times may for instance be given as a simple time constant (0-63%), as a time constant plus a lag time, as the 0-90% rise time or as an unspecified rise time. Since the rise time $\tau_{0.90}$ will be more than twice the value of the simple time constant $\tau_{0.63}$ it would be of great benefit to customers, and users of various types of sensors, if manufacturers could agree on the use of specified standards in their presentation of performance characteristics.

The test equipment for humidity sensors has performed according to expectations. The total uncertainty in the determination of dew point temperature is less than 0.18 K and the total uncertainty in the determination of relative humidity varies between 0.5 %RH (at $\varphi = 30$ %) and 1.4 %RH (at $\varphi = 90$ %).

8 References

1. ASHRAE Brochure on psychrometry. ISBN 0-910110-07-7, 1977, ASHRAE, Atlanta, USA.

2. ASS, 1988. Inspection and Performance Checking of Ventilation Systems. (The National Board of Occupational Safety and Health.) Report H23. Solna, Sweden.

3. Bergsten, L, Laaksonen, L, Petersen, B, 1987. A catalogue of environmental test procedures - A demonstration and a discussion of the idea. (The Swedish National Testing & Research Institute.) Technical report SP-rapp 1987:05 and Nordtest Technical report 078. Borås, Sweden.

4. Börjesson, A, Byheden, S, 1991. Environmental tests. (The Swedish National Testing & Research Institute.) Internal assignment report F2 0120, 1991-01-15. Borås, Sweden.

5. IEA Annex 18: Demand controlled ventilating system - State of the art review. (The Swedish Council for Building Research.) Report D9:1990, ISBN 91-540-5169-X. Stockholm, Sweden.

6. Fahlén, P, 1989. Testing of DCV sensors. (The Swedish National Testing & Research Institute.) Project description and test program. 1989-01-19. Borås, Sweden.

7. Fahlén, P, Andersson, H, Ruud, S, 1991. Demand controlled ventilation - Evaluation of commercially available sensors. 12th AIVC Conference, 24-27 September. Ottawa, Canada.

8. Raatschen, W, 1991. Advanced Humidity Controlled Ventilation - Case study. (Dornier GmbH.) January 1991. Fiedrichshafen, Germany.

9. Raatschen, W, 1991. Advanced Humidity Conrol Device for the Prevention of Mould . Proceedings of the 12th AIVC Conference, vol. 2, September 1991, Ottawa, Canada.

10. Raatschen, W, 1992. IEA Annex 18 - Demand Controlled Ventilating Systems - Sensor Market Survey. (The Swedish Council for Building Research.) Report D2:1992, ISBN 91-540-5417-6. Stockholm, Sweden.

11. Till, C E, Handegord, G O, 1961. Proposed humidity standard. (National Research Council.) Research paper no. 134, September 1961. Ottawa, Canada.

12. VDI 3786:4, 1985. Meteorological Measurements Concerning Questions of Air Pollution - Air Humidity. (Verein Deutscher Ingenieure.) July 1985. Dusseldorf, Germany.

Appendix A: Test equipment

Contents

A1 Introduction

Measurement of the humidity content of air is an important part of many assignments related to HVAC-installations and building physics. Since most sensors require frequent check-ups and recalibrations it is of importance to have access to accurate and reliable equipment for such calibrations.

Various methods of calibration are currently being employed by calibration laboratories over the world. For simple check-ups salt solutions may be used with quite acceptable results. When primary calibration facilities are considered the most frequently used methods are

- Thermodynamic dew-point hygrometers
- Thermodynamic wet bulb psychrometers
- Vapour pressure hygrometers
- Gravimetric hygrometers
- Standard atmosphere devices (saturator chambers)

The various alternatives are discussed by e.g. Till and Handegord (ref. A1) and will not be covered further in this report. Suffice it to say that for various reasons, among other things previous experience in using this principle in humidity controlled climate chambers, a standard atmosphere device was chosen as the preferred concept by the department of energy technology at the Swedish National Testing & Research Institute.

Standard atmosphere systems may operate as two-temperature or two-pressure devices. In this case a two-temperature system is used. The principle of operation is outlined in section A3. Using a closed two-chamber system also makes it possible to conduct tests with atmosheres which differ in composition from the ambient air. This could for instance involve changing the carbon dioxide content or adding various hydro carbons while at the same time humidity is being controlled.

The design and construction of the calibrator described in this report was made at the department of energy technology at the Swedish National Testing & Research Institute (SP). In this context we would like to express our gratitude to Mr. Hedlin of the Prairie Regional Station, National Research Council of Canada (NRC), for sharing his experience and some design values from a similar set up operated by NRC. The project presented in this report was jointly financed by SP, the Swedish Council for Building Research and the Swedish Board for Technical Development.

A2 Principle of operation

The humidity calibrator is a closed system, controlled atmosphere, device of the two temperature type. The principle of operation has been extensively described by Till and Handegord (ref. A1). A brief account of the system will be given in this section accompanied by some further elucidations regarding special appplications. The basics are best understood by means of the lay-out diagram in figure A2.1.

The system consists of two tanks with individually controlled temperatures. One tank contains the humidity saturator, and this tank is kept at the desired dew point temperature. The other tank contains the calibration chamber, and this tank is kept at the desired dry bulb temperature. The saturator and calibration chambers are connected by air tight piping and air is circulated continuously between the chambers. By adjustment of the two temperatures and/or the pressure inside the system any desired temperature and humidity condition may be created inside the calibration chamber.

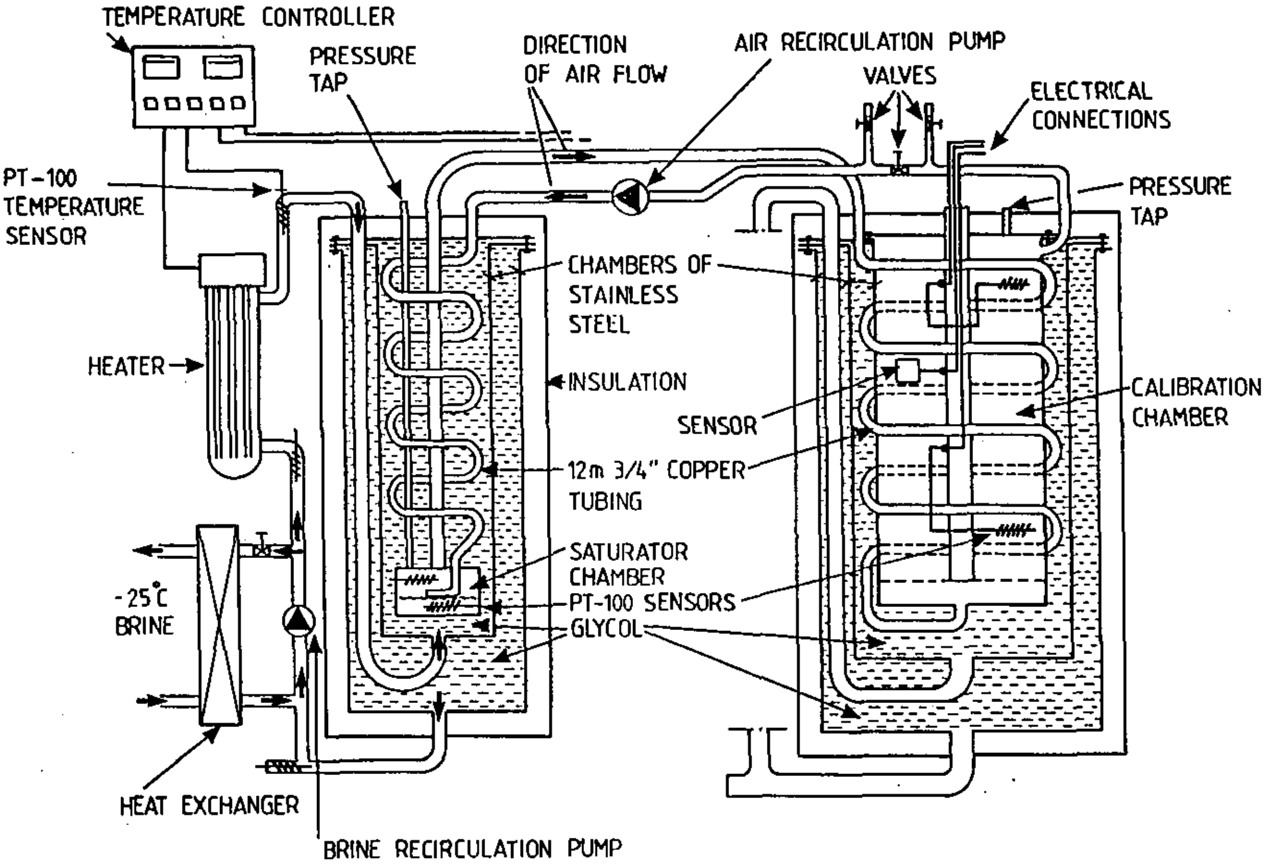


Figure A2.1. A schematic diagram of the two temperature type humidity calibrator.

The saturator

In this tank air is continously circulated over a free surface of water (or ice if the temperature is below 0 °C). When equilibrium conditions have been attained the air is saturated with water vapour at the temperature inside the saturator, t_c (the cold side). This temperature corresponds to the desired dew point temperature and is measured by means of two Pt-100 platinum resistance temperature sensors, one in the liquid phase and one in the vapour phase (see figure A2.2).

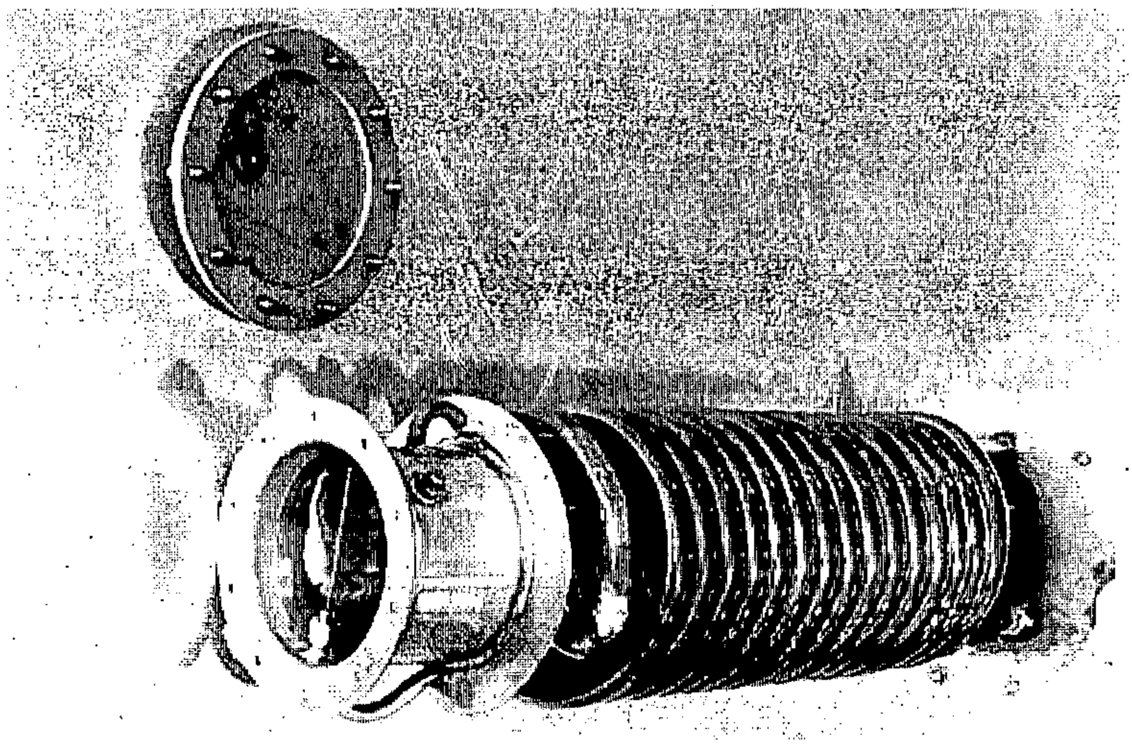


Figure A2.2. A photograph of the saturator unit showing the air heat exchanger coil, the air inlet pipe and the bottom temperature sensor.

Air enters the saturator horizontally close to the water surface. The inlet pipe is tangential with the circumference of the cylindrical chamber, and the outlet pipe is located at the top centre of the chamber. This design creates a vortex action inside the saturator, which enhances mixing of air and vapour while at the same time acting as a centrifugal separator of water droplets. Since the system is closed, after a few passes the air entering the chamber will already have the same moisture content as the saturated state, unless there are other sources or sinks of moisture in the system.

To promote attainment of equilibrium conditions air entering the saturator is first passed through a heat exchanger coil inside the temperature controlled tank. Thus the heat exchange inside the saturator should be miniscule, since air entering the chamber already has the same temperature and moisture content as air leaving the chamber. Therefore any temperature differences should also be miniscule. The temperature, and the temperature difference between the water and vapour phases, can be measured by two temperature sensors while the pressure inside the chamber can be monitored via a pressure tap, which extends through the thermostatic bath.

The saturator chamber is entirely contained within a temperature controlled tank. A cooling agent (a mixture of water and ethylene glycol) enters the tank at the bottom at a carefully controlled inlet temperature. This temperature is regulated by a PID-controller supporting an external electric heater via an SCR-unit. The cooling agent, removing any excess heat from the chamber, flows to the top of the cylindrical tank, where it overflows into a concentric outer jacket. In the outer jacket the cooling agent flows to the bottom, where it is extracted by a pump. The flow in the outer jacket is hence counter current to the flow in the inside tank.

To facilitate a rapid cooling down of the saturator from the initially ambient temperature conditions the cooling agent is passed through a plate type heat exchanger. The primary side of this heat exchanger is cooled by a central cooling system operating at a temperature of -20 to -25 °C. The heat exchanger also provides a base load for the SCR-controlled heater.

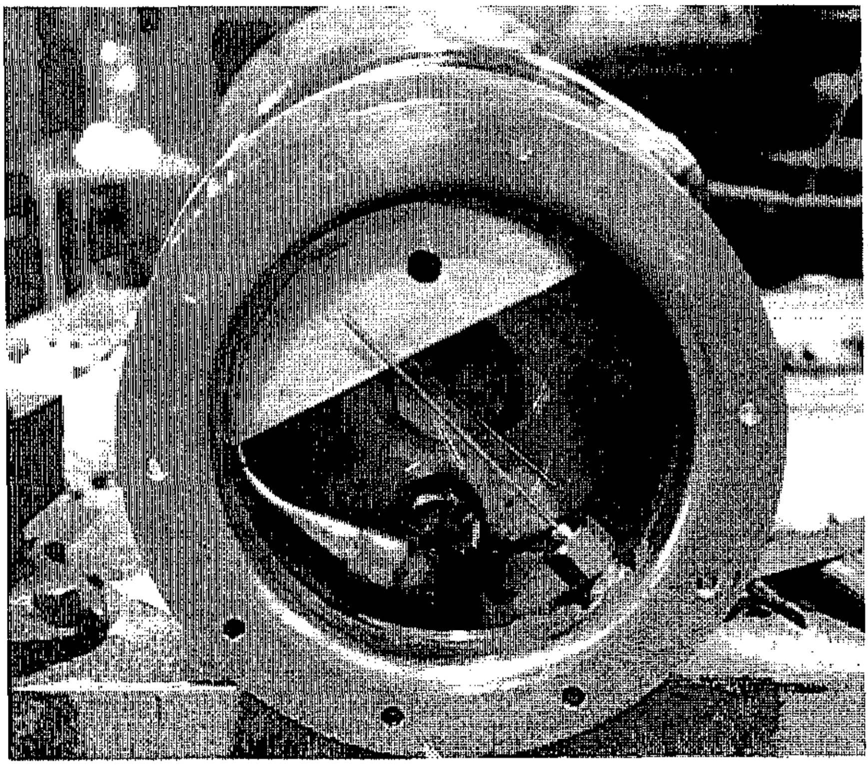


Figure A2.3. A close up of the saturator unit showing the bottom part with the air inlet pipe and the bottom temperature sensor.

The calibration chamber

The calibration chamber consists of a cylindrical tank, which is sufficiently large to make it possible to calibrate up to 10 sensors simultaneously. This tank is fully enclosed inside a thermostatic bath consisting of two concentric cylinders in a fashion similar to that of the saturator. Water enters with a carefully controlled temperature at the bottom of the inner cylinder and flows to the top. After exchanging heat with the calibration chamber the water spills over into the outer shell and is extracted at the bottom by a pump.

The water is cooled by a central cooling system via a plate type heat exchanger. The central cooling system feeds the primary side of the heat exhanger at a constant temperature of +5 °C. Fine tuning of the temperature is then achieved by means of an external electric heater supplied by an SCR-unit.

Air enters the calibration chamber at the bottom and is extracted at the top. Some of the heat dissipated by the sensors will be lost through the walls of the chamber and carried away by the heat transfer medium. On the other hand a substantial part of the heat will be conveyed out of the tank with the conditioned air flow. This heat will have to be removed in the saturator tank but is in general negligible compared to the heat supplied to the air in the heat exchanger coil prior to entering the calibration chamber.

To promote an even temperature distribution, and to avoid stagnation zones, the air enters the chamber through two radial slits. This will induce a certain amount of swirl in the chamber. The spatial temperature difference is checked by measuring the temperature both at the bottom and at the top by means of two platinum resistance thermometers. The temperature in this tank, t_h (the hot side), gives the dry bulb temperature of the calibration atmosphere. The dew point, and thus the moisture content and the vapour pressure, of the air supplied to the calibrating chamber is accurately controlled by the saturator. A knowledge of the two temperatures t_c and t_h together with the total pressure inside the system will also provide values of the relative humidity and wet bulb temperature inside the calibration chamber. The total pressure inside the chamber can also be controlled via connecting valves on the tubing between the hot and cold tanks. The pressure is monitored through a pressure tap on the top of the tank.

Sensors to be calibrated are mounted on a "sword" attached to the lid of the calibration chamber. The "sword" is equipped with gas tight electrical connectors so that the sensors can comunicate with the world outside the tank. The temperature sensors inside the tank are also fixed to the "sword" (see figure A2.5).

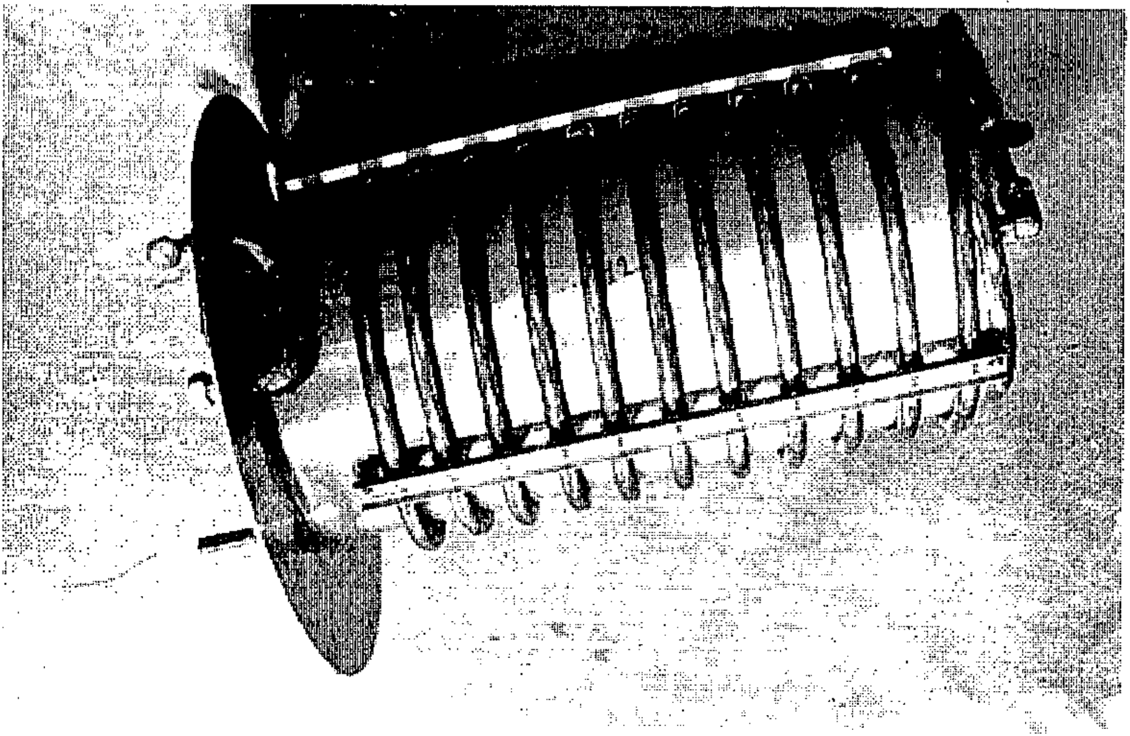


Figure A2.4. A photograph of the calibrating unit showing the air conditioning heat exchanger coil.

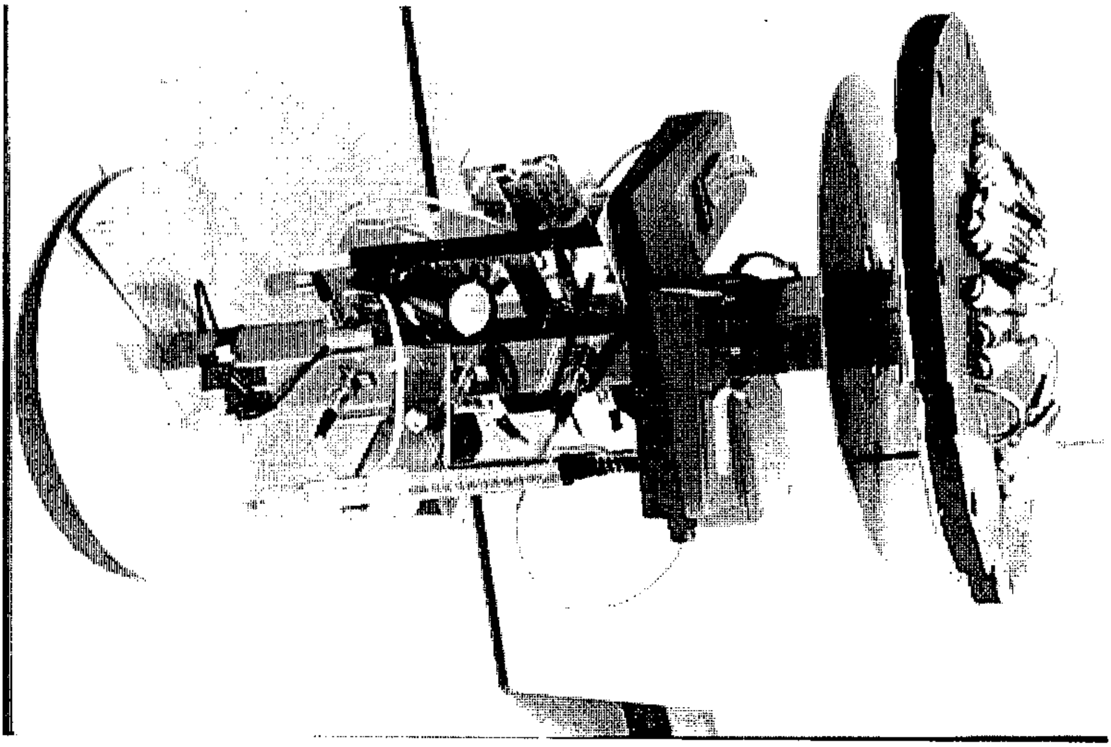


Figure A2.5. A close up of the "sword" with a number of sensors attached. At the bottom the air entrance can be seen while the external electrical connectors and the pressure tap can be seen on the top of the lid.

A2.1 Applications

The design of the calibrator makes it possible to carry out a number of different types of calibrations and investigations using the same set up. In the calibration of humidity sensors the equipment may be used for virtually all types that are currently on the market. In this context the calibrator can be employed for a variety of humidity measurements such as

- Determination of dry bulb temperature
- Determination of dew point temperature
- Determination of relative humidity
- Determination of wet bulb temperature
- Determination of vapour pressure

Other investigations may concern sensors for

- Determination of carbon dioxide concentration
- Determination of VOC concentration

Sensors for both of these quantities are generally sensitive also to the humidity. In particular when calibrating NDIR type carbon dioxide sensors it is imperative to have a minimum back-ground humidity level. Otherwise the vibrational energy levels of the carbon dioxide molecule will not be sufficiently stimulated, and the sensor output will become erratic.The possibility of accurately controlling the humidity level is also of great importance when VOC-sensors are calibrated since many of these sensors are also sensitive to humidity.

A2.2 Determination of dry bulb temperature

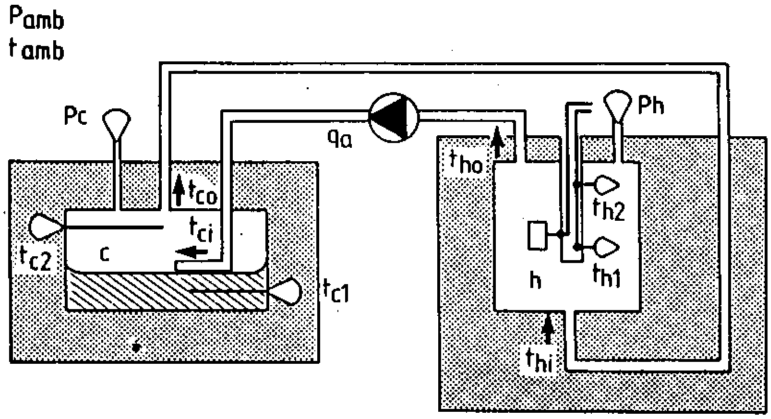


Figure A2.6. Measuring positions in the humidity calibrator.

The dry bulb temperature is measured at two positions in the calibration chamber (see figure A2.6). Temperature measurements are made by means of Pt-100 sensors in accordance with IEC 751. Since both the air and the walls of the chamber are at virtually the same temperature installation effects such as heat conduction in the casing of the sensor, heat exchange by radiation etc will be very small. Self heating effects are minimized by using a low measuring current (1 mA) and use of an accurate DVM (accuracy 1 µV) keeps the error of measurement in order. As only static measurements are considered the dynamic characteristics of the sensors are of interest only in the sense that it must be possible to check the temporal stability of the system.

The accuracy of the dry bulb temperature is not of great importance when calibrating dew point sensors or other sensors reacting to the absolute humidity. On the other hand, when the relative humidity is the measurand being considered, the accuracy of the dry bulb temperature is equally important as the dew point temperature (see A2.4). The design value of the measurement uncertainty is 0.02 K including all sources of error. It is the ambition of the project to keep both spatial and temporal temperature deviations well below 0.05 K. The uncertainty of measurement is further discussed in appendix B.

A2.3 Determination of dew point temperature

The dew point temperature is determined directly by measuring the temperature of the saturator chamber (see figure A2.6). This temperature is measured both in the liquid and the vapour phase by the same type of sensor used to measure the dry bulb temperature. The same type of accuracy is aimed at as that of the dry bulb temperature, i.e. a measurement uncertainty of less than 0.02 K and temporal as well as spatial variations not exceeding 0.05 K.

A2.4 Determination of relative humidity

The relative humidity in the calibration chamber is calculated from the values of the temperature (t_c) and pressure (p_c) in the cold tank together with the temperature (t_h) and pressure (p_h) in the hot tank (see figure A2.6). Assuming that the moisture content (x_c) in the saturator chamber is the same as the moisture content (x_h) in the calibration chamber then

$$x_h = \frac{M_w}{M_a} \bullet \frac{p_{w,h}}{(p_{0,h} - p_{w,h})} = x_c = \frac{M_w}{M_a} \bullet \frac{p_{s,c}}{(p_{0,c} - p_{s,h})} \qquad \text{(eq. A2.1)}$$

Introducing the relative humidity φ equation A2.1 (φ_c=1.0, $p_{s,c}$=$p_{s,h}$) becomes

$$\frac{\varphi_h \bullet p_{s,h}}{(p_{0,h} - \varphi_h p_{s,h})} = \frac{p_{s,c}}{(p_{0,c} - p_{s,h})} \qquad \text{(eq. A2.2)}$$

Solving for φ_h one obtains

$$\varphi_h = \frac{p_{s,c}}{p_{s,h}} \bullet \frac{p_{0,h}}{p_{0,c}} \qquad \text{(eq. A2.3)}$$

By means of the Magnus relation (VDI 3786) the saturated vapour pressures in the two tanks can be expressed in terms of the prevailing temperatures,

$$p_s = C_1 \exp\left(\frac{C_2 t}{C_3 + t}\right) \qquad \text{(eq. A2.4)}$$

The constants C_1,C_2 and C_3 are given in table A2.1 below.

Table A2.1. Constants to be used in the Magnus equation (VDI 3786)

Phase	**t (°C)**	**C_1 (hPa)**	**C_2 (non-dimensional)**	**C_3 (°C)**
ice	<0	6.11	22.44	272.44
water	<0	6.11	17.84	245.43
water	>0	6.11	17.08	234.18

$$\varphi_h = \frac{\exp\left(\frac{C_2 t_c}{C_3 + t_c}\right)}{\exp\left(\frac{C_2 t_h}{C_3 + t_h}\right)} \bullet \frac{p_{0,h}}{p_{0,c}} \qquad \text{(eq. A2.5)}$$

Thus by measuring the temperatures and pressures in the hot and cold tanks respectively the relative humidity can be determined with the prerequisite that the air leaves the cold tank fully saturated and that there are no sources or sinks of moisture outside the saturator chamber.

A2.5 Determination of wet bulb temperature

The wet bulb temperature is calculated by means of the psychrometer formula according to Sprung (VDI 3786),

$$p_w = p_s - A \bullet p_0 \bullet (t - t_{wb}) \qquad \text{(eq. A2.6)}$$

where $A = 6.6 \bullet 10^{-4}\ K^{-1}$ (water on the wet thermometer)

$A = 5.8 \bullet 10^{-4}\ K^{-1}$ (ice on the wet thermometer)

p_w = vapour pressure in hPa, at temperature t °C

p_s = saturation vapour pressure in hPa, above water or ice respectively, at temperature t_w °C

p_0 = total air pressure in hPa

t = temperature of the dry thermometer in °C (i.e. t_h °C)

t_{wb} = temperature of the wet thermometer in °C

The vapour pressures in equation A2.6 can be calculated by means of equation A2.4 and used in the following implicit relationship for the determination of wet bulb temperature,

$$t_{wb} = t - \frac{p_s(t_{wb}) - p_w}{A p_0} \qquad \text{(eq. A2.7)}$$

This expression involves t_{wb} on both sides and must be evaluated by means of some iterative method.

A2.6 Determination of pressure

The total pressure $p_{0,c}$ in the saturator and the total pressure $p_{0,h}$ in the calibration chamber are measured directly via the corresponding pressure taps. The absolute pressures in the tanks will differ slightly from that indicated by the pressure instruments depending on the height and temperature of the air column between the instrument and the desired level in the tank. Even if the columns are of equal height the resulting pressure deviations may differ since the air is normally colder in the column to the saturator than it is in the column to the calibration chamber. In this particular equipment the resulting difference is always less than 2 Pa and has no bearing on the calculated results. Differences due to the circulation pressure drop are generally larger (15-25 Pa).

Vapour pressures can be calculated using the Magnus equation (equation A2.4 above). Thus the vapour pressure is measured indirectly by means of temperature measurements.

A2.7 Determination of carbon dioxide concentration

When carbon dioxide sensors are investigated the humidity is controlled to some fixed value (e.g. φ=30 %) to permit correct operation of the sensors. A tube of certified reference gas, with an accurately known carbon dioxide content, is attached to the external valve on the suction side of the air pump (see the principle drawing in figure A2.1). The other external valve is left open to the atmosphere while the intermediate valve is kept shut-off. After some time the output signal from the sensors stabilizes and a steady state situation is reached. The open external valve is then changed to an almost fully closed position and the intermediate valve is opened. Air inside the tank is now circulated by the air pump while the high pressure reference gas tube remains attached. A small amount of air is permitted to leak out of the system to be continuously replaced by new reference gas.

Reference gas can be ordered to customer specifications concerning the content of carbon dioxide and the accuracy by which this content is known. The reference gas normally used by SP has the following concentration according to the issued certificates,

Concentration x_{CO2} **(ppm)**	**Uncertainty** Δx_{CO2} **(ppm)**
500	10
1 000	20
1 500	30

The carbon dioxide content can of course also be monitored continuously by a laboratory instrument, but this will in general not improve the accuracy unless highly qualified and regularly calibrated equipment is used.

A2.8 Determination of VOC concentration

Calibration of VOC-sensors could in principle be investigated by means of reference gas in the same manner that carbon dioxide sensors are investigated. This was indeed the intention when the calibration system was designed. In practice, however, the experience is that plastic casings etc., which are part of the sensor assemblies, emit VOC-substances to some extent. These emissions are sufficienly large to make it impossible to operate the system even partially closed. To prevent a continuous increase in the VOC-content of the tanks a fairly large purging gas flow is required. This in turn makes it impractical to use reference gases due to the large quantities necessary.

So far a test set up according to figure A2.7 has been used. The basic principle is that test tubes of selected diameters, containing the constituents of the decided VOC-cocktail, are placed inside a chamber. The diameter, height and content of the test tubes decide the rate of evaporation and these parameters are chosen accordingly. One end of the chamber containing the VOC-mixture is connected to the suction side of the air pump while the other end is connected to the open air outside the building.

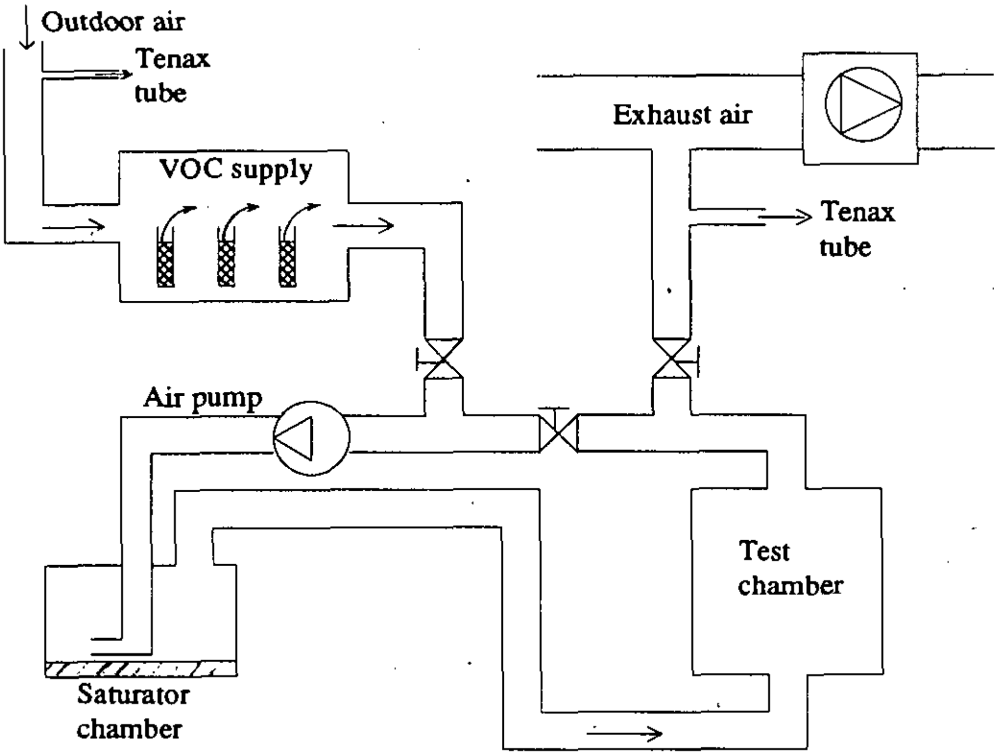


Figure A:2.7. The test set up used for VOC-sensors.

The intermediate valve in the calibrator is shut off and the other external valve is left open and is connected to the exhaust air system of the building. In this fashion the test equipment operates as a fully open system with a purging flowrate decided by the pump and control valves in the system. The average composition of the VOC-air mixture can be determined by measuring the amount of VOC which has evaporated from the test tubes and the purging flow rate. As an extra check the composition and concentration are analyzed by means of adsorption tubes ("Tenax"-tubes) both at the inlet and at the outlet. Air humidity is still controlled by the saturator chamber.

Experience has shown that the VOC-content of the outside air may vary considerably during the day, e.g. depending on the traffic situation. Thus it has been an absolute necessity to monitor the incoming air. Another consideration is that control of the humidity has indeed been a necessary feature of the equipment, even when VOC-sensors are being investigated. Many of the sensors tested so far have turned out to be sensitive also to the humidity level and one sensor was a combined humidity/VOC-sensor.

A2.9 Computer programs

A PC-system is used to control the analogue scanner. One computer program is available to select the operating parameters of the scanner, such as

- required measuring channels
- configuration of the channels (voltage, resistance, thermocouples, measuring range)
- scanning interval
- calibration constants of individual sensors
- transfer and storage of measured data

Another program is used to convert the outputs of the sensors being investigated to the respective measurand (e.g. relative humidity, carbon dioxide concentration etc.). This program also provides real time graphical presentation of the sensor outputs.

Finally evaluation programs are used for analysis and presentation of the measured signals. At the same time the control parameters of the humidity calibrator, i.e. the temperatures and pressures in the tanks, are recalculated to equivalent relative humidities, moisture contents etc.

A3 Specifications

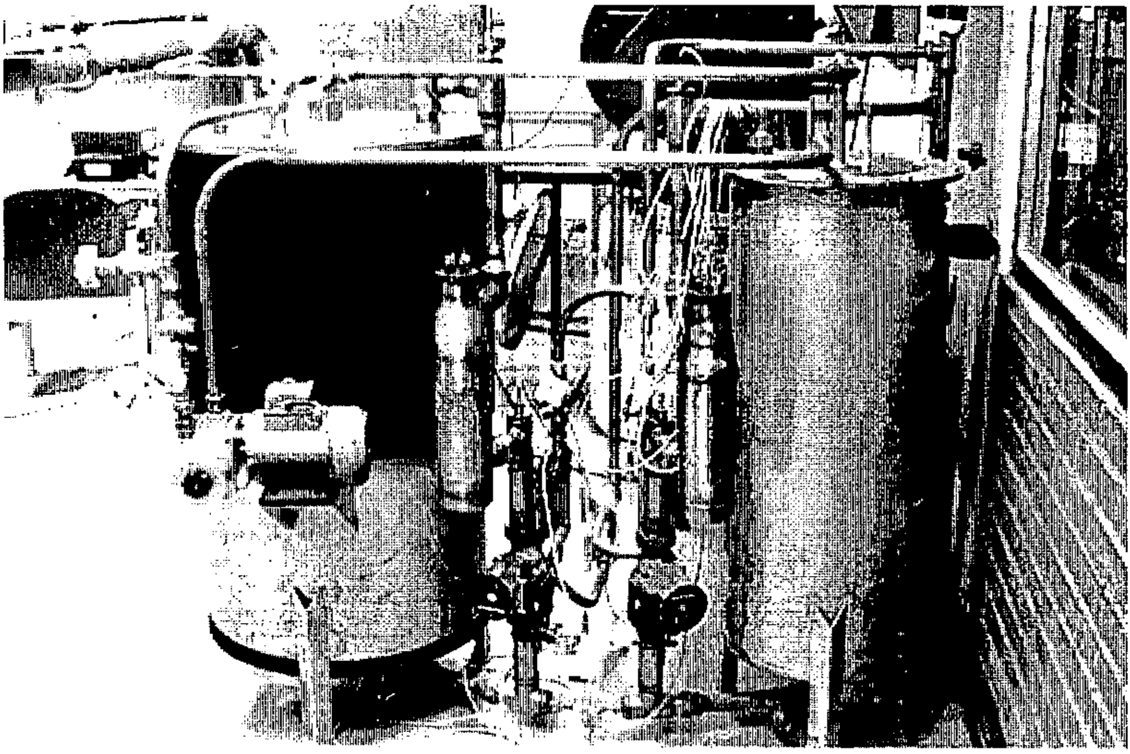


Figure A3.1. Photograph of the humidity calibrator.

The humidity calibrator is shown in figure A3.1. Basic design data such as capacities, uncertainty and stability of measurements are covered in sections A3.1-A3.2 below.

A3.1 Capacity data

A3.1.1 Saturator tank (cold tank)

Saturator chamber

Dimensions:	Diameter = 145 mm, height = 128 mm, volume = 2.11 dm^3
Material:	Stainless steel (SS 2343)
Air inlet pipe:	Copper tube, internal diameter = 17 mm, heat transfer area = 0.53 m^2 in the thermostatic bath (on the inlet side)
Air outlet pipe:	Copper tube, internal diameter = 19 mm
Water (distilled):	Volume = 0.66 dm^3, depth = 40 mm
Pressure range:	90 kPa(a) < p_c < 110 kPa(a)
Pressure tap:	Copper tube, internal diameter = 5 mm, length = 650 mm
Temperature range:	-10 °C < t_c < +20 °C (normal operating range for calibration)
Temperature sensors:	Pt 100, one in the water (no. 5), one in the saturated air (no.6)

Thermostatic bath (inner)

Dimensions:	Diameter = 250 mm, height = 800 mm, volume = 39 dm^3
Material:	Stainless steel (SS 2343)
Cooling agent inlet pipe:	Copper tube, internal diameter = 41 mm, inlet at the bottom
Cooling agent outlet pipe:	Overflow at the top via 14 holes of diameter = 16 mm
Cooling agent:	Water(50%) / ethylene-glycol (50%)
Pressure range:	0 kPa(e) < p < 50 kPa(e), (liquid head plus pump pressure)
Temperature range:	-20 °C < t_c < +50 °C

Thermostatic bath (outer)

Dimensions:	Diameter = 380 mm, height = 950 mm, net volume = 68 dm^3
Material:	Stainless steel (SS 2343)
Insulation:	Armaflex, 18 mm thick
Cooling agent inlet pipe:	Overflow at the top via 14 holes of diameter = 16 mm
Cooling agent outlet pipe:	Copper tube, internal diameter = 41 mm, outlet at the bottom
Cooling agent:	Water(50%) / ethylene-glycol (50%)
Pressure range:	0 kPa(e) < p < 50 kPa(e), (liquid head plus pump pressure)
Temperature range:	-20 °C < t_c < +50 °C

Circulation of the cooling agent

Pipe:	Copper tube, internal diameter = 32 mm, length = 2 m
Insulation:	Armaflex, 9 mm thick
Cooling agent:	A total volume (including tanks) of approx 100 dm^3 mixture of water(50%) / ethylene-glycol (50%)
Pump:	Grundfos UPS 32-80, flowrate = 7 m^3/h, pressure = 40 kPa, power input = 200 W
Heater:	Power input = 0-2 kW
Heat exchanger:	Alfa Laval CB 12-14, 2 kW with inlet temperatures of -17 °C (primary side) and ±0 °C (secondary side)
Pressure range:	0 kPa(e) < p < 50 kPa(e)
Temperature range:	-20 °C < t_c < +50 °C
Temperature sensors:	Pt 100, one at the inlet to the heater (no. 7),one at the inlet to the inner tank (no. 8), one at the outlet of the outer tank (no.9)

A3.1.2 Calibration tank (hot tank)

Calibration chamber

Dimensions:	Diameter = 350 mm, height = 750 mm, volume = 72 dm^3
Material:	Stainless steel (SS 2343)
Air inlet pipe:	Copper tube, internal diameter = 17 mm, heat transfer area = 0.79 m^2 in the thermostatic bath (on the inlet side)
Air outlet pipe:	Copper tube, internal diameter = 17 mm
Pressure range:	90 kPa(a) < p_h < 110 kPa(a)
Pressure tap:	Copper tube, internal diameter = 5 mm, length = 80 mm
Temperature range:	+10 °C < t_h < +30 °C (normal operating range for calibration)
Temperature sensors:	Pt 100, one at the bottom (no. 1), one at the top (no.10)

Thermostatic bath (inner)

Dimensions:	Diameter = 450 mm, height = 850 mm, volume = 135 dm^3
Material:	Stainless steel (SS 2343)
Heat transfer medium inlet pipe:	Copper tube, internal diameter = 41 mm, inlet at the bottom
Heat transfer medium outlet pipe:	Overflow at the top via 28 holes of diameter = 16 mm
Heat transfer medium:	Water (50%) / Glycol (50%)
Pressure range:	0 kPa(e) < p < 50 kPa(e), (liquid head plus pump pressure)
Temperature range:	+10 °C < t < +50 °C

Thermostatic bath (outer)

Dimensions:	Diameter = 580 mm, height = 1000 mm, net volume = 129 dm^3
Material:	Stainless steel (SS 2343)
Insulation:	Armaflex, 18 mm thick
Heat transfer medium inlet pipe:	Overflow at the top via 28 holes of diameter = 16 mm
Heat transfer medium outlet pipe:	Copper tube, internal diameter = 41 mm, outlet at the bottom
Heat transfer medium:	Water (50%) / Glycol (50%)
Pressure range:	0 kPa(e) < p < 50 kPa(e), (liquid head plus pump pressure)
Temperature range:	+10 °C < t < +50 °C

Circulation of the heat transfer medium

Pipe:	Copper tube, internal diameter = 32 mm, length = 2 m
Insulation:	Armaflex, 9 mm thick
Cooling agent:	A total volume (including tanks) of 180 dm^3 mixture of water(50%) / ethylene-glycol (50%)
Pump:	Grundfos UPS 32-80, flowrate = 7 m^3/h, pressure = 40 kPa, power input = 200 W
Heater:	Power input = 0-2 kW
Heat exchanger:	Alfa Laval CB 12-14, 2 kW with inlet temperatures of -17 °C (primary side) and ±0 °C (secondary side)
Pressure range:	0 kPa(e) $< p <$ 50 kPa(e)
Temperature range:	-20 °C $< t <$ +50 °C
Temperature sensors:	Pt 100, one at the inlet to the inner tank (no. 2), one at the
inlet to	the heater (no. 3), one at the outlet of the outer tank (no.4)

A3.1.3 Air circulation

Pipe (to the saturator):	Copper tube, internal diameter = 17 mm, length = 5 m
Pipe (from the saturator):	Copper tube, internal diameter = 19 mm, length = 25 m
Insulation:	Armaflex, 9 mm thick
Valves:	One control valve (to regulate the circulation flow rate), two shut-off valves (to facilitate external connections)
Air volume:	V_a = 80 dm^3 (including the saturator and calibration chambers)
Design flowrate:	q_a = 7 m^3/h (= 88 ACH)
Design pressure drop:	Δp_a = 15 kPa
Pump:	Vrey TF71/8 W, flowrate = 7 m3/h, pressure difference = 20 kPa, power input = 370 W
Air leakage:	q_l = 10^{-4} m^3/h at a gauge pressure of + 3 kPa(e) (=0.0013 ACH)
Pressure range:	$p_c <$ 1 MPa(e)
Temperature range:	±0 °C $< t_c <$ +80 °C

A3.1.4 External cooling

Cooling agent:	Water (50%) / ethylene-glycol (50%)
Supply temperature:	-20 to -25 °C
Supply pressure:	100 - 200 kPa(e)

A3.1.5 Elecrical connections

External power supply: Three-phase 32 A CEE-type connector to a power supply cabinet. Distribution to the individual consumers via automatic 30A/600V fuses.

A3.1.6 Control equipment

Cooling agent (cold tank)

Controller: Eurotherm 818 S, temperature range -50 °C to +100 °C, Pt 100 sensor, 3-wire connection, manual set point (-50.0 °C to +100.0 °C), external set point (0-10 V), analogue output signal (0-10 V), display range -50.0 °C to +100.0 °C, PID operation (featuring self-tuning possibilities), SCR output (3-phase, 10 A)

Heat transfer medium (hot tank)

Controller: Eurotherm 818 S, temperature range -50 °C to +100 °C, Pt 100 sensor, 3-wire connection, manual set point (-50.0 °C to +100.0 °C), external set point (0-10 V), analogue output signal (0-10 V), display range -50.0 °C to +100.0 °C, PID operation (featuring self-tuning possibilities), SCR output (3-phase, 10 A)

A3.1.7 Data collection

Analogue signals: Analogue scanner of the type Solartron 3510. A maximum of 10 reed relay connector cards with 20 measuring channels on each card (10 channels if Pt 100 sensors are connected in four-wire fashion). Constant current supply to sensors with a choice of 0.1 mA, 1 mA or 8.33 mA. Measuring ranges of the DVM are either set automatically or in preselected ranges of 0-10 mV, 0-100 mV, 0-1 V, 0-10 V or 0-100 V. The minimum digital scale division is 1 µV.

All measured data are transferred to a PC-system for subsequent analysis and presentation.

A3.1.8 Connection of measuring equipment

Pt 100 sensors:	Connecting box by the calibrator with 10 DIN-type sockets. A 60-pole Cannon-type connector coupled to a 40-conductor cable transmits the signals to the scanner.
Other analogue signals:	Connecting box by the calibrator with 20 lab type sockets. A 60-pole Cannon-type connector coupled to a 40-conductor cable transmits the signals to the scanner.

A3.1.9 Connection of sensors

Calibrator tank:	10 DIN-type 5-pin connectors are installed inside the calibrator tank (with gas tight seals). Power supplied to sensors and the measuring signals are communicated via these connectors.
Measuring system:	Sensor output signals are transmitted to the data collection system via connecting boxes as described in A3.1.8.
Power supply:	Stabilized power supplies of 0-30 VDC, 24 VAC and 230 VAC are available to feed various types of sensors.

A3.2 Uncertainty and stability of measurements

The uncertainty of measurement is further discussed in appendix B. Design values are given below.

Saturator chamber (cold tank)

Measurement: The uncertainty of measurement should be less than 0.02 K in the range -20 to +30 °C. This includes errors due to installation, calibration etc.

The resolution normally used is 0.01 K (the measuring system permits a maximum resolution of 0.0025 K).

The rise time (10-90%) of the temperature sensors used is of the order of 10 s (depending on air flow rate etc).

Temporal stability: Time dependent variations should be less than 0.05 K (the maximum deviation).

Spatial stability: The time averaged difference between the two sensors in the saturator should be less than 0.02 K.

Calibration chamber (hot tank)

Measurement: The uncertainty of measurement should be less than 0.02 K in the range -20 to +30 °C. This includes errors due to installation, calibration etc.

The resolution normally used is 0.01 K (the measuring system permits a maximum resolution of 0.0025 K).

The rise time (10-90%) of the temperature sensors used is of the order of 10 s (depending on air flow rate etc).

Temporal stability: Time dependent variations should be less than 0.05 K (the maximum deviation).

Spatial stability: The time averaged difference between the two sensors in the calibration chamber should be less than 0.02 K with no test sensors fitted inside the chamber. When test sensors are installed the deviation may be larger due to dissipation of heat from these sensors. The deviation should not be permitted to exceed 0.05 K if sensors for relative humidity are calibrated.

A4 References

A1. Till, C E, Handegord, G O, 1961. Proposed humidity standard. (National Research Council.) Research paper no. 134, September 1961. Ottawa, Canada.

Appendix B: Uncertainty of measurement

Contents

B1 Introduction

Uncertainty of measurement can be determined and expressed in accordance with two principally different methods, classifying components of uncertainty due to

1. Random- and systematic errors (e.g. SS 01 41 50, ref. 3)
2. Estimated- and expected components of uncertainty (CIPM 49, ref. 1)

In this report the second approach will be used since this is the procedure which is recommended by the Swedish organization for accreditation of testing and calibration laboratories (SWEDAC). The basic principle behind this approach is that uncertainties of measurment can only be distinguished by the method used to determine their magnitudes. Estimates based on repetitive measurements are called estimated components of uncertainty and are calculated according to

$$s_{\bar{x}} = \left[\frac{1}{n(n-1)} \sum_{1}^{n}(x_i - \bar{x})^2\right]^{½} \qquad \text{(eq. B1)}$$

If subjective methods are used to determine the magnitude of a component of uncertainty this component is called an expected component of uncertainty of the variable x and it is designated w_x;

$$w_x^2 = [\,\Sigma(a_{xj})^2/3]^{½} \qquad \text{(eq. B2)}$$

a_{xj} is half the maximum interval of expected uncertainty of variable x and it is assumed that the distribution function of this component has equal probability in the interval $(\bar{x} - a_{xj}, \bar{x} + a_{xj})$. This assumption results in a "standard deviation" given by $s=a_{xj}/\sqrt{3}$.

Contrary to the method of classifying components of uncertainty in random- and systematic errors the method recommended by BIPM and SWEDAC provides for a way of combining the two principle components of uncertainty into a combined uncertainty of measurement, u, according to

$$u_x = [s_{\bar{x}}^2 + w_x^2\,]^{½} \qquad \text{(eq. B3)}$$

Multiplying this combined uncertainty of measurement by a numerical factor k gives the total uncertainty of measurement U,

$$U_x = k \bullet u_x \qquad \text{(eq. B4)}$$

The numerical factor will depend on the number of measurements available to calculate s and is in some ways equivalent to the Student t-factor used in the determination of confidence intervals for random errors. In this report a value of k=2.5 will be used (a confidence level > 95 %).

Using the humidity standard described in appendix A implies that the only measurements necessary to determine any type of humidity measurand are two temperatures (t_c and t_h) and two pressures (p_c and p_h).

B2 Determination of dry bulb temperatures

The uncertainties in the measurement of temperature consist of the following major components:

1. *Variations in the operating conditions (stability).*
   Random fluctuations in the circulated air flow rate, the temperature of the thermostatic baths, supply voltage etc. result in an estimated component of uncertainty ("random error") according to

$$s_{\bar{T}} = [\frac{1}{n(n-1)} \sum_{1}^{n} (T_i - \bar{T})^2]^{1/2} \qquad \text{(eq. B5)}$$

2. *Conditions of installation.*
   Thermal conduction in metallic casings and electric conductors to sensors, temperature stratification, heat exchange by radiation, thermoelectric emfs etc. generate expected components of uncertainty, the magnitudes of which are estimated by means of their expected maximum influences a_j.

$$w_{Tj} = |a_{Tj}/\sqrt{3}| \qquad \text{(eq.B6)}$$

3. *Point of operation.*
   In the case of sensors with non-linear characteristics (applies to all sensors to some extent) varying operational conditions will generate an uncertainty due to the uncertainty in the actual point of operation in accordance with item 1 and the uncertainty due to the conditions of installation in accordance with item 2,

$$w_{TE1} = s_{\bar{T}E} = \left|\frac{\partial E}{\partial T}\right| \bullet s_{\bar{T}} \qquad \text{(eq. B7)} \qquad \text{and}$$

$$w_{TE2} = \left|\frac{\partial E}{\partial T} \bullet (\sum_{i=1}^{n} w_{Tj}^2)^{1/2}\right| \qquad \text{(eq. B8)} \qquad \text{respectively,}$$

   where E(T) is the temperature dependent error of the sensor according to the calibration certificate.

4. *Uncertainty due to the calibration process.*
   The uncertainty due to the calibration process will contain the uncertainty of traceability to the National Primary Calibration Laboratory (in Sweden SP, department of physics and electrical engineering) as well as the uncertainty in the secondary calibration process at the department of energy technology. It should be noted that a major part of the uncertainty due to calibration will be caused by installation errors in the calibration baths. Installation errors will differ between the calibration situation and the actual measurement situation. Calibration errors mainly give rise to expected components of uncertainty according to

$$w_{TC} = |a_{TC}/\sqrt{3}| \qquad \text{(eq. B9)}$$

According to Fahlén, 1987, $a_{TC} < 0,001 \left| T - T_{amb} \right|$ in a carefully made installation.

Final result.

The final result for the *estimated* component of uncertainty is given directly by equation B5,

$$s_{\bar{T}} = \left[\frac{1}{n(n-1)} \sum_{1}^{n} (T_i - \bar{T})^2\right]^{1/2} = 0.025 \text{ K} \quad \text{(see the table below)}$$

Typical values for the standard deviation of the mean value in the measurement of temperature (based on 32 and 71 values respectively)

t_{c1} (°C)	16.934	0.456	
s_{tc1} (K)	0.026	0.022	
t_{c2} (°C)	16.912	0.483	
s_{tc2} (K)	0.015	0.025	
t_{h1} (°C)	20.219	20.098	
s_{th1} (K)	0.009	0.025	
t_{h2} (°C)	20.191	20.062	
s_{th2} (K)	0.027	0.020	

The final result for the *expected* component of uncertainty is given by combining individual uncertainties in accordance with equation B2,

$$w_T = \left[w_{TE1}^2 + w_{TE2}^2 + \sum_{j=1}^{n} w_{Tj}^2 + w_{TC}^2 \right]^{1/2}$$

Expected uncertainty due to installation effects: $w_{T1} < 0.001/\sqrt{3} = 0.0005$ K

Expected uncertainty due to thermal stratification: $w_{T2} < 0.02/\sqrt{3} = 0.01$ K

Expected uncertainty due to the point of operation (caused by random variations) : $w_{TE1} < 0.001$ K

Expected uncertainty due to the point of operation (caused by other expected uncertainties) : $w_{TE2} < 0.001$ K

Expected uncertainty due to calibration: $w_{TC} < 0.01/\sqrt{3} = 0.005$ K

$$w_T < \left[\sum_{j=1}^{n} w_{Tj}^2 + w_{TE1}^2 + w_{TE2}^2 + w_{TC}^2 \right]^{1/2}$$

Insertion of numerical values results in

$$w_T < [0.0005^2 + 0.01^2 + 0.001^2 + 0.001^2 + 0.005^2]^{1/2} < 0.012 \text{ K}$$

The combined uncertainty for the mean value of the temperature measurement is given by equation B3,

$$u_T = [s_{\bar{T}}^2 + w_T^2]^{½} = [0.025^2 + 0.012^2]^{½} < 0.028 \text{ K}$$

The total uncertainty of measurement for the mean value of a temperature measurement is given by

$$U_T = k \bullet u_T = 2.5 \bullet 0.028 < 0.07 \text{ K}$$

This result compares well with the design objective of being able to determine the dew point temperature with an overall uncertainty of less than 0.1 K.

B3 Determination of pressures

The uncertainties in the measurement of pressure consist of the following major components:

1. *Variations in the operating conditions (stability).*
   Random variations in the circulated air flow rate, the temperature of the thermostatic baths, supply voltage etc. result in pressure fluctuations causing an estimated component of uncertainty ("random error") according to

   $$s_p = \left[\frac{1}{n(n-1)} \sum_{1}^{n} (p_i - \bar{p})^2\right]^{½} \qquad \text{(eq. B10)}$$

2. *Conditions of installation.*
   Dynamic pressure components, ambient fluctuations, temperature effects, variable density and height of the air columns etc. generate expected components of uncertainty, the magnitudes of which are estimated by means of their expected maximum influences a_j.

   $$w_{pj} = |a_{pj}/\sqrt{3}| \qquad \text{(eq.B11)}$$

3. *Point of operation.*
   In the case of sensors with non-linear characteristics (applies to all sensors to some extent) varying operational conditions will generate an uncertainty due to the uncertainty in the actual point of operation in accordance with item 1 and the uncertainty due to the conditions of installation in accordance with item 2,

   $$w_{pE1} = s_{pE} = \left|\frac{\partial E}{\partial p}\right| \bullet s_p \qquad \text{(eq. B12)} \quad \text{and}$$

   $$w_{pE2} = \left|\frac{\partial E}{\partial p} \bullet \left(\sum_{i=1}^{n} w_{pj}^2\right)^{½}\right| \qquad \text{(eq. B13)} \quad \text{respectively,}$$

   where E(p) is the pressure dependent error of the sensor according to the calibration certificate.

4. *Uncertainty due to the calibration process.*
   The uncertainty due to the calibration process will contain the uncertainty of traceability to the National Primary Calibration Laboratory (in Sweden "The Swedish Aeronautical Research Organization") as well as the uncertainty in the secondary calibration process at the department of energy technology. Installation errors may differ between the calibration situarion and the actual measurement situation. Calibration errors mainly give rise to expected components of uncertainty according to

   $$w_{pC} = |a_{pC}/\sqrt{3}| \qquad \text{(eq. B14)}$$

Final result.

The final result for the *estimated* component of uncertainty is given directly by equation B1,

$$s_p = \left[\frac{1}{n(n-1)} \sum_{1}^{n} (p_i - \bar{p})^2\right]^{½}$$

Typical values for the standard deviation of the mean value in the measurement of pressure			
p_h (kPa)	101.3		
Δp_h (kPa)	0.1		
p_c (kPa)	103.6		
Δp_c (kPa)	0.1		

The final result for the *expected* component of uncertainty is given by combining individual uncertainties in accordance with equation B2,

$$w_p = \left[w_{pE1}^2 + w_{pE2}^2 + \sum_{j=1}^{n} w_{pj}^2 + w_{pC}^2 \right]^{½}$$

Expected uncertainty due to installation effects: $w_{p1} < 0/\sqrt{3} = 0$ Pa

Expected uncertainty due to differences in height and air density between the two measuring points for pressure and the sensor location: $w_{p2} < 0.01/\sqrt{3} = 0.006$ Pa

Expected uncertainty due to the point of operation (caused by random variations) : $w_{pE1} < 4$ Pa

Expected uncertainty due to the point of operation (caused by other expected uncertainties) : $w_{pE2} < 0.0004/\sqrt{3} = 0.0002$ Pa

Expected uncertainty due to calibration ($0 < a_{pC} < 40$ Pa): $w_{pC} < 40/\sqrt{3} = 23.1$ Pa

$$w_p < \left[\sum_{j=1}^{n} w_{pj}^2 + w_{pE1}^2 + w_{pE2}^2 + w_{pC}^2 \right]^{½}$$

Numerical values , as specified above, gives

$$w_p < [\, 0^2 + 0.006^2 + 4^2 + 0.0002^2 + 23.1^2 \,]^{½} < 23.5 \text{ Pa}$$

The combined uncertainty for the mean value of the pressure measurement is given by

$$u_p = [s_p^2 + w_p^2]^{½} = [\, 100^2 + 23.5^2 \,]^{½} < 103 \text{ Pa}$$

The total uncertainty of measurement for the mean value of a pressure measurement is given by

$$U_p = k \bullet u_p = 2.5 \bullet 103 < 258 \text{ Pa}$$

B4 Determination of dew point temperature

Determination of the dew point temperature in the hot calibration chamber involves uncertainties due to

- temperature measurement in the cold saturator chamber
- methodical errors involving the purity of water, planeness of the water surface, equality of temperature of water in the liquid and vapour phases, and equilibrium (saturated) condition between the vapour and liquid phases in the saturator.

B4.1 Uncertainty due to temperature measurements

The uncertainty due to temperature measurements was covered in section B2. The uncertainty components are given by

$$s_{dp} = s_{\bar{T}} < 0.03\ \mathrm{K}$$

$$w_{dp1} = w_T < 0.05\ \mathrm{K}$$

$$u_{dp1} = u_T < (s_{\bar{T}}^2 + w_T^2)^{1/2} = 0.06\ \mathrm{K}$$

$$U_{dp1} = U_T < k \bullet (s_{\bar{T}}^2 + w_T^2)^{1/2} = 0.15\ \mathrm{K}$$

B4.2 Influence of the purity of water

Only distilled water is being used in tanks which are made of stainless steel. According to Till and Handegord, 1961, (ref. B4) no measurable influence was detected when using "old" or freshly distilled water. This factor will be further investigated on the specific equipment described in this report.

$$w_{dp2} \approx 0\ \mathrm{K}$$

B4.3 Planeness of the water surface

According to Till and Handegord, 1961, extremely small droplets would have to be formed in the saturator tank to significantly influence the saturated vapour pressure. The air flows used in the equipment are considered sufficiently low not to agitate the water surface,

$$w_{dp3} \approx 0\ \mathrm{K}$$

B4.4 Equality of the temperature of moist air and water surface

In a steady state situation heat transfer between the liquid and vapour phases should be miniscule. The whole saturator is surrounded by a temperature controlled bath and the recirculated air is preconditioned to achieve the correct temperature before entering the saturator chamber. Measurements presented by Till and Handegord (ref. B4) in numerous positions inside the saturator indicate a deviation of less than 0.01 K. On this particular equipment only two temperature sensors are used in the saturator tank. Deviation between the two sensors is less than 0.02 K. Thus the expected component of uncertainty is given by

$$w_{dp4} = a_{dp4}/\sqrt{3} = 0.02/\sqrt{3} \approx 0.01 \text{ K}$$

B4.5 Equilibrium (saturated) condition between the vapour and liquid phases

In this equipment equilibrium conditions prevail in a closed air-water system containing a free water surface. The water content of the air must then be that of saturated air at the temperature of the water surface unless there are other sources or sinks of water vapour. Two major possibilities for such sources exist,

- adsorption/desorption on surfaces inside the system.
- mass transfer due to air leakage between the humidity calibrator and the ambient atmosphere.

Adsorption/desorption is considered to have a negligible influence since practically all surfaces inside the equipment are smooth and metallic (stainless steel tanks and copper tubing). Only if the saturator were to be operated at temperatures exceeding the ambient temperature would there be a possibility of a major sink (in this case condensation may occur in the connecting tubes between the tanks). Since calibration is normally performed with a temperature of 20 °C in the hot tank, which is approximately the ambient temperature, this does not take place in practice.

Leakage to the ambient atmosphere is mainly of concern when the vapour pressure in the calibrator is above that of the ambient. In this case the "saturation efficiency" ε_S is of importance,

$$\varepsilon_s = \frac{p_{w,c} - p_{w,h}}{p_{wc,s} - p_{w,h}} \qquad \text{(eq. B15)}$$

According to Till and Handegord (ref. B4) the water vapour pressure in the calibration chamber, p_{wh}, can be expressed as

$$p_{w,h} = \frac{\varepsilon_s \cdot p_{wc,s} + \ell \cdot p_{w,amb}}{1+\ell} \qquad \text{(eq. B16)}$$

where $p_{w,amb}$ is the water vapour pressure in the ambient and ℓ is the leakage factor

$$\ell = \frac{\text{mass of air exchanged with the ambient}}{\text{mass of air circulated in the equipment}}$$

A pressurization test indicated a leakage of 0.0013 ACH (see appendix A3.1.3). With a total internal volume of 0.08 m^3 and a circulated volume flow of 7 m^3/h this gives an approximate leakage factor of $\ell = 0.0013/0.08/7 = 0.0023$.

Prior to more detailed investigations it is assumed that the expected uncertainty component due to leakage is less than 0.2 % concerning $p_{w,h}$ and 0.05 K concerning the dew point, i.e.

$$w_{dp5} = a_{dp5}/\sqrt{3} = 0.05/\sqrt{3} \approx 0.03 \text{ K}$$

According to Till and Handegord (ref. B4) this uncertainty was less than 0.02 K in the temperature range $0<t_c<20$ °C. In this calibrator the leakage factor at a gauge pressure of +3000 Pa(e) is 0.0023 whereas the leakage factor according to reference B4 was 0.00018 at a gauge pressure of +2000 Pa(e). In normal calibration work the gauge pressure is +2,3 kPa Pa(e) in the cold tank and -2 to +2 Pa(e) in the hot tank.

B4.6 Total uncertainty of the dewpoint temperature

The *estimated* component of uncertainty is given directly by equation B.5 in section B2,

$$s_{dp} = \left[\frac{\Sigma(T_{ci} - \bar{T}_c)^2}{n(n-1)} \right]^{1/2} < 0.03 \text{ K}$$

The *expected* component of uncertainty is given by

$$w_{dp} = (w_{dp1}{}^2 + w_{dp2}{}^2 + w_{dp3}{}^2 + w_{dp4}{}^2 + w_{dp5}{}^2)^{1/2} =$$
$$= (0.05^2 + 0 + 0 + 0.01^2 + 0.03^2)^{1/2} = 0.06 \text{ K}$$

The *combined* uncertainty is calculated as

$$u_{dp} = (s_{dp}{}^2 + w_{dp}{}^2)^{1/2} = (0.03^2 + 0.06^2)^{1/2} = 0.07 \text{ K}$$

and finally the *total* uncertainty in the determination of the dew point temperature is

$$U_{dp} = k \bullet U_{dp} = 2.5 \bullet 0.07 = 0.18 \text{ K}$$

B5 Determination of relative humidity

When equilibrium conditions prevail in the humidity calibrator the moisture content x will be the same in the entire calibrator. There are fundamental equations relating all humidity quantities and thus a knowledge of the four measurands t_c, p_c, t_h and p_h (assuming x to be constant) makes it possible to calculate also the relative humidity, wet bulb temperature and moisture content in the calibration chamber. The uncertainties involved in determination of these derived quantities are determined by the uncertainties in the four measurands (see B2-B4) and the propagation of these uncertainties through the fundamental equations being used.

The relationship between relative humidity and moisture content is given by

$$x = \frac{M_w}{M_a} \bullet \frac{p_w}{(p_0 - p_w)} = \frac{M_w}{M_a} \bullet \frac{\varphi p_s}{p_0 - \varphi p_s} \qquad \text{(eq. B17)}$$

where M_w = molar mass of water vapour,
M_a = molar mass of dry air,
p_0 = total atmospheric pressure,
p_w = partial pressure of water vapour,
p_s = saturated vapour pressure at the temperature in question
φ = the relative humidity.

Thus in the cold saturator chamber $p_w(T_c) = p_s(T_c)$ and $\varphi = 1.0$. Since $x_c = x_h = x_s(T_c)$ one obtains

$$\frac{M_w}{M_a} \bullet \frac{p_{s,c}}{(p_{0,c} - p_{s,c})} = \frac{M_w}{M_a} \bullet \frac{p_{w,h}}{(p_{0,h} - p_{w,h})} \qquad \text{(eq. B18)}$$

Substituting $p_w = \varphi \bullet p_s$ yields ($\varphi_c = 1.0$)

$$\frac{\varphi_h \cdot p_{s,h}}{(p_{0,h} - \varphi_h \cdot p_{s,h})} = \frac{p_{s,c}}{(p_{0,c} - p_{s,c})}$$

Solving for φ_h gives

$$\varphi_h = \frac{p_{s,c}}{p_{s,h}} \bullet \frac{p_{0,h}}{p_{0,c}} \qquad \text{(eq. B19)}$$

According to Magnus equation (see for instance VDI 3786, ref. B5)

$$p_s = C_1 \cdot \exp\left(\frac{C_2 \cdot t}{C_3 + t}\right) \qquad \text{(eq. B20)}$$

where C_1 = 6.11 hPa (over water), C_2 = 17.08, C_3 = 234.18 °C and t is the saturation temperature in °C.

Using this relationship equation B.19 transforms to

$$\varphi_h = \frac{\exp(\frac{C_2 \cdot t_c}{C_3+t_c})}{\exp(\frac{C_2 \cdot t_h}{C_3+t_h})} \bullet \frac{p_{0,h}}{p_{0,c}} = \frac{e_c}{e_h} \bullet \frac{p_{0,h}}{p_{0,c}} \qquad \text{(eq. B21)}$$

Thus $\varphi_h = \varphi_h\,(t_c, t_h, p_{0,c}, p_{0,h}, C_2, C_3)$

Logarithmic differentiation of φ gives

$$\frac{\Delta\varphi_h}{\varphi_h} = \frac{\Delta e_c}{e_c} - \frac{\Delta e_h}{e_h} + \frac{\Delta p_{0,h}}{p_{0,h}} - \frac{\Delta p_{0,c}}{p_{0,c}} \qquad \text{(eq. B22)}$$

But $e = \exp\,(\frac{C_2 \cdot t}{C_3+t})$ and thus

$$\Delta e = \frac{\partial e}{\partial t} \bullet \Delta t + \frac{\partial e}{\partial C_2} \bullet \Delta C_2 + \frac{\partial e}{\partial C_3} \bullet \Delta C_3 \qquad \text{(eq. B23)}$$

$$\frac{\partial e}{\partial t} = \frac{e \cdot C_2 \cdot C_3}{(C_3+t)} \qquad \text{(eq. B24)}$$

$$\frac{\partial e}{\partial C_2} = e \bullet \frac{t}{(C_3+t)} \qquad \text{(eq. B25)}$$

$$\frac{\partial e}{\partial C_3} = -\, e \bullet \frac{C_2 \cdot t}{(C_3+t)^2} \qquad \text{(eq. B26)}$$

Substituting the values of Δe_c and Δe_h expressed in terms of the partial derivatives (equations B23 - B26) into equation B22 provides the following expression

$$\frac{\Delta\varphi_h}{\varphi_h} = \frac{C_2 \cdot C_3}{(C_3+t_c)^2} \bullet \Delta t_c + \frac{C_2 \cdot C_3}{(C_3+t_h)^2} \bullet \Delta t_h + \frac{\Delta p_{0,c}}{p_{0,c}} - \frac{\Delta p_{0,h}}{p_{0,h}} +$$

$$+ \left[\frac{t_c}{(C_3+t_c)} - \frac{t_h}{(C_3+t_h)}\right] \bullet \Delta C_2 + \left[\frac{C_2 \cdot t_h}{(C_3+t_h)^2} - \frac{C_2 \cdot t_c}{(C_3+t_c)^2}\right] \bullet \Delta C_3 \qquad \text{(eq. B27)}$$

In comparison with C_3 both t_c and t_h are fairly small so $(C_3+t_c) \approx (C_3+t_h) \approx C_3+t$ where $t = (t_c+t_h)/2$

This approximation simplifies equation B27 to

$$\frac{\Delta\varphi_h}{\varphi_h} \approx \frac{C_2 \cdot C_3}{(C_3+t)^2} [(\Delta t_c+\Delta t_h+(t_c-t_h)\frac{\Delta C_2}{C_2} + C_2(t_h-t_C)\frac{\Delta C_3}{C_3}] + \frac{\Delta p_{0,c}}{p_{0,c}} - \frac{\Delta p_{0,h}}{p_{0,h}} \quad \text{(eq. B28)}$$

$$\frac{\Delta\varphi_h}{\varphi_h} \approx A \cdot \Delta t_c + A \cdot \Delta t_h + B \cdot \Delta C_2 + C \cdot \Delta C_3 + D \cdot \Delta p_{0,c} + E \cdot \Delta p_{0,h}$$

Equation B28 relates the resulting uncertainty in the determination of the relative humidity in the calibration chamber (the hot chamber) to the component uncertainties of the measurements (Δt_c, Δt_h, $\Delta p_{0,c}$, $\Delta p_{0,h}$) and to the expected components of uncertainty in the tabulated constants of the Magnus equation (ΔC_2 and ΔC_3).

$$|A| = \left| \frac{C_2 \cdot C_3}{(C_3+t)^2} \right| \approx \frac{17.08 \cdot 234.18}{(234.18+10)^2} = 0.0671 \text{ K}^{-1} \quad (0 < t < 20 \text{ °C})$$

$$|B| = |(A/C_2)(t_c-t_h)| < (0.0671/17.08)(0-20) = 0.0786$$

$$|C| = |A(C_2/C_3)(t_c-t_h)| < 0.0671 \cdot (17.08/234.16)(20-0) = 0.0986 \text{ K}^{-1}$$

$$|D| = \left| \frac{1}{p_{0,c}} \right| = 0.99 \cdot 10^{-5} \text{ Pa}^{-1}$$

$$|E| = \left| \frac{1}{p_{0,h}} \right| = 0.99 \cdot 10^{-5} \text{ Pa}^{-1}$$

Assuming the figures provided for the constants C_2 and C_3 are correct the uncertainties are given by

$$w_{C2} = a_{C2}/\sqrt{3} = 0.01/\sqrt{3} = 0.006$$

$$w_{C3} = a_{C3}/\sqrt{3} = 0.01/\sqrt{3} = 0.006 \text{ K}$$

The *estimated* component of uncertainty is given by

$$s_\varphi = \varphi \cdot [(A \cdot s_{tc})^2+(A \cdot s_{th})^2+(D \cdot s_{pc})^2+(E \cdot s_{ph})^2]^{1/2} =$$

$$= \varphi[(0.0671 \cdot 0.025)^2 \cdot 2+(0.99 \cdot 10^{-5} \cdot 2)^2 \cdot 2]^{1/2} = 0.0024 \cdot \varphi$$

With $\varphi < 1.0$ $s_\varphi < 0.0024$ or in terms of % RH $s_\varphi < 0.24$ % RH

The *expected* component of uncertainty is given by

$$w_\varphi = \varphi(A\cdot w_{tc})^2+(A\cdot w_{th})^2+(B\cdot w_{C2})^2+(C\cdot w_{C3})^2+(D\cdot w_{pc})^2+(E\cdot w_{ph})^2)^{1/2} =$$

$$= \varphi\bullet[(0.0671\cdot 0.06)^{2}\cdot 2 + (0.0786\cdot 0.006)^2 + (0.0986\cdot 0.006)^2 +$$
$$+ (0.99\cdot 10^{-5}\cdot 10)^{2}\cdot 2]^{1/2} = \varphi\bullet[32.4\cdot 10^{-6}+0.2\cdot 10^{-6}+0.3\cdot 10^{-6}+1.96\cdot 10^{-8}]^{1/2} =$$
$$= 0.0057\bullet\varphi$$

with $\varphi < 1.0$ then $w_\varphi < 0.0057$ or in terms of % RH $w_\varphi < 0.57$ % RH

The *combined* uncertainty of the relative humidity is

$$u_\varphi = (s_\varphi{}^2 + w_\varphi{}^2)^{1/2} = \varphi\bullet(0.0024^2+0.0057^2)^{1/2} = 0.0062\bullet\varphi$$

and the *total* uncertainty is estimated to be

$$U_\varphi = K\bullet u_\varphi = 2.5\bullet 0.0062\bullet\varphi = 0.0155\bullet\varphi$$

In terms of % RH this would imply a total uncertainty of $U_\varphi = 0.5$ % RH at $\varphi = 30$ % RH, $U_\varphi = 0.9$ % at $\varphi = 60$ % RH and $U_\varphi = 1.4$ % at $\varphi = 90$ % RH.

B6 Determination of wet bulb temperature

The psychrometer formula according to Sprung reads (VDI 3786, ref. B5)

$$p_w = p_s - A \cdot p_0(t - t_{wb}) \qquad \text{(eq. B29)}$$

$$t_{wb} = \frac{p_w - p_s(t_{wb})}{A \cdot p_0} + t \qquad \text{(eq. B30)}$$

Equation B30 provides an implicit relationship between the wet bulb temperature (t_{wb}), the saturation vapour pressure at the wet bulb temperature ($p_s(t_{wb})$), the actual vapour pressure (p_w) and the dry bulb temperature (t). The constant A is given as $6.6 \cdot 10^{-4}\ K^{-1}$.

Differentiation of equation B30 results in the following expression for the uncertainty of the wet bulb temperature,

$$\Delta t_{wb} = \Delta t + \frac{1}{A \cdot p_0} [\, \Delta p_w - \Delta p_s + (p_s - p_w) \bullet \frac{\Delta p_0}{p_0} + (p_s - p_w) \bullet \frac{\Delta A}{A} \,] \qquad \text{(eq. B31)}$$

But according to the Magnus equation

$$p_s = p_s(t_{wb}) = C_1 \exp \left[\frac{C_2 \cdot t_{wb}}{C_3 + t_{wb}}\right] = C_1 \bullet e_{wb} \qquad \text{(eq. B32)}$$

$$\Delta p_s = e_{wb} \bullet [\Delta C_1 + \frac{C_2 \cdot C_3}{(C_3 + t_{wb})} \bullet \Delta t_{wb} + (\frac{t_{wb}}{C_3 + t_{wb}}) \bullet \Delta C_2 - \frac{C_2 t_{wb}}{(C_3 + t_{wb})^2} \bullet \Delta C_3] \qquad \text{(eq. B33)}$$

$$p_w = p_s(t_{dp}) = C_1 \exp(\frac{C_2 \cdot t_{dp}}{C_3 + t_{dp}}) = C_1 \bullet e_{dp} \qquad \text{(eq. B34)}$$

$$\Delta p_w = e_{dp} \bullet [\Delta C_1 + (\frac{C_2 \cdot C_3}{C_3 + t_{dp}}) \bullet \Delta t_{dp} + (\frac{t_{dp}}{C_3 + t_{dp}}) \bullet \Delta C_2 - \frac{C_2 t_{dp}}{(C_3 + t_{dp})^2} \bullet \Delta C_3] \qquad \text{(eq. B35)}$$

Including the expressions for Δp_s and Δp_w in equation B31 yields an estimate of Δt_{wb}.

B7 Determination of carbon dioxide concentration

The uncertainties in the calibration of carbon dioxide sensors derive both from the calibration equipment and the sensor and consist of the following major components:

1. *Variations in the operating conditions (stability).*
   Random variations in the circulated air flow rate, the supply of reference gas, the temperature of the thermostatic baths, supply voltage etc. result in carbon dioxide fluctuations causing an estimated component of uncertainty ("random error") according to

   $$s_{\bar{x}CO2} = \left[\frac{1}{n(n-1)} \sum_{1}^{n} (x_{CO2} - \bar{x}_{CO2})^2\right]^{½} \qquad \text{(eq. B36)}$$

2. *Conditions of installation.*
   Ambient fluctuations, temperature effects, variable composition of the reference gas, concentration gradients inside the calibration chamber, humidity variations etc. generate expected components of uncertainty, the magnitudes of which are estimated by means of their expected maximum influences a_j.

   $$w_{CO2,j} = \left| a_{CO2,j} / \sqrt{3} \right| \qquad \text{(eq.B37)}$$

3. *Point of operation.*
   In the case of sensors with non-linear characteristics (applies to all sensors to some extent) varying operational conditions will generate an uncertainty due to the uncertainty in the actual point of operation in accordance with item 1 and the uncertainty due to the conditions of installation in accordance with item 2,

   $$w_{CO2,E1} = s_{\bar{x}CO2,E} = \left| \frac{\partial E}{\partial x_{CO2}} \right| \bullet s_{\bar{x}CO2} \qquad \text{(eq. B38)} \qquad \text{and}$$

   $$w_{CO2,E2} = \left| \frac{\partial E}{\partial x_{CO2}} \bullet \left(\sum_{i=1}^{n} w_{CO2,j}^2 \right)^{½} \right| \qquad \text{(eq. B39)} \qquad \text{respectively,}$$

   where $E(x_{CO2})$ is the concentration dependent error of the sensor according to the calibration certificate.

4. *Uncertainty due to the calibration process.*
   The uncertainty due to the calibration process will contain the uncertainty of traceability to the National Primary Calibration Laboratory as well as the uncertainty in the secondary calibration process at the department of energy technology. In the case of carbon dioxide concentration the supplier of the gas has to be relied upon (see figure B1). Installation errors may differ between the calibration situation and the actual measurement situation.

Calibration errors mainly give rise to expected components of uncertainty,

$$w_{CO2,C} = |a_{CO2,C}/\sqrt{3}| \qquad \text{(eq. B40)}$$

Final result.
The final result for the *estimated* component of uncertainty is given directly by equation B1,

$$s_{\bar{x}CO2} = [\frac{1}{n(n-1)} \sum_{1}^{n} (x_{CO2} - \bar{x}_{CO2})^2]^{½}$$

Typical values for the standard deviation of the mean value in the measurement of carbon dioxide concentration for sensors S5 and S6

x_{CO2} (ppm)	617		1817
s_{CO2} (ppm)	1.2		1.6
x_{CO2} (ppm)	414		1838
s_{CO2} (ppm)	0.8		1.0

The final result for the *expected* component of uncertainty is given by combining individual uncertainties in accordance with equation B2,

$$w_{CO2} = [\, w_{CO2,E1}^2 + w_{CO2,E2}^2 + \sum_{j=1}^{n} w_{CO2,j}^2 + w_{CO2,C}^2]^{½}$$

Expected uncertainty due to installation effects: $w_{CO2,1} < 0/\sqrt{3} = 0$ ppm

Expected uncertainty due to the influence of humidity: $w_{CO2,2} < 3/\sqrt{3} < 2$ ppm

Expected uncertainty due to the influence of temperature: $w_{CO2,3} < 5/\sqrt{3} < 3$ ppm

Expected uncertainty due to the influence of pressure: $w_{CO2,4} < 1/\sqrt{3} < 0.6$ ppm

Expected uncertainty due to the influence of supply voltage: $w_{CO2,5} < 5/\sqrt{3} < 3$ ppm

Expected uncertainty due to the influence of supply frequency: $w_{CO2,6} < 1.7\,/\sqrt{3} < 1$ ppm

Expected uncertainty due to the point of operation (caused by random variations) : $w_{CO2,E1} < 0.05 \bullet 1.6 < 0.08$ ppm

Expected uncertainty due to the point of operation (caused by other expected uncertainties) : $w_{CO2,E2} < 0.05 \bullet 0.02 \bullet x_{CO2}/\sqrt{3} < 0.0006 \bullet x_{CO2}$ ppm

Expected uncertainty due to the composition of the reference gas: $w_{CO2,C} < 0.02 \bullet x_{CO2}/\sqrt{3} = 0.012 \bullet x_{CO2}$ ppm

$$w_{CO2} < [\, \sum_{j=1}^{n} w_{CO2,j}^2 + w_{CO2,E1}^2 + w_{CO2,E2}^2 + w_{CO2,C}^2]^{½}$$

At a CO_2-concentration of 1000 ppm the numerical values given above provides

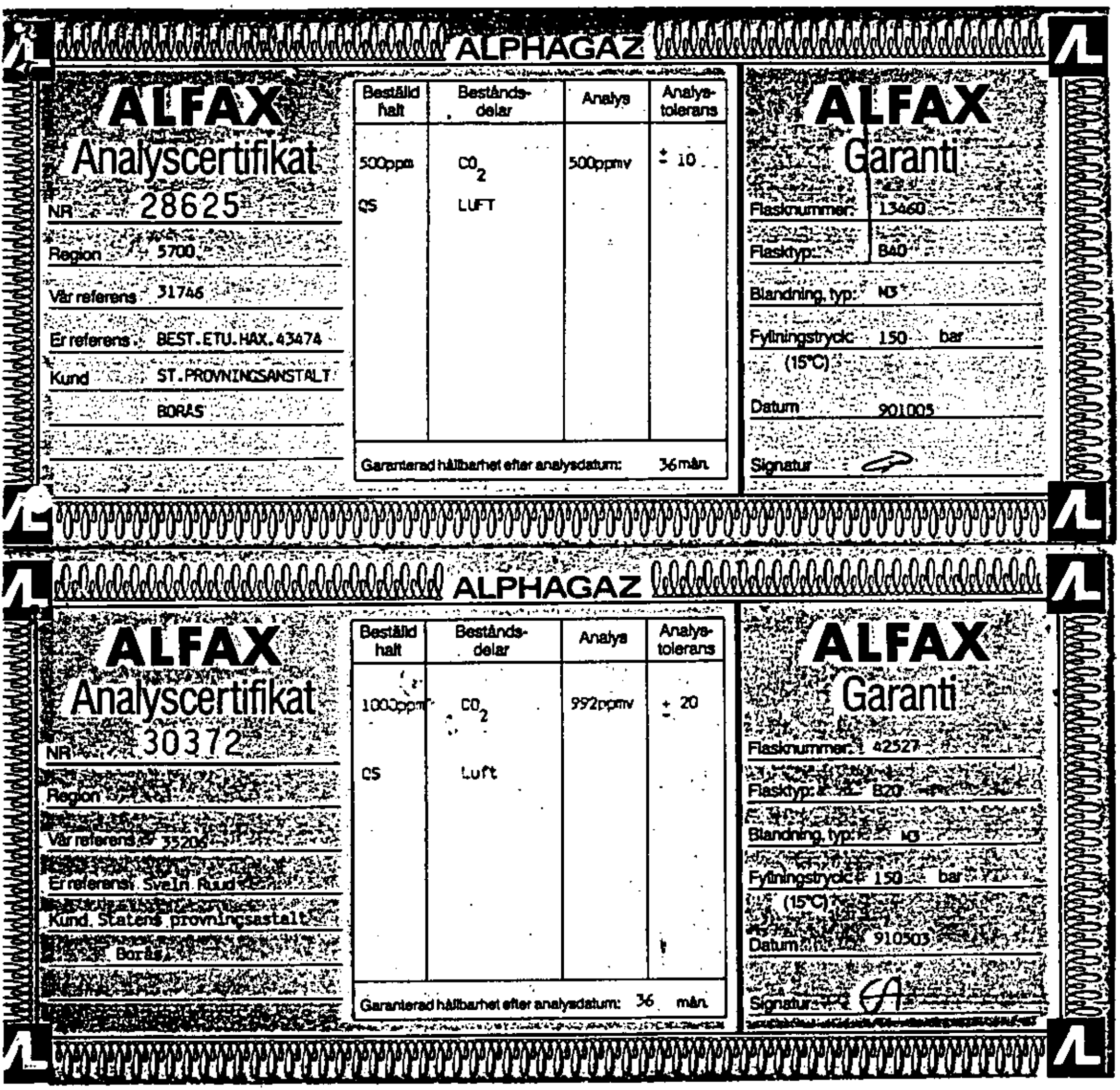
$$w_{CO2} < [0^2+2^2+3^2+0.6^2+3^2+1^2+0.08^2+(0.0006\bullet 1000)^2+(0.012\bullet 1000)^2]^{½} < 13.0 \text{ ppm}$$

The combined uncertainty for the mean value of the concentration measurement is given by

$$u_{CO2} = [s_{\bar{x}CO2}{}^2 + w_{CO2}{}^2]^{½} = [1.6^2 + 13.0^2]^{½} < 13.1 \text{ ppm}$$

The total uncertainty for the mean value of a carbon dioxide calibration measurement is given by

$$U_{CO2} = k\bullet u_{CO2} = 2.5\bullet 13.1 < 33 \text{ ppm}$$



ALPHAGAZ

ALFAX
Analyscertifikat
NR 28625
Region 5700
Vår referens 31746
Er referens BEST.ETU.HAX.43474
Kund ST.PROVNINGSANSTALT
BORÅS

Beställd halt	Beståndsdelar	Analys	Analystolerans
500ppm	CO_2	500ppmv	± 10
QS	LUFT		

Garanterad hållbarhet efter analysdatum: 36 mån.

ALFAX
Garanti
Flasknummer: 13460
Flasktyp: B40
Blandning, typ: N3
Fyllningstryck 150 bar
(15°C)
Datum 901005
Signatur

ALPHAGAZ

ALFAX
Analyscertifikat
NR 30372
Region [illegible]
Vår referens 35206
Er referens Svein Ruud
Kund. Statens provningsastalt
Borås

Beställd halt	Beståndsdelar	Analys	Analystolerans
1000ppm	CO_2	992ppmv	± 20
QS	Luft		

Garanterad hållbarhet efter analysdatum: 36 mån.

ALFAX
Garanti
Flasknummer: 42527
Flasktyp: B20
Blandning, typ: N3
Fyllningstryck 150 bar
(15°C)
Datum 910503
Signatur

Figure B1. Example of a calibration certificate for a flask of reference gas.

B8 Determination of VOC concentration

The uncertainties in the calibration of VOC-sensors derive both from the calibration equipment and the sensor and consist of the following major components:

1. *Variations in the operating conditions (stability).*
   Random variations in the circulated air flow rate, the supply of reference gas, the temperature of the thermostatic baths, supply voltage etc. result in VOC fluctuations causing an estimated component of uncertainty ("random error") according to

   $$s_{\bar{x}VOC} = [\frac{1}{n(n-1)} \sum_1^n (x_{VOC} - \bar{x}_{VOC})^2]^{1/2} \qquad \text{(eq. B40)}$$

2. *Conditions of installation.*
   Ambient fluctuations, temperature effects, variable composition of the reference gas, concentration gradients inside the calibration chamber, humidity variations etc. generate random components of uncertainty, the magnitudes of which are estimated by means of their expected maximum influences a_j.

   $$w_{VOC,,j} = |a_{VOC,,j}/\sqrt{3}| \qquad \text{(eq. B42)}$$

3. *Point of operation.*
   In the case of sensors with non-linear characteristics (applies to all sensors to some extent) varying operational conditions will generate an uncertainty due to the uncertainty in the actual point of operation in accordance with item 1 and the uncertainty due to the conditions of installation in accordance with item 2,

   $$w_{VOC,E1} = s_{\bar{x}VOC,E} = |\frac{\partial E}{\partial x_{VOC}}| \bullet s_{\bar{x}VOC} \qquad \text{(eq. B43)} \qquad \text{and}$$

   $$w_{VOC,E2} = |\frac{\partial E}{\partial x_{VOC}} \bullet (\sum_{i=1}^{n} w_{VOC,,j}{}^2)^{1/2}| \qquad \text{(eq. B44)} \qquad \text{respectively,}$$

   where $E(x_{VOC})$ is the concentration dependent error of the sensor according to the calibration certificate.

4. *Uncertainty due to the calibration process.*
   The uncertainty due to the calibration process will contain the uncertainty of traceability to the National Primary Calibration Laboratory as well as the uncertainty in the secondary calibration [illegible]. In the case of VOC concentration evaporation of the pure components is relied upon (c.f. appendix A2.8). Calibration errors mainly give rise to expected components of uncertainty,

Final result.

The final result for the *estimated* component of uncertainty is given directly by equation B1,

$$s_{\bar{x}voc} = \left[\frac{1}{n(n-1)} \sum_{1}^{n} (x_{voc} - \bar{x}_{voc})^2\right]^{1/2}$$

Typical values for the standard deviation of the mean value in the measurement of VOC concentration (sensors S1 and S4)

x_{VOC} (mg/m³) **Supply rate**	0.0		3.4
x_{VOC} (mg/m³) **Tenax tube**	0.2		3.7
x_{VOC} (mg/m³)	0.0		0.0
s_{VOC} (mg/m³)	0.0		0.0
x_{VOC} (mg/m³)	99.8		99.8
s_{VOC} (mg/m³)	0.0		0.0

The sensitivity of the sensors is too small to provide any information as to the time variations in VOC concentration. The difference between the supply rate of VOC and the value determined by analysis of Tenax sampling tubes is mainly depending on VOC contamination of the outside air.

The final result for the *expected* component of uncertainty is given by combining individual uncertainties in accordance with equation B2,

$$w_{VOC} = \left[w_{VOC,E1}^2 + w_{VOC,E2}^2 + \sum_{j=1}^{n} w_{VOC,j}^2 + w_{VOC,c}^2\right]^{1/2}$$

Expected uncertainty due to installation effects: $w_{VOC,1} \le 0/\sqrt{3} = 0$ mg/m³

Expected uncertainty due to the influence of humidity: $w_{VOC,2} < 0.06/\sqrt{3} < 0.035$ mg/m³

Expected uncertainty due to the influence of temperature: $w_{VOC,3} < 0.20/\sqrt{3} < 0.12$ mg/m³

Expected uncertainty due to the influence of pressure: $w_{VOC,4} < 0/\sqrt{3} = 0$ mg/m³

Expected uncertainty due to the influence of supply voltage: $w_{VOC,5} < 0.02/\sqrt{3} < 0.12$ mg/m³

Expected uncertainty due to the influence of supply frequency: $w_{VOC,6} < 0.01/\sqrt{3} < 0.006$ mg/m³

Expected uncertainty due to the point of operation (caused by random variations) : $w_{VOC,E1} = 0$ mg/m³

Expected uncertainty due to the point of operation (caused by other expected uncertainties) : $w_{VOC,E2} < 0.1 \bullet 0.48/\sqrt{3} < 0.028$ mg/m³
Expected uncertainty due to the composition of the reference gas:
$w_{VOC,C} < 0.02 \bullet x_{VOC} / \sqrt{3} = 0.012 \bullet x_{VOC}$ mg/m³

$$w_{VOC} < \left[\sum_{j=1}^{n} w_{VOC,,j}^{2} + w_{VOC,E1}^{2} + w_{VOC,E2}^{2} + w_{VOC,C}^{2} \right]^{½}$$

The combined uncertainty for the mean value of the concentration measurement is given by

$$u_{VOC} = \left[s_{\bar{x}VOC}^{2} + w_{VOC}^{2} \right]^{½} = \left[s_{\bar{x}VOC}^{2} + \sum_{j=1}^{n} (w_{VOC,j})^{2} + w_{VOC,E1}^{2} + w_{VOC,E1}^{2} + w_{VOC,C}^{2} \right]^{½} < 0.18 \text{ mg/m}^3 \quad (\text{with } x_{VOC} < 4 \text{ mg/m}^3)$$

The total uncertainty for the mean value of a VOC calibration measurement is given by

$$U_{VOC} = k \bullet u_{VOC} = 2.5 \bullet 0.18 < 0.46 \text{ mg/m}^3 \text{ (at a level of 4 mg/m}^3\text{)}$$

B9 Operational experience

The experience in using the test equipment described in appendix A has in general been acceptably good. Some considerations regarding these matters are given below.

B9.1 Humidity

The equipment used for calibration of humidity sensors has performed according to expectations. Stabilization after a change of operating conditions is in most cases quite rapid (approximately 10 - 20 minutes). Accuracy in the determination of dew point temperature agrees within 0.1 K of values determined by a dew point hygrometer which was calibrated at NIST.

The influence of air velocity on the rise time of humidity sensors has not been possible to investigate using the calibration equipment. Sensors intended for duct mounting will have to be tested in that particular situation by switching between two air flows with different humidities. Absolute accuracy is unimportant for the determination of rise time since this only involves relative changes in the output of the sensor.

B9.2 Carbon dioxide

The humidity calibration equipment has proven to be a valuable asset also in the evaluation of CO_2 sensors. The possibility to control both the humidity, temperature, pressure and composition of the atmosphere simultaneously was a necessity in order to carry out the tests on cross-over sensitivity.

No problems were experienced in providing an atmosphere of constant CO_2 concentration using flasks of certified reference gas conneted to the calibration system. The only major question mark in this test is the absolute accuracy in the composition of the reference gas.

B9.3 VOC

This particular part of the test program turned out to be a major stumbling block due to the unexpectedly high emission rates of VOC from the sensors themselves. This prevented the use of a closed system containing a specified reference gas. An improvised test set up had to be conceived using an open system with continuous evaporation of the individual substances. This made it difficult to keep the actual operating conditions for the sensors constant so only average values over a period of time could be ascertained. These average values were also checked by adsorption on Tenax-type sampling tubes with subsequent analysis using gas- and mass chromatogrophy.

The long and short of this evaluation is that both the choice of reference gas/gases and the actual test are questions not easily resolved. Major changes in the test concept are required to provide a method of test having both a high validity and a reasonable accuracy in absolute terms.

ecbcs bookshop

ANN 18 1992: 2

SP
Swedish National Testing and Research Institute
Box 857, S-501 15 BORÅS, SWEDEN
Telephone: + 46 33 16 50 00, Telefax: + 46 33 13 55 02

SP REPORT 1992:13
ISBN 91-7848-331-X
ISSN 0284-5172