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Poster 1

Accuracy and Development of Tracer-Gas Measurement Equipment

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ABSTRACT

1979 a project was launched at Technological Institute, Copenhagen with the purpose of developing a method for continuous measurement of air change rates in occupied dwellings. Today - 10 years later - we can introduce the first generation of mass-produced measuring equipment performing measurements of air change rates employing the method of constant concentration of tracer gas. The principles used in the first model, which was introduced 1981, are largely identical to those used in the latest model. However, components and programmes have been changed several times. Furthermore, through the years new programmes that expand the capability of the measuring equipment have been developed.

The paper will discuss the development that has taken place over the 10 years, which problems have caused the biggest trouble and how they were solved. Also, the types of measurement performed with the equipment will be touched upon, and we shall take a closer look at a couple of special measurements. Finally, the accuracy of the equipment as well as the cost of reaching today's level of development will be discussed.

1. INTRODUCTION

The energy crisis in 1973 dramatically increased the interest in measuring the air change rate of dwellings. All buildings should be made as tight as possible in order to reduce the energy consumption for heating the infiltration air; and air change rate measurements were used to determine the effect of different methods of making buildings tight.

In Denmark the successful campaign to make buildings tight and to reduce airing had a serious "side-effect": Our lacking knowledge about the air change rates in buildings had made us go too far in our efforts to save energy, and we were faced with an indoor air quality problem in many buildings.

To build up the necessary knowledge about air change rates in buildings a project was launched at Technological Institute with the purpose of developing a method for continuous measurement of air change rates of occupied dwellings, and of determining the air change in various dwellings. Equipment to measure air change rates employing the the method of constant concentration of tracer gas was developed and in the autumn of 1981 the measuring equipment was ready for its first appearance in the field.

2. THREE GENERATIONS OF TRACER-GAS MEASUREMENT EQUIPMENT

2.1 The first generation

The first Danish equipment ever for continuous measurement of air change rates was being constructed at the Technological Institute in Copenhagen in 1979 on a grant from the Minstry of Trade. The project had the following impressive title: "Development of a method for continuous measurement of the natural air change, the relative humidity and temperature levels etc. in the tightened part of occupied dwellings, as well as single measurements of the size of the natural air change in dwellings with air-to-air heat exchangers".

The international cooperation that had been established through AIC (Air Infiltration Centre) greatly influenced the project right from the beginning. At AIC-congresses measurement methods could be discussed and fruitful contacts established. Especially our cooperation with Professor David T. Harrje of Princeton University was very productive. As a result of this cooperation one of his students, Timothy McNally, worked on our project for a year as a Fullbright student.

It only took 2 years to build the equipment; impressive, when considering that fact that it was many months before the ambitions had been reduced to a feasible level. Figure 1 shows the first generation measuring equipment ready for the first measurements.

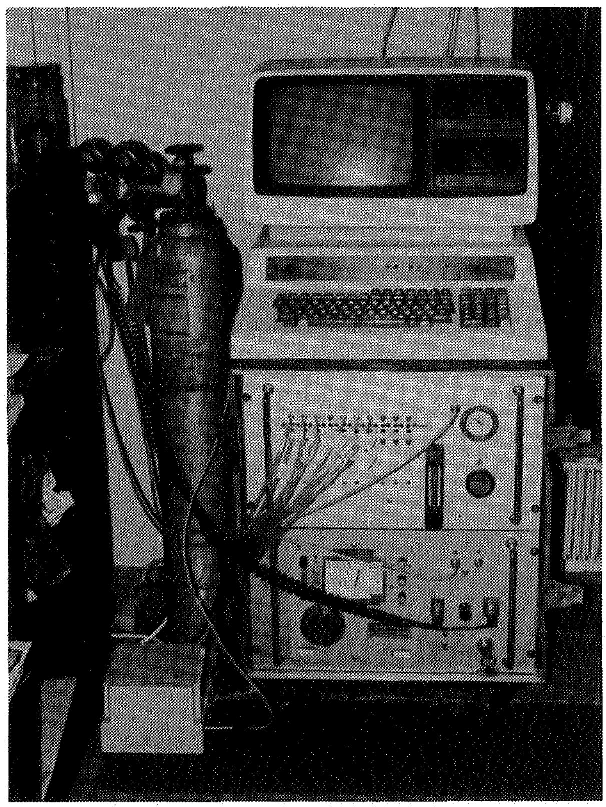

Fig. 1: First generation of tracer-gas measuring equipment

The equipment was designed to perform measurements in buildings with up to 10 rooms. The concentration in the rooms was kept at 50 ppm nitrous oxide, and the air change rate was calculated from the quantity of nitrous oxide necessary to dose to maintain the concentration. The tracer gas was dosed through 10 solenoid valves, and through another 10 solenoid valves air samples were collected from the 10 rooms.

With measurements in the field the equipment evolved from the development phase to the maintenance phase, and this phase turned out to be tremendous. It is a well known fact that a chain is not stronger than its weakest link, and this chain consisted of quite a number of weak links, ranging from the tailor made sampling and dosing equipment, and purchased gas analyzers and microcomputers, to the home-made computer programme.

To keep down expenses for the tracer gas and to avoid the uncertainty of the gas mixture concentrations we chose to dose with pure nitrous oxice. However, this requires a lot of the tightness of the dosing system all the way from the gas cylinder to the dosing points in the rooms. Most of the leaks in the dosing system were found at the tracer-gas cylinder or the pressure reduction valve on the tracer-gas cylinder. Even though, at each start-up, the equipment was tested for leaks with soap water we did not always find all leaks; therefore, we introduced a very efficient check-up of leaks and other "illnesses" in the dosing system which rescued many a measurement. The check-up method was to keep track of the consumption of tracer gas. Before and after each measurement the tracer-gas cylinder was weighed, and the gas consumption thus ascertained was compared with the total amount of doses emitted by the measuring equipment during the measurement.

The sampling system must also be tight. This was one of the biggest problems in the first generation measuring equipment. At a concentration of around 50 ppm nitrous oxide where the equipment was placed and in the rooms to be measured, a little false air had no significant effect; but if the equipment was placed outside the measuring area the error would be considerable.

At first, software errors were predominantly due to the fact that the dosing algorithm was adjusted so as to keep a constant concentration in the rooms, also when the air change rates varied considerably due to opening of windows etc. Later, the errors were more self-inflicted, introduced by frequent changes in the programme. Even small, apparently innocent, changes had drastic effects. Once, a small change in the programme caused us to lose an entire week's measurements. The measurement worked according to schedule, but at the end of the week no measuring data at all had been stored on the diskette.

Errors in the dosing system, the sampling system and the software may just be accepted - after all, it was a prototype. Errors in mass-produced equipment, however, is harder to accept; and the purchased parts for the tracer-gas equipment were not any more reliable than the parts produced by ourselves.

Quite involuntarily the equipment had to be operated by 2 persons. During the first measurement we found out that the box containing the entire system was too heavy and unhandy for one man to get in and out of vans and houses. This did not matter much, however, as 2 persons were necessary for installing the tubing as well as testing and starting up the equipment in one day.

Having been used for 18 months the first generation equipment was ready for a reconstruction. The immediate reason was a recommendation from the Health and Safety Executive that we do not use nitrous oxide as a tracer gas. Furthermore, we had encountered mechanical problems with the tightness of the sampling system, and fouling of the air lines in the system. Quite simply, the sampling system had been clogged up by dust, because we had "forgotten" to equip all sampling tubes with filters.

2.2 The second generation

Figure 2 shows the equipment after reconstruction; as a matter of fact it was a completely new system, as only few components from the first equipment were used again.

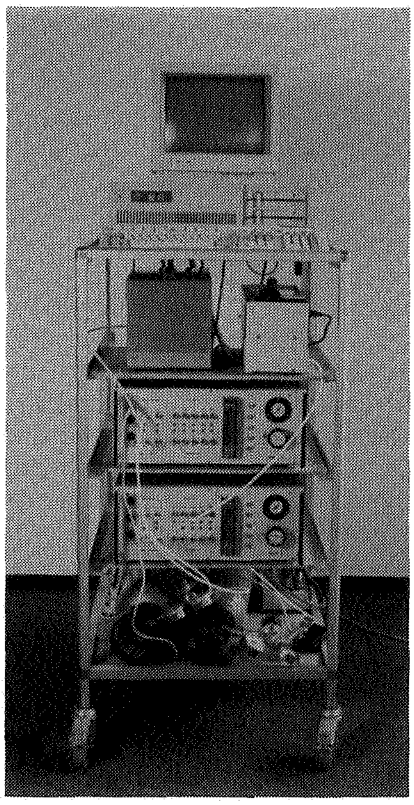

Fig. 2 Second generation of tracer-gas measuring equipment

The most substantial improvements in the second generation equipment were:

- Grouping of the equipment into units that could be carried by one person.
- Replacement of gas analyzer so as to be able to measure the tracer gas SF_6.
- New sampling system that was tight and equipped with filters on the inlet.
- Grouping of the dosing system in units of five dosing points each, thus prepared for measurements with two tracer gases.

With minor modifications this equipment has been used since 1983, and another four systems of this type have been built in the years until 1987. Three systems are at the Technological Institute, one is in Belgium, and one in Norway. The second generation equipment has generally worked satisfactorily, but the maintenance costs have been heavy. Especially, the costs for calibration of gas analyzers, pressure transducers, dosing nozzles, and temperature sensors. Again, the problem was too poor quality of the purchased components. In particular, it was not worthwhile trying to economize on the electronics (computers, A/D converters, etc.).

2.3 The third generation

1985 saw the beginning of the third generation equipment. This time the purpose was to produce a commercial product, reliable, handy, and easy to operate. The third generation is being produced by Brüel & Kjær, and uses the same principles as the second generation. Figure 3 shows the second and third generations.

The most substantial improvements from the second to the third generation are:

- The equipment is considerably smaller and less heavy.
- The communication between computer, gas analyzer, and dosing and sampling units has been fully digitalized, i.e. A/D converters in the computer can be avoided, and, consequently, small lap top computers can be used.
- The Brüel & Kjær gas monitor is stable over a long period of time; consequently, automatic recalibration of the monitor during measuring can be omitted.

- Supplementary air has been introduced on all dosing tubes, to dilute the tracer gas and to transport it faster to the dosing point.
- Automatic calibration of dosing nozzles has been introduced.
- An independent CPU in the dosing and sampling unit has made it possible to continuously monitor the dosing flow 10 times/second. This reduces the requirements for pressure reduction valves on the tracer-gas cylinders.
- More flexible and user-friendly software. For example, routines for calculating the age of the air have been introduced, and measurements with two tracer gases are now possible. Figure 4 shows an example of a screen picture.

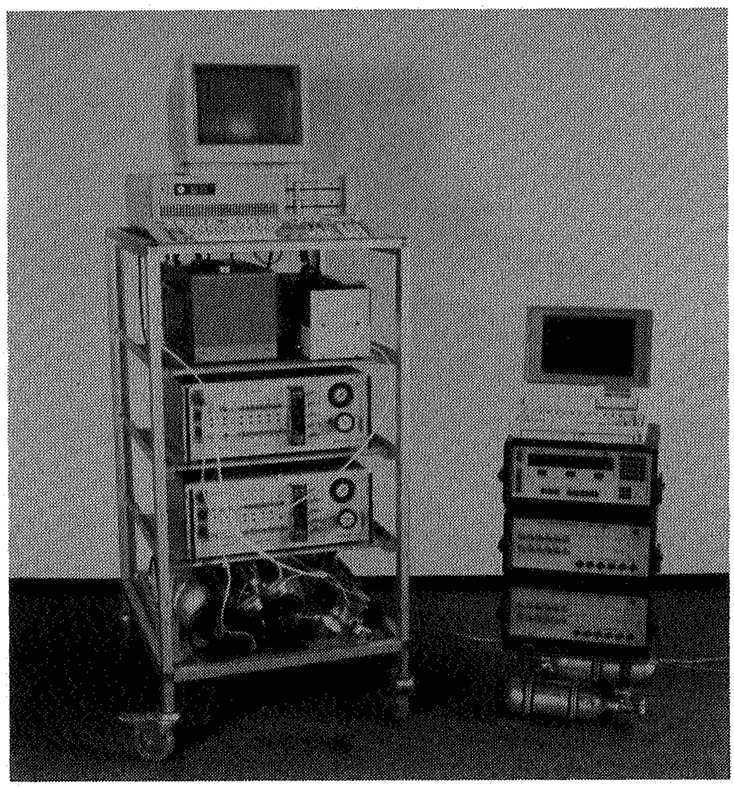

Fig. 3 The second and third generation of tracer-gas measuring equipment next to each other

In addition to these improvements the reliability of the equipment has been accentuated. The dosing system, for instance, is assembled in a clean room to avoid particles in the air lines that may clog up the dosing nozzles. Furthermore, semiconductor sensors for temperature measurements have been replaced by Pt100 sensors, and the number of cables for connection of the system has been reduced from seven to three.

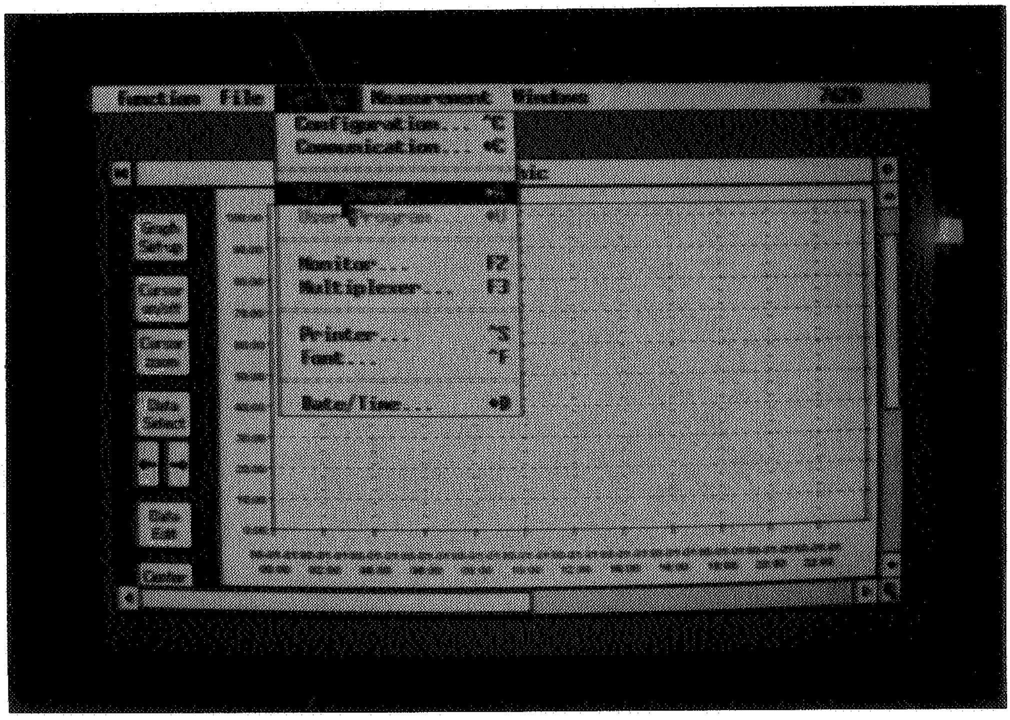

Fig. 4 Screen picture from the software that controls the tracer-gas measurements

As a new feature, to reduce the number of futile measurements, status flags have been introduced. For every measurement from the gas monitor there will be a number of flags giving information on its function. For example, a flag indicates whether the infrared source in the gas monitor is functioning correctly, whether the chopper frequency is correct, and whether the measurement is unreliable due to vibration noise. Likewise, the dosing and sampling unit indicates whether the suction tubing is clogged up, or whether the pumps are yielding sufficient pressure.

In addition to these measures, Brüel & Kjær's standard product test should also have improved the reliability of the equipment. Among other things, this standard includes testing at high and low temperatures, test for electrical shock, and a bump test, where the equipment is dropped 1000 times onto a desk from 25 mm height.

Of the new equipment, so far only the gas measurement principle has been tested for a longer period of time, as 2 of Brüel & Kjær's analyzers have for the past year been used together with the second generation tracer-gas measuring equipment for measuring with 2 tracer gases.The purpose of the measurements is to determine the air flow between the crawl space and the living rooms in one-family houses.

This third generation measuring equipment, shown on the below figure, comprises the sum of 10 years' experience in tracer-gas measurements in Denmark, and should result in making tracer-gas measurements a tool for solving problems, instead of being an art in itself.

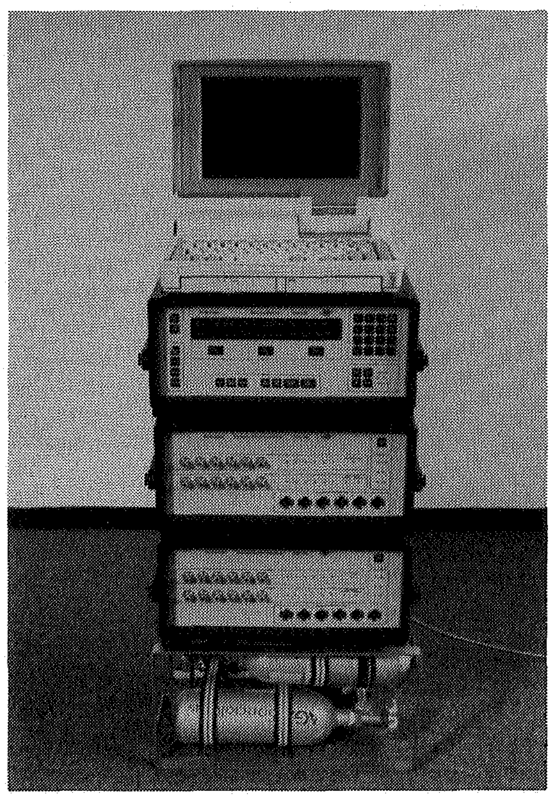

Fig. 5 Third generation of measuring equipment

3. MEASUREMENTS

Since 1981 approx. 75 air change measurements with tracer-gas measuring equipment have been performed at the Technological Institute, of which 41 have been performed in dwellings, 22 in schools and child care institutions, 5 in offices, and a single one in an industrial company. The equipment has been in operation for a total of approx. 430 days.

We would like to specially point out the largest and most difficult of those measurements - an air change measurement at a small brewery. Setting up the equipment alone took several days, as a total of 1500 m of tubing had to be installed, with 250 m as the longest stretch. The volume of the brewery was 100,000 m^3, and the method used was the constant concentration measurement with a target concentration of 300 ppb. Even though we had forced down the monitor, so that we measured with errors of approx. 20%, we did use 80 kg tracer gas for a week's measurements. The purpose of the measurement was to find out why the beer bottles in a store room in the centre of the building very quickly were covered with dust which made them look old. The first day's measurements showed that the store room was very well ventilated with air from other parts of the brewery and with infiltration air. Only about 10% of the air change measured in the store room came from the ventilation system for the store room. Furthermore, it was found that the outdoor air contained the same amount of dust as the air in the store room and had the same grain mixture, and thus the dust on the bottles was caused by too big air change in the store room.

A rather curious incident occured: We almost got the entire brewery closed down, because the local safety officer found that it was highly dangerous to be near our mixing fans.

Another interesting measurement was performed in a low-energy office building. All offices were equipped with a hinged window, a fan, and an electric heater. When the fan was turned on, the heater was turned off, so it was almost impossible to waste energy. The system was not completely reliable, though, as opening the window did not turn off the heat. Everybody in the office section expressed their satisfaction with the indoor climate, even though we measured an air change rate down at 0.1 times/hour. As a matter of fact, we even got as low as 0.05 times/hour during the night.

Another curious incident occurred here. Management found it peculiar that there was a peak in the air change rate around three o'clock in the afternoon. They feared that the increase in the air change rate was due to the employees leaving at that time instead of at four o'clock as according to agreement. However, a printout of the air change rates for all offices revealed the one office only caused the increase in air change. It turned out that the window in that office was often open at 3 o'clock because the employees in the office section had their coffee break there.

4. ACCURACY

Tracer-gas measuring methods are very accurate. When used in the laboratory they show good conformity with recognized reference methods for measuring air flow. When used in air change measurements with the constant concentration of tracer gas method the accuracy normally is better than 5%. Whether these accuracies also apply to field measurements, depends on the stability of the measuring equipment as well as on which additional sources of error to include in the field measurements. Based on an analysis of measuring errors in the case of flow measurements in ducts and in the case of air change measurements in rooms, we shall below estimate the error of tracer-gas measurements. Measuring flow in ducts will in this connection be considered the basis of the error analysis, as it has the best defined sources of error.

The accuracy of measuring methods cannot be discussed unless the quantity to be measured has been clearly defined. Is it m^3/h dry air at 20^oC and 1 atm, or is it m^3/h at actual pressure, temperature and humidity? We have chosen to measure m^3/h at 20^oC, 1 atm, and actual humidity.

Below is a list of the sources of error we could think of for our third generation measuring equipment:

Gas concentration measurement of the tracer gas SF6:

Zero point errors		5 ppb
Range error		10 o/oo
Zero drift (over 1 month)		5 ppb
Range drift (over 1 month)		15 o/oo
Zero drift due to temperature ($18-26^oC$)		2 ppb
Range drift due to temperature ($18-26^oC$)		12 o/oo
Zero drift due to pressure (970-1050 mbar)		2 ppb
Range drift due to pressure (970-1050 mbar)		4 o/oo
Interference from water vapour ($0-15^oC$ Tdew)	0 ppb	
Interference from CO_2 (350-2000 ppm)	0 ppb	
Errors on calibration gas (14.8 ppm)		20 o/oo

The error for gas measurements is 8 ppb on Zero point and 30 o/oo on the measured value, when calibrating the monitor each month.

Dosing of tracer gas:

The tracer gas is dosed through a nozzle at the speed of sound. Therefore, the dosing is only depending on pressure and temperature of the gas upstream the nozzle. The error for the dosed gas quantity is dependant on the errors for these two measurements, the errors on measuring nozzle constants and errors on registrating dosing time. The nozzle constants are automatically measured in the dosing unit by a special calibration routine.

Error when establishing nozzle constant, approx.	18 o/oo
Error from variation in pressure measurement, approx.	5 o/oo
Error from variation in temperature measurements, approx.	5 o/oo
Error for dosing time, approx.	5 o/oo
Error due to tracer-gas impurities	10 o/oo
Leakage in dosing unit per channel	0.24 ml/h

The error for dosed quantity is 0.24 ml/h + 22 o/oo when calibrating the dosing unit each month.

Contamination of the sample during transport:

For our equipment the greatest risk of contamination of the sample is, when it is inside the dosing and sampling unit.
Error due to contamination of air sampler   5 ppb

In addition to errors in the measuring equipment, also the measuring method causes some errors. When measuring flow in ducts with constant emission of tracer gas there is only one source of error: Insufficient mixture of the tracer gas into the air. This kind of error can be estimated by means of a traverce measurement in the sampling point. The dispersion of the tracer-gas concentration indicates the upper limit for this measuring error. A typical mixture error when measuring flow in ducts is 20 o/oo.

Total error when measuring in duct with flow of 100 m^3/h and a dose of 0.5 ml/s:

Error, tracer-gas measurement (18 ppm)	30 o/oo
Error, dosing	22 o/oo
Error, contamination of sample (only negative errror)	0 o/oo
Error, insufficient mixture	20 o/oo
Total error for measurement	42 o/oo

Total error when measuring in duct with flow of 100000 m^3/h and a dose of 15 ml/s:

Error, tracer-gas measurement (0.54 ppm)	33 o/oo
Error, dosing	22 o/oo
Error, contamination of sample (only negative error)	9 o/oo

Error, insufficient mixture	20 o/oo
Total error for measurement	49 o/oo

When air change rates are measured with the method of constant concentration of tracer gas, it is possible to measure in one room or in many rooms with a more or less free air flow between the rooms. If the measuring area is divided into many rooms, the outdoor air change rate for each room as well as for the entire measuring area can be determined. It is relatively easy to show that the error on the measurement of the outdoor air change rate for one of the rooms in a measuring area can be very large if the room has a considerable air exchange with other rooms in the area. Large errors on the measurement of outdoor air change rates for the individual rooms, however, do not give a large error for the measurement of air change rate for the whole measuring area.

When the entire air change rate for the measuring area is measured, two errors caused by the method used should be taken into consideration:

1. The difference between the concentration in the measuring point and the average tracer-gas concentration of the air leaving the measuring area.
2. The error caused by fluctuations in the tracer-gas concentration in the measuring point.

Example: A measurement in a 300 m^3 building with an air change rate of 1.0 times/h. The difference between the average tracer-gas concentration in the room and the average tracer-gas concentration in different points at outer walls, ceilings and floors is max. +/-4%. The fluctuation of the concentration in each measuring point is also max. +/-4%.

For this measurement the error will be as follows:

Error, tracer-gas measurement (1 ppm)	31 o/oo
Error, dosing (Gaussian distribution)	22 o/oo
Error, dosing (only negative error)	2 o/oo
Error, contamination of sample (only negative error)	5 o/oo
Error, measurement of mean concentration	40 o/oo
Difference between concentration in air leaving measuring area and mean concentration in room	40 o/oo
Error, fluctuation of tracer-gas concentration (averaging time when calculating air change rate 1 hour)	57 o/oo
Total measuring error	96 o/oo

When filtering concentration measurements by means of kalman-filter, or when averaging over longer periods of time, the error for the actual measurement can be reduced considerably.

5. CONCLUSION

It is our hope that the development through the last 10 years has resulted in equipment which is easy to operate, easy to transport, does not require frequent calibration, and which does not consume a lot of tracer gas. The above mentioned characteristics will ensure that the expenses for performing tracer-gas measurements can be considerably reduced, and will therefore help propagate the measuring method to a wider audience. Even the fact that today you can buy a complete measuring system, will make the measuring method more known. When looking at the accuracy of the measuring method we can draw the conclusion that not much can be gained by refining the measuring equipment, as parameters such as accuracy of calibration gases and variation in time as well as in place in tracer-gas concentrations in the room now constitute the largest sources of error. Data for the variation in tracer-gas concentrations under measurement are scarce, so it is still difficult to give certain estimations about the accuracy of the measuring method in different situations. The current estimation of the accuracy at around 5% seems fairly correct, though.

The fact that the development of measuring equipment and methods incurred great costs will probably not come as a surprise, but the size of the costs is impressive nonetheless. Developing the first generation of measuring equipment took approx. 2.5 man years. When the second generation of measuring equipment was ready approx. 3.5 man years had been spent, and upon completion of the third generation a total of 12 man years had been spent.