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# INDOOR AIR QUALITY MEASUREMENTS IN AN AIR-CONDITIONED OFFICE BUILDING

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ABSTRACT

Air quality measurements along with airflow rate measurements of air-conditioning system were conducted in an office building occupied by workers with clerical activities. Contaminants measured were $CO_2$, SPM (suspended particulate matters), NOx and airborne bacteria.

Indoor $CO_2$ and SPM levels were found to be quite high, 1,600 ppm ($CO_2$) and 0.25 mg/m$^3$ (SPM), respectively, at their maximum and exceeded Japanese Standards.

The cause of the high concentration was found to be airleakage in the outdoor air intake duct. The airleakage rate was estimated applying mass-balance model of $CO_2$. Results indicated that the actual outdoor air intake rate was less than half of that expected. The applicability of the model was examined and it was considered to be practically satisfactory.

## INTRODUCTION

During recent years, with strong demand for improvement in airtightness of building envelopes as an energy conservation measure, there has been increased awareness of the health effects that may result from prolonged exposure to indoor air contaminants in office buildings. Numerous reports on these problems, so-called "sick-building syndrome," "building illness," or simply "sick building," were presented to many conferences and journals. Comprehensive reviews were made by WHO (1983) and Stowijk (1984).

In Japan we have a "Law for Maintenance of Sanitation in Buildings" (1983), which is used to establish and which defines indoor air quality levels in buildings having total floor area of more than 3,000 m$^2$ and equiped with a central air-conditioning system. For instance $CO_2$ and SPM (suspended particulate matters) levels are to be less than 1,000 ppm and 0.15 mg/m$^3$, respectively, and monthly measurement by building maintenance engineers and annual inspection by regional health centers must be performed. But with the few exceptions made by Muramatsu (1984) most measurements have not been published because the major concern is whether the indoor air quality level of each building meets the law or not. We have been conducting on-the-spot measurements since before the oil crisis and have published the reports (Yoshizawa 1967, 1976, 1978, 1980 and Sugawara 1967). There are several papers besides ours, but the data are not enough.

This paper presents the results of our air quality measurements in an office building to learn the actual status of the indoor air quality and to find the problems related to it. Measurements of NOx and airborne bacteria as well as $CO_2$ and SPM were made. Not many data are available in the literature on NOx and bacteria levels. $CO_2$ and SPM levels exceeded the Japanese standards in many cases, and indoor NOx levels were higher than outdoors depending on the case.

Airleakage in the outdoor air intake duct, which was the major cause of the elevated $CO_2$ and SPM, was found. Such undesigned airleakage often exists because of defects in construction

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procedures and improper use of the building. Although airleakage in the building envelope may sometimes improve indoor air quality, airleakage in partitions, especially in those dividing a room and an outdoor air intake duct, deteriorates the air quality. Since airleakage is not a desirable factor in terms of energy conservation and accurate prediction of air quality level, we tried to estimate the airleakage usig a $CO_2$ mass -balance model. The applicability of the model was also examined.

## OUTLINE OF THE MEASUREMENTS

### Building Measured

The object building was an office building constructed in downtown Tokyo in 1974 with ten floors above ground and a basement of two floors. The structure was of steel-framed reinforced concrete and its total floor area was about 6,400m$^2$. Figure 1 shows a plan of the forth floor where air quality measurements were made and where windows were all closed during the measurements. Its floor area was 470m$^2$ and designed capacity was 86 persons.

### Date Surveyed

The measurements were conducted on 9 and 10 December 1980.

### Air-Conditioning System

The building was air-conditioned with an air-handling unit set on each floor. The outdoor air intake was located on the ninth floor and supplied a single-duct system. The air-handling unit of the measured floor had a roughing filter not capable of eliminating tobacco smoke.

A flow visualization test with smoke showed leakage of return air from the office room into the outdoor air intake duct, as shown in Figure 2. This decreased the effective outdoor air intake rate to levels less than expected.

### Measuring Procedures

Factors measured and instruments used are listed in Table 1. Fluctuation patterns of Contaminant levels were monitored at a control point in the office room in question, as shown in Figure 1. Gas sampling for airborne bacteria was made continuously, while sampling for other contaminants was done on hourly basis using the grab sampling method. Samples were taken in polyethylene bags with manual pumps and analyzed as quickly as possible with gas analyzer set on the other floor of the building. Some loss of contaminants, therefore, would be expexted but an almost negligible amount because of the immediate analysis.

Horizontal concentration distributions of contaminants, except for airborne bacteria, were made at 14 points in the room, as shown in Figure 4, once a day at 4 p.m. Airflow rate in each duct was measured only once because operating conditions were kept unchanged over the measerement period. A supplemental duct was used for measurement of volume from the diffusers. Density of the occupants and person smoking were counted hourly by the survey team.

## RESULTS

### Fluctuation Patterns in Density of Occupants and Person Smoking

Densities of occupants and person smoking are shown in Figure 3. About 70 persons, apploximately 80% of designed capacity of the room, were occupying the space during the work period (9 a.m. to 5 p.m.) of both day, 9 and 10 December. Five to six persons, on the average, out of the occupants were smoking all the time. Percentage of the persons smoking was about 7%. The occupant number deceased to 30 during lunch break.

### Operating Pattern of Air-Handling Unit

Air-handling unit was normally turned on at 8:30 and off at 17:00. But it was accidentally turned off from 12:05 to 13:00 of the 10 December, as shown in Figure 3.

### Airflow Rates

Airflow rates from diffusers of the room are shown in Figure 1. Total of these values amounts to approximately 6,650 $m^3/h$, while the airflow rate obtained from the measurement at the supply air duct was 7,092 $m^3/h$. Difference between them is less than 7%.

The airflow rate measured at the outdoor air intake duct of the air-handling unit was 4,972 $m^3/h$. It was not, however, an actual outdoor air intake rate because of the airleakage mentioned before. Actual outdoor air intake rate will be estimated later.

## Fluctuations in Contaminant Levels

Concentration fluctuations of contaminants are shown in Figure 3 along with the occupant density.

The maximum indoor levels are as follows;

| | | |
|---|---|---|
| $CO_2$ | 1,600 ppm | (18:00, December 10) |
| NO | 170 ppb | ( 8:00, December 10) |
| $NO_2$ | 40 ppb | (15:00, December 9) |
| SPM | 250 cpm [0.25 $mg/m^3$] | (18:00, December 9) |
| Airborne Bacteria | 0.4 cfu* | (17:30, December 10) |

* cfu: colony forming unit

The values, 1,600 ppm of $CO_2$ and 0.25 $mg/m^3$ of SPM, far exceeded the allowable levels of the Law for Maitenance of Sanitation in Buildings (1983). This high concentration was considered to be the result of the airleakage.

Fluctuation patterns of $CO_2$ and SPM seem to depend on the occupant density and the operational pattern of air-handling unit rather than on the outdoor level. That is, levels of two contaminants increased when the occupant density increased or when the air-handling unit was turn off and looked almost independent of outdoor concentration fluctuation. The effects of turning the unit on and off were clearly seen from 9:00 to 10:00 and after 17:00 of both days. An interesting event happened during lunch break of December 10 when two contradictory things —— one a decrease in occupant number and other an accidental breakdown of the unit —— occured simaltanously. The levels of $CO_2$ and SPM remained unchanged or slightly increased on December 10, while they decreased during lunch break of December 9 when the unit operated normally.

The fluctuations in NO and $NO_2$, on the other hand, seemed not to be affected by occupant density and unit operational pattern.

Because of the low concentration, no significant trend can be seen in the airborne bacteria level curves except for one case where one can recognize a sharp rise in the curve after 17:00 of December 10. This is considered to be the result of turningoff the air-handling unit.

Except for the fact that indoor NO levels were slightly higher than outdoors, we can see no remarkable evidence of the influence of smoking on the indoor contaminant levels because the number of persons smoking was small.

It may be considered that the high NO concentration at beginning of December 10 came from the influence of outdoor air. The increasing levels of SPM at the end of December 9 and 10 may be the influence of activities of the overtime workers and the cleaning workers in addition to shutdown of the air-handling unit.

## Horizontal Concentration Distributions

Figure 4 shows the horizontal distributions of each contaminant concentration measured at 4 p.m. Figure 5 shows cumulative frequency distribution curves of each contaminant concentration obtained from the horizontal distribution measurements.

All of the $CO_2$ and some of the SPM data exceeded the Japanese standards, 1,000 ppm for $CO_2$ and 0.15 $mg/m^3$ for SPM.

Horizontal distributions of NOx were relatively uniform throughout the room and absolute values of their concentrations are different depending on the date. Concentrations of $CO_2$ and SPM, on the contrary, were distributed nonuniformly. Their absolute values measured on both days are quite similar each other. These trends are also seen in the curves of cumulative frequency of which shapes and absolute values of $CO_2$ and SPM data from both days are quite similar to each other while those of NOx are not.

## DISCUSSION

### Grouping of the Contaminants According to Their Origins

As mentioned before, the contaminants measured in the survey were divided into two groupes from their fluctuation patterns and horizontal distributions. One was a groupe of $CO_2$ and SPM and other was groupe of NO and $NO_2$.

The difference is explained by their origins. Sources of $CO_2$ and SPM are mainly human activities, including smoking, which are repeated in a similar manner every day. That is the reason the absolute values, fluctuation patterns, and horizontal distributions of $CO_2$ and SPM concentrations were indepentent of date but dependent on occupant density.

Sources of NOx are, on the other hand, exhaust gases from combustion appliances, automobile, and smoking. Within the room in question, no appliances were used and not many persons were smoking; the major source of NOx was, therefore, automobile exhaust gas from outdoors. As outdoor concentration levels of exhaust gas were different on each day, the indoor NOx levels fluctuated and distributed differently depending on the date and were almost insensitive to occupant density.

Although airborne bacteria should have followed the $CO_2$ and SPM patterns judging from their origins, the tendencies similar to those of $CO_2$ and SPM were not observed clearly, probably because of the low absolute levels of airborne bacteria.

### Estimation of the Actual Outdoor Air Intake Rate

$CO_2$ and SPM concentrations in the room were significantly high and it was suspected that the airleakage into the outdoor air intake duct might have reduced the outdoor air intake rate to levels considerablly lower than expected.

A mass-balance model was used to estimate the actual outdoor air intake rate using $CO_2$ as a tracer. Table 3 shows that the ratios of $CO_2$ through the air-handling unit obtained from the measurements. Taking account of measurement errors, $CO_2$ passing ratio is almost 100%, which means $CO_2$ was practically not absorbed by the unit.

The following hypotheses were assumed for the estimation.

1. $CO_2$ distributes uniformly and instantaneously throughout the space in question;
2. The major source of $CO_2$ is only human metabolism and generation from other sources, such as tobacco, is small enough to be ignored.

An airflow rate, Q, measured at the intake of the air-handling unit would be the actual outdoor air intake rate, Qf, plus any leakage, QL, expressed as

$$Q = QL + Qf \qquad (1)$$

If Co is outdoor $CO_2$ concentration, Ci the indoor $CO_2$ concentration, and C the $CO_2$ concentration of the mixture of outdoor air and leaked air from the room, the mass-balance of $CO_2$ would be expressed as

$$Q \times C = QL \times Ci + Qf \times Co \qquad (2)$$

Since Q, Co, C, and Ci in Equation (1) and (2) are measurable, unknown valuables, QL and Qf, can be sloved.

Results are shown in Table 2. Data used for the caliculation were taken quasi-steady data over the sampling period. The actual outdoor air intake rate was lower than 30 $m^3/h/person$, the standard value authorized by SHASE (The Society of Heating, Air-Conditioning and Sanitary Engineers Japan, 1973). It can be concluded that the majour reason for high indoor $CO_2$ and SPM levels was the leakage of the room air into the outdoor air intake duct.

### Estimation of $CO_2$ Generation Rate from the Occupants

To determine the accuracy of the estimation, we calculate the $CO_2$ generation rate from the occupants using same mass-balance model and compare it to standard value widely used among designers.

Taking m as a $CO_2$ generation rate from one occupant, N as an occupant number, Qs as a total airflow rate supplied, Cs as a concentration of the supplied air, Qr as a total airflow rate exhuasted, and Ci as an indoor $CO_2$ concentration, the mass-balance equation is

$$Ci \times Qr = N \times m + Cs \times Qs$$

If natural ventilation rates are very small compared to Qs and Qr,

$$Qs = Qr$$

Therefore the mass-balance equation is expressed as

$$m = Qs\ (Ci - Cs)\ /\ N \qquad (3)$$

Results, as shown in Table 3, indicate that $CO_2$ generation rate averaged over four cases is 0.024 $m^3$/h/person, which is similar to the standard value, 0.022 $m^3$/h/person, in the case of "light desk work" at wnich human relative metabolic rate is rated as 1.0 (AIJ 1978). As the difference between them is about 9%, the accuracy of the model is considered to be satisfactory, taking into account the complexity of factors related to the model and measurement.

## CONCLUSION

1. $CO_2$ levels in the office room considerablly high, 1,600 ppm at their maximum, and exceeded a Japanese standard level, 1,000 ppm, in most cases.

2. SPM (suspended particulate matters) levels were also high, 0.25 mg/$m^3$ at their maximum, and exceeded a standard level, 0.15 mg/$m^3$, depending on the case.

3. The maximum concentration of airborne bacteria was 0.4 cfu (colony forming unit).

4. The maximum indoor NOx levels were 170 ppb (NO) and 40 ppb ($NO_2$), respectively.

5. Concentration fluctuation of $CO_2$ and SPM correspond well to the occupant density and air-handling unit operational pattern while fluctuation of NOx did not.

6. Horizontal concentration distributions of NOx were relatively uniform, and absolute values and cumulative frequency curves of the horizontal distribution data were different depending on the date.

7. Horizontal distribution of $CO_2$ and SPM were not uniform compared to NOx, and absolut values and cumulative frequency curves obtained from the horizontal distribution data were of little difference depending on the date.

8. We divided the contaminants of this measurements into two groups according to their origins, which characterized their fluctuation and horizontal distribution patterns. One consisted of $CO_2$ and SPM, whose origins were human activities; other group consisted of NO and $NO_2$, whose sources were mainly outdoors.

9. Airleakage from the outdoor air intake duct was found and this recirculation was suspected as being the major cause of the high concentration of $CO_2$ and SPM. The actual outdoor intake rate was less than half the expected value because of the leakage according to the mass-balance model estimation

10. The applicabilty of the model was examined and it was considered to be practical.

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TABLE 1
Factors Measured and Instruments Used for the Measurement

| Factors | Instruments | Notes |
|---|---|---|
| $CO_2$ | Infra-red $CO_2$ Analyzer<br>Beckman, Model IR315A | |
| $NO_x$ | Chemiluminecence Type<br>Nitrogen Oxides Analyzer<br>Monitor Labs, Model 8440 | |
| SPM | Light Scattering Type<br>Densitymeter<br>Shibata Kagaku Ltd.<br>Model P-5 | 1 cpm indicated by this instrument is equal to 0.001 mg/m$^3$ according to calibration using stearic acid particles |
| Airborne Bacteria | Slit Type Sampler<br>Mattson Carvin Co.<br>Model 200J | |
| Airflow Rate | Hotwire Anemometer<br>Kanomax, Model 24-1111 | |

TABLE 2
Results of Estimation of the Actual Outdoor Air Intake Rates

| Date | Time | Mesured Data Used for Caliculation | | | | $Q_f$($m^3$/h) ($Q_f$/Q) | $Q_f/N_c^*$ | $Q_f$/N |
|---|---|---|---|---|---|---|---|---|
| | | $C_o$ (ppm) | $C_i$ (ppm) | C (ppm) | Q ($m^3$/h) | | | |
| 9th | 10-12 | 510 | 1177 | 838 | 4972 | 2504 (50%) | 29.1 | 33.8 |
| 9th | 14-16 | 537 | 1274 | 937 | 4972 | 2253 (46%) | 26.2 | 34.5 |
| 10th | 10-11 | 525 | 1302 | 1006 | 4972 | 1877 (38%) | 21.8 | 27.4 |
| 10th | 14-17 | 512 | 1388 | 1041 | 4972 | 1952 (40%) | 22.7 | 29.2 |
| Average | | - | - | - | - | 2147 (44%) | 25.0 | 32.0 |

$^*N_c$ : Designed Capacity of the Room (persons)

TABLE 3
$CO_2$ Generation Rates from Occupants

| Date | Time | $PR^*_{(CO_2)}$ (%) | $C_s$ (ppm) | $C_i$ (ppm) | $Q_s$ ($m^3/h$) | N (persons) | m ($m^3$/h/person) |
|---|---|---|---|---|---|---|---|
| 9th | 10-12 | 91.9 | 899 | 1177 | 7092 | 68.3 | 0.029 |
| 9th | 14-16 | 99.3 | 1045 | 1274 | 7092 | 65.3 | 0.025 |
| 10th | 10-11 | 102.9 | 1091 | 1302 | 7092 | 68.5 | 0.022 |
| 10th | 14-17 | 106.9 | 1205 | 1388 | 7092 | 66.8 | 0.019 |
| Average | | - | - | - | - | - | 0.024 |

$^*PR_{(CO_2)}$ : $CO_2$ Passing Ratio through the Air-Handling Unit

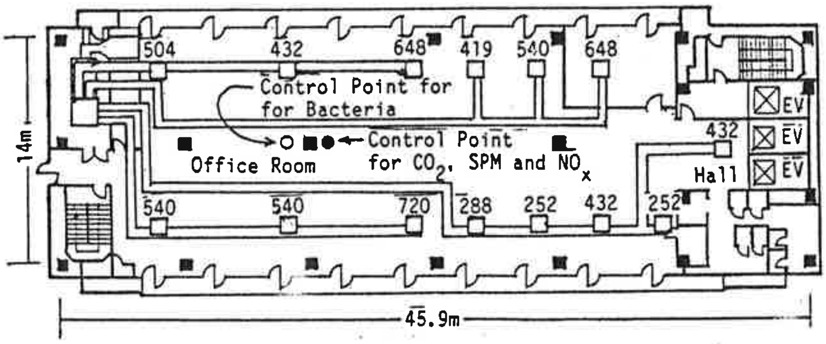



*Figure 1. Plan view of the room surveyed and of the air supply ducts and results of the airflow rate ($m^3$/h) measurements from diffusers*

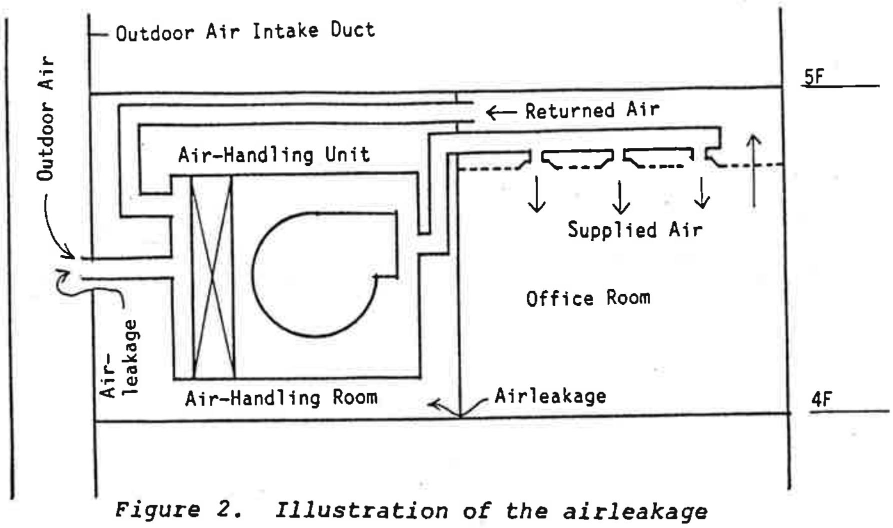



*Figure 2. Illustration of the airleakage*

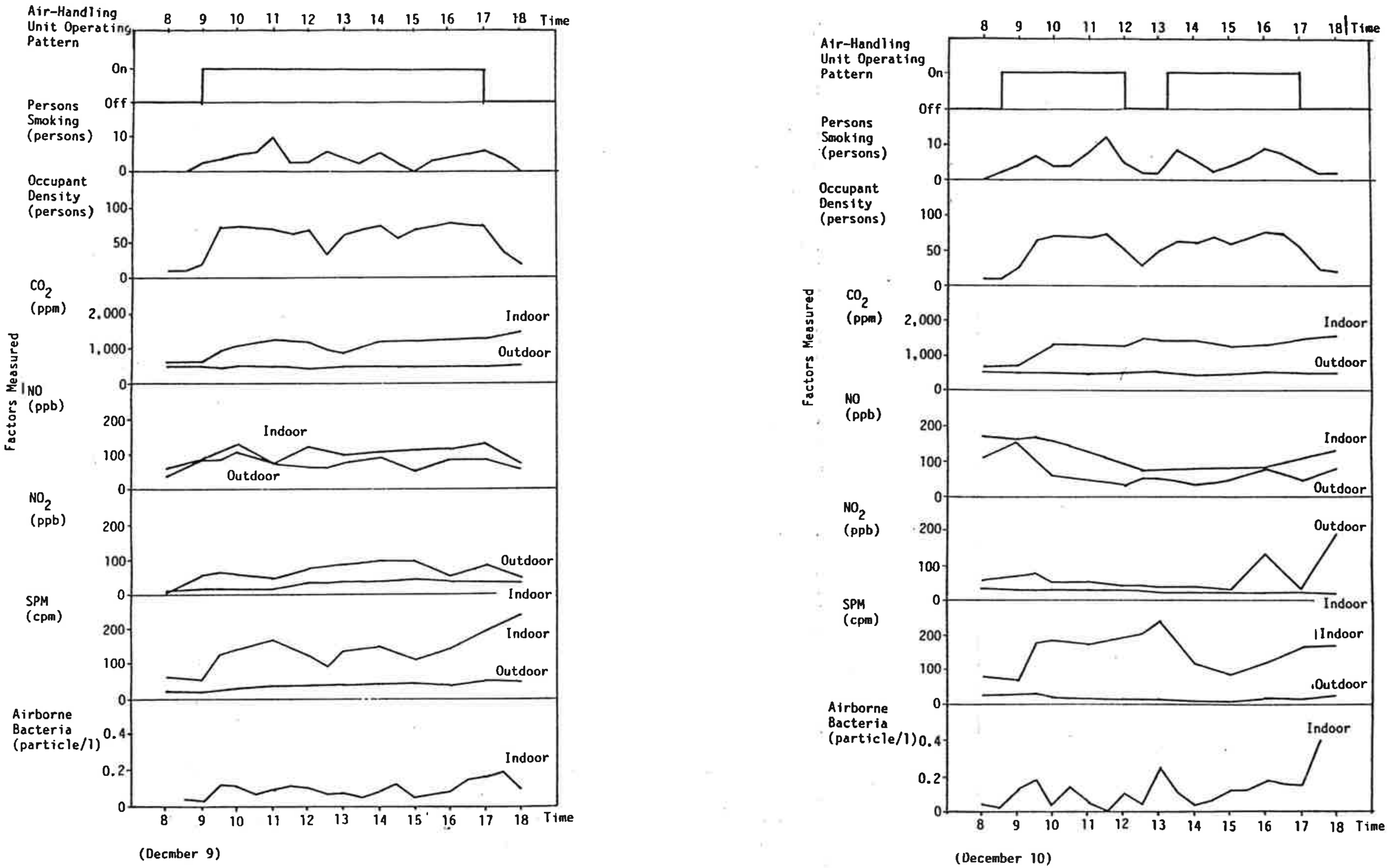
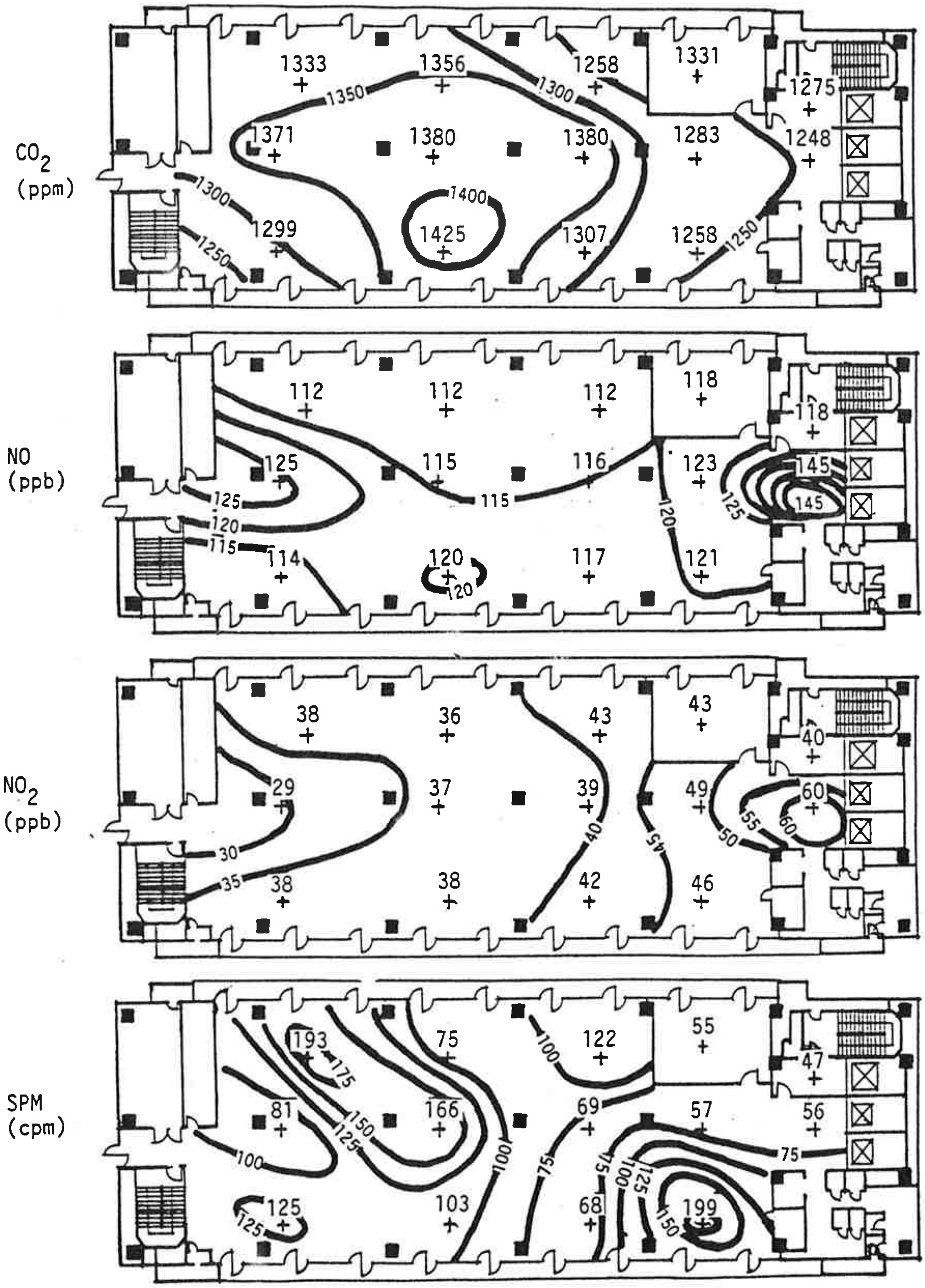
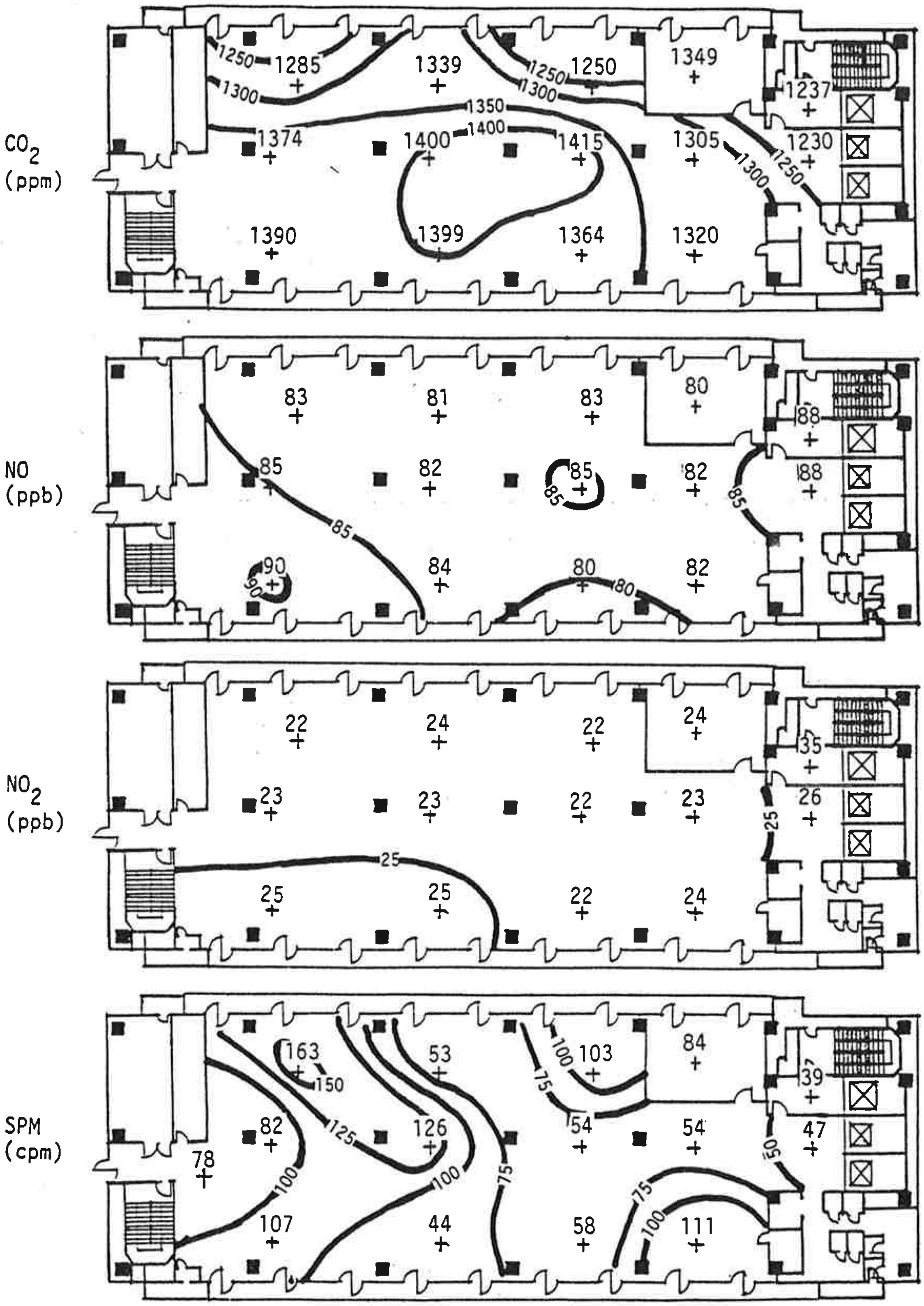



*Figure 3.  Fluctuation patterns of measured factors*




(December 9)

*Figure 4. Horizontal distributions of contaminants*




(December 10)

*Figure 4 continued*

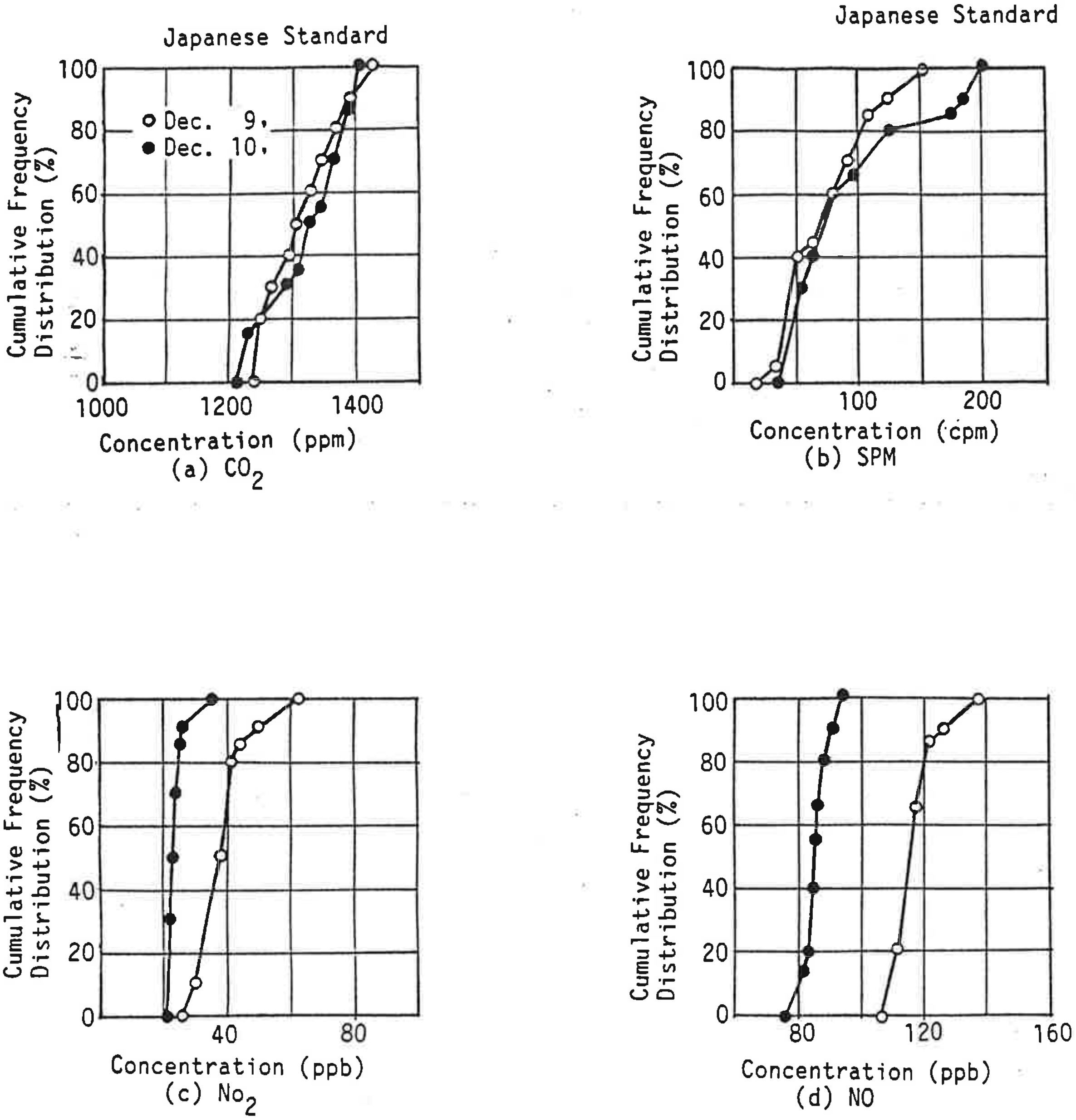



*Figure 5. Cumulative frequency distribution curves obtained from horizontal contaminant concentration distribution measurement*

# Discussion

P. MOREY, NIOSH, Morgantown, WV: Your slides showed that the Japanese standard for airborne bacteria is 160 colony-forming units per cubic meter. How was this standard derived? Is the Japanese standard based on a dose response relationship? Did you measure total bacteria (35°C incubation)? Or did you count only certain genera such as Staphylococcus or Streptococcus spp.?

IKEDA: I showed the Japanese indoor air quality standard for $CO_2$ and suspended particulate matters and the ambient air standard for $NO_2$, but I did not show any kind of airborne bacteria standard because we have no such standard in Japan. However, I think that an airborne bacteria level of 160 cfm/cubic meter is not an unsuitable guideline judging from our experiences. We measured only total bacteria and incubated them at 37°C. We did not identify kinds of bacteria.

I. DHIA, Cool Science, Inc., Dallas, TX: Humidity is an important reference for air quality and comfort level, and I believe humidity can affect the reading that Dr. Ikeda has measured on this specific project. I think humidity can have effect on $CO_2$, NO, CO, bacteria level in air, which will change air quality modestly.

IKEDA: Dr. Dhia's comment is quite reasonable. I also think that humidity has important effects on many indoor air contaminants, especially on airborne bacteria levels. Unfortunately we did not measure the humidity, but we have been measuring it since the measurement after this.