ASSESSMENT OF VENTILATION AND AIR QUALITY IN A LIBRARY BUILDING

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ABSTRACT

Measurements of airflow were carried out in a library building. The constant-injection and pulse-injection tracer-gas techniques were used to measure airflow in air handling units and estmates flow rates supplied to each floor. Tracer-gas measurements were compared with measurements made using a pitot-tube. Air exchange rate, ventilation efficiency and age of air were examined. The concentrations of carbon dioxide (CO_2), carbon monoxide (CO), formaldehyde (HCHO) and dust particles were monitored. In addition, a questionnaire was completed by library staff and users in order to provide a subjective assessment of indoor air quality.

1. INTRODUCTION

Complaints of sickness among people who work in "tight buildings", especially those housing equipment and machines, has become a significant problem over recent years. Measures to improve the energy efficiency of buildings, such as increased insulation and "tight" doors and windows, reduce heat losses but also keep in unwanted contaminants. This has led to an increase incidence indoor air pollutant in modern buildings.

The Pilkington Library completed in 1980 is located on the campus of Loughborough University of Technology. Complaints about indoor air quality in the building have been made by the Library's staff and users. These include reference to stale air, overheating, odour of food and car exhaust emissions, and physical discomfort such as headaches, dizziness and dryness of eyes. In order to determine how these complaints are related to the performance of the ventilation system in the building, the Building Technology Group has conducted an evaluation of the building's ventilation and indoor air quality. This evaluation involved measurement of building ventilation rates, ventilation effectiveness, and concentrations of selected indoor air pollutants. In addition, a questionnaire was completed by the library staff and users to assess the indoor air quality. These objective measurements and the subjective assessment were conducted between November 1991 and March 1992.

2.0 DESCRIPTION OF PILKINGTON LIBRARY AND ITS VENTILATION SYSTEM

The Pilkington Library was constructed over a period of 1979 - 1980 and first occupied in September 1980. Figure 1 shows a photograph of the library. It is a four-storey building with two basement levels. The floor areas for levels 1, 2, 3 and 4 are 2230, 2624, 3029 and 1380 m^2, respectively. Levels 1, 2, 3 are primarily open space with books shelves for library storage and seats for library user; there are also some rooms for offices and private study. Level 4 consists mainly of offices and rooms for teaching purposes. The two basements are occupied by the mechanical ventilation system. Figure 2 shows the air handling system of the Pilkington Library.

The mechanical ventilation system of the library consists of 6 air handling units in the basement plant rooms. The conditioning of the air-space at levels 1, 2 and 3 is provided individually by three air handling units and supplemented by an additional air handling unit for the dual-duct system. The air space at level 4 is conditioned solely by an air handling unit while the remaining air handling unit provides ventilation for the plant rooms. The air distribution system of the library basically consists of the core and perimeter supply. The core supply serves the general area while the perimeter supply serves the peripherical area.

These air handling units have variable air volume (VAV) supply fans. Air handling units 1, 2, 3 and 6 control fresh and recirculated air intake-rates by control of dampers in the outdoor and recirculated air intake ducts, respectively. Air handling units 4 and 5 handle solely fresh-air intake without recirculated air. The ventilation air from the air handling unit is delivered to the occupied space through a network of supply ducts that run up the building's supply air chases and through the plenum above the suspended ceilings on each level. The core extract fan in the plant room delivers the return air from the occupied space and flows into the suspended ceiling plenum through return air openings. This return air then flows through the plenum, and into the vertical return air shafts. Some of the return air is recirculated while the rest is exhausted.

The air handling systems at the Pilkington Library are designed to handle variable fresh and recirculated air intake rates. They introduce minimum quantity of fresh air during very cold weather to reduce space heating load.

3. DESCRIPTION OF MEASUREMENTS

3.1 Measurements of Airflow in Air Handling Units

Measurements of airflow were carried out in air handling units by using the pitot-static traverse method and tracer-gas techniques such as constant-injection and pulse-injection[1].

Velocity pressure and tracer gas tappings were positioned along the ducts at the air handling units. The velocity tappings allowed insertion of a pitot tube which could be traversed across the duct cross-section in order to measure velocity at various distances from the duct wall. Velocity pressures were measured using an EMD 2500 micromanometer made by Airflow Development, UK.

For the constant-injection technique (See Figure 3), SF_6 tracer gas was supplied at a constant rate into the fresh air inlet of the duct using a mass flow controller, type F100/200, made by Bronkhorst High-Tech BV, Ruulo, Holland. The controller had a maximum flow capability of 50 L/min and a measurement accuracy of ±1%. The flow rate was controlled using a variable power supply and the rate of tracer gas injection was displayed on a digital unit.

For the pulse-injection technique, tracer gas was injected into the fresh air inlet of duct using a syringe. Multipoint injection was necessary for the approximation of a uniform concentration across the cross-section of the duct at the measurement point. It was necessary to measure the concentration of the tracer gas at the downstream point to determine the integral of the concentration. This was achieved by filling an air sample bag by means of a small pump. Sampling was begun 10 seconds before the pulse was injected, and continued until the pulse was completely purged from the duct.

The concentration of tracer gas was measured using an Infra-red gas analyser, type BINOS 1000, made by Rosemount GMGH, Hanau, Germany. The accuracy of the analyser was estimated to be within ±2%.

3.2 Measurement of Air Exchange Rates

The air exchange rate at each level in the library building was measured using the tracer-gas decay technique. This technique involved an initial injection of SF_6 tracer gas into the air space through the air handling unit. The tracer gas was allowed to mix for 10 minutes to establish a uniform concentration in the air space. The decay of SF_6 tracer gas was then monitored once every 2 minutes, over a period of 30 minutes, using the MIRAN Portable Analyser, type 1B2, made by Foxboro Company, USA . The tracer gas concentration data was analysed to determine the air-exchange rate for each level.

3.3 Age of Air and Ventilation Efficiency

Evaluation of the ventilation efficiency of the mechanical ventilation system in a building is crucial as it provides information on the performance of the system to supply and extract air from the conditioned space. Information on the ventilation rate of the building is adequate if the air distribution in the building is uniform. Non-uniformities in air distribution, i.e. air in some areas of a conditioned air space is stagnant (or not well ventilated), are believe to be responsible for some complaints about air quality.

Ventilation efficiency was evaluated in the Pilkington Library at levels 1, 2 and 3. These evaluations consisted of measurements of local age of air in the library and average age of air at system exhaust. The age of air at each level was measured using the tracer-gas decay technique. This technique involved an initial injection of SF_6 tracer gas into the air space through the air handling unit. The tracer gas was allowed to mix for 5 minutes to establish a uniform concentration in the air space. The decay of the tracer gas was monitored in the library and at the exhaust duct in the plant room once every 2 minutes, using the MIRAN Portable Analyser and BINOS 1000 Infra-red gas analysers, respectively, over a period of time (depending on the air exchange rate at that particular level). The tracer-gas concentration data at the library and at the exhaust were analysed to determine the age of air (τ). The ventilation efficiency of the mechanical ventilation system was determined by dividing the age of air at the exhaust (τ_E) by the age of air in the Library (τ_L).

3.4 Monitoring Concentrations of CO_2, CO, HCHO and Aerosol Particles

Monitoring of indoor air pollutants such as CO_2, CO, HCHO and dust particles was carried out at each level of the library. Areas with highest concentrations of pollutants were selected and measurements were conducted.

The concentrations of CO_2, CO and HCHO were measured using the MIRAN Portable Air Analyser. The concentration of aerosol particles was measured using the dust monitor, type 1.12, made by Grimm Ltd, Germany. The monitor was capable of measuring particles 0.1 to 10 μm in diameter with an accuracy of ±5%.

4. RESULTS AND DISCUSSION

4.1 Evaluation of Airflow Rates in Air Handling Units

Airflow rates in the air handling units were measured with a pitot tube and the constant-injection and pulse-injection tracer-gas techniques. Table 1 compares measurement of airflow rate made with the pitot tube and tracer-gas techniques.

Air Handling Unit	Airflow Rate (m^3/s)			Difference (%)	
	Pitot Tube	Constant Injection	Pulse Injection	$(F_{ci}-F_p)/F_p$	$(F_{pu}-F_p)/F_p$
1	5.361	5.208	5	-2.85	-6.73
2	10.87	11.11	10	2.21	-8.00
3	10.55	9.804	11.08	-7.07	5.02
4	Not Taken	2.252	2.226	-	-

F_{ci} = Airflow rate based on constant-injection technique, (m^3/s)
F_{pu} = Airflow rate based on pulse-injection technique, (m^3/s)
F_p = Airflow rate based on pitot-static traverse method, (m^3/s)

Table 1 Measurements of airflow rate in air handling units

Airflow rates obtained from the pitot-static traverse method and tracer-gas techniques were in close agreement. The difference between airflow rate estimated using constant-injection technique measurements and measurements made using a pitot-tube was in the range -7.1 to 2.2%. In the case of airflow rate measurements made using the pulse-injection technique and pitot-static traverse method, the difference was in the range -8.0 to 5.0%.

4.2 Evaluation of Air Exchange Rates

Measurements were carried out on a calm day with a north-westerly wind at a speed of 1 m/s. Air infiltration could be neglected as the external wind pressure was low. The air exchange rates at levels 1, 2 and 3 tabulated in Table 2 are therefore provided solely by the mechanical ventilation system.

Level	Air Exchange Rate (air change per hour)
1	3.57
2	2.5
3	2.72

Table 2 Air exchange rate in the Pilkington Library

The air exchange rate on level 1 was within the recommended value of 3 to 4 air changes per hour given in the CIBSE Guide "Installation and Equipment Data"[2]. However, the air exchange rates on levels 2 and 3 were below the recommended values.

The air temperature and relative humidity for both indoors and outdoors were measured. The outdoor air temperature and relative humidity were 14°C and 60%, respectively. The indoor air temperatures and relative humidities monitored for levels 1, 2 and 3 were 22.5°C and 38%, 22°C and 33%, and 21.5°C and 45%, respectively. The recommended air temperature and relative humidity in a library are 20°C[3] and 50 - 60%[2], respectively. Thus we concluded that the indoor air temperature was slightly above the recommended value but the relative humidity was much lower than the desired level.

4.3 Evaluation of the Age of Air and Ventilation Efficiency

The results of age of air and ventilation efficiency at levels 1, 2 and 3 are tabulated in Table 3.

Level	Age of Air at Exhaust, τ_E (min)	Average Age of Air in Library, τ_L (min)	Ventilation Efficiency, ε (τ_E/τ_L)
1	15.36	16.82	0.914
2	16.05	20.25	0.792
3	14.38	22.49	0.639

Table 3 Age of air and ventilation efficiences in the Pilkington Library

The measurements showed that the average age of air in the library on level 1 was the lowest (i.e., the amount of time that had elapsed since the air had entered level 1 was the shortest), followed by the age of air on levels 2 and 3.

When there is a uniform distribution of air over the conditioned air-space, the ventilation efficiency, $\varepsilon = 1$. However, when there is a non-uniform distribution of air over the conditioned air-space or in another words, some stagnant zones within the conditioned air-space, values of ε are significantly less than 1. Table 3 shows that air handling unit 1 had best performance, i.e., ε performed the best with ε very close to unity, followed by the air handling unit for level 2 and 3.

4.4 Evaluation of Concentrations of Indoor Air Pollutants

The concentration of carbon dioxide in the library varied from location to location. The highest concentration registered as 1437 ppm was measured at the main entrance on level 3. This value exceeds the ASHRAE's standard[4] recommended value of 1000 ppm for continuous exposure. This suggests that there is poor distribution of fresh air over the conditioned air-space or the ventilation rate is insufficient.

Measurements showed that the concentration of carbon monoxide was 2 ppm. This value is well below the acceptable indoor concentration of 9 ppm[5].

The average concentration of formaldehyde in the library was found to be 0.95 ppm. This value is well above the acceptable indoor concentration of 0.1 ppm. This contaminant is emitted mainly from insulation materials. High concentration of formaldehyde can lead to eye irritation.

The concentration of dust particles less than 5 μm in diameter was found to be 0.01517 mg/m^3. The maximum concentration of dust particles was 0.100 mg/m^3. For long exposure, the recommended maximum level of particulates in the range of 0.1 to 100 μm diameter is 0.075 mg/m^3 as given by the National Primary Ambient Air Quality Standards[4]. In general, the dust particle level was acceptable apart from some locations, such as areas near the photo-copying machines and in the stairwell.

5. SURVEY AT PILKINGTON LIBRARY

In addition to the objective measurements conducted in the library, a subjective assessment was made of the effects of air quality on the health of the library staff and users. This was carried out by distributing a questionnaire to related persons while the objective measurements were being conducted. A sample of the questionnaire[6] is shown in Appendix 1.

The total number of staff working at the library was 20 and the average number of library users were estimated to be about 1500 per day. For this assessment, a total of 49 questionnaires were printed; 14 sets were distributed to the library staff and the remaining 35 were distributed randomly to library users. Half the selected staff, 7 are male and half are female. The sample of library users comprised 26 males and 9 females. The average ages of the staff and users were 34 and 24 respectively.

5.1 Assessment of the Questionnaires

Questionnaires completed by staff and library users were assessed separately. Staff were classified as long-term users as they work in the library for almost 8 hours a day, 5 days a week. Library users were classified as short-term occupants as they used the building for an average period of 4 hours or less per day.

The main types of complaints from the staff and users are shown in Figure 4 and 5 respectively. The majority of complaints, in both groups, were stuffy atmosphere followed by odour. Significant numbers of staff and users also found the library to be overheated, dry and draughty. Figure 6 and 7 reflect the opinions of the staff and users on the air quality at each level, respectively. The vast majority of staff felt that air quality at levels 1 and 3 was acceptable but 63% of the them felt that it was not acceptable at level 2. In addition, a small

number of staff complained about odour of food and car exhaust. A visual inspection of the building showed that the fresh air intake of the mechanical ventilation system was rather close to a refectory and car-park. Most of the library's users were satisfied with the air quality in levels 1, 2 and 3. Only 11.7% overall said that it was unacceptable.

Figure 8 shows the distribution amongst staff of days lost from work per annum. The majority of the staff were absent for an average of 1 to 3 days per annum; 20% of them were absent for 4 to 6 days and 7 % of the staff absent for more than 6 days and 14% of staff were not absent from work at all. Figure 9 shows that most days were lost from work because of respiratory problems, followed by influenza, eye problems and migraine, in order of decreasing incidence.

This subjective assessment showed that air quality at the Pilkington Library is within tolerable limits and that the number of days lost due to illness is within the acceptable range.

5.2 Comments on Ventilation and Air Quailty in the Library

The information obtained from the measurements and questionnaires show that the Pilkington Library does have some ventilation and air quality problems. Some of these problems are directly responsible for the complaints.

5.2.1 Comments on Ventilation

Results obtained from air exchange rate measurements showed that level 1 had an acceptable air exchange rate but not levels 2 and 3. Poor ventilation of these level space will lead to a build-up of CO_2 and airborne contaminants, such as water vapour, body odour and emanations from books. The distribution of air over the conditoned space is just as important as the air exchange rate of the conditioned space. Results obtained from the evaluation of the age of air and ventilation efficiency showed that there was non-uniformity in air distribution on levels 2 and 3. Low air exchange rates and non-uniformity of air distribution were partly responsible for the complaints of odour in these areas. As a whole, the library had a relative humidity in the range of 33 to 45%, significantly lower than the recommended value 50 - 60%. This explains the complaints about dryness in the library. Investigation showed that relative humidities were low because of the humidifers at the air handling units were not in operation. Generally, the air temperature in the library was within the thermal comfort condition.

5.2.2 Comments on the Air Quality

In this study, only selected indoor air pollutants were monitored. The concentration of CO_2 varies from location to location. On the whole, the CO_2 level was acceptable except at the main entrance on level 3. The complaints of air stuffiness may be due to the lack of fresh air to dilute the CO_2. The concentration of HCHO was found to be well above the acceptable level[7-9] and this may be partly responsible for the health problems such as eye irritation. Generally, the concentration of dust particle in the library was under controlled except near the photo-copying machines and in the stairwell. High levels of dust particles can result in respiratory problems such as mucous membrane irritation and impairment of the respiratory system.

Visual inspection of the library's surroundings showed that the fresh air inlets of the mechanical ventilation system were rather close to the refectory and the car-park. This leads to complaints of odours of food and car's exhaust leaking into the library.

5.3 Remedial Measures

Some remedial measures to overcome the ventilation and air quality problems.

5.3.1 Ventilation

i) The air exchange rates of levels 2 and 3 need to be increased to the recommended value of 3 - 4 air changes per hour. This could be achieved by increasing the speed of the centrifugal fan at the respective air handling units.

ii) Non-uniformity of air distribution may be due to blockage of the supply diffusers mounted in the false ceilings.
Visual inspection of the diffuser is required.

5.3.2 Indoor Air Quality

i) The concentration of CO_2 at the main entrance on level 3 may be reduced when the air exchange rate increased or the blocked supply diffusers are cleared. If high concentration of CO_2 still persist, an increased supply fresh air will be required at that area.

ii) Reduction of HCHO concentration would be best achieved by controlling the sources rather than increased ventilation.

iii) High concentration of dust particles in the photo-copying's areas could be avoided if the photo-copying machines were relocated in a room with an extract fan. The high concentration of dust particles in the stairwell could reduce by more frequent cleaning of the floor carpet.

iv) Odour of the food and car's exhaust could reduce by provision of an activated charcoal filter at the fresh air inlet.

6. CONCLUSIONS

The constant-injection and pulse-injection technique were used successfully to measure airflow in air handling units in the library. The differences between airflow rates estimated using the constant-injection and pulse-injection techniques and those determined using a pitot-tube were in the range -7.1 to 2.2% and -8.0 to 5.0%, respectively. Tracer-gas techniques were found to be a simple and useful method for measuring airflow in air handling units.

Results obtained from objective measurements and the subjective assessments revealed that the library building has some ventilation and air quality problems. The relative humidity in the building was well below the desired level and air exchange rates for level 2 and 3 were less than the recommended value. The average concentration of formaldehyde in the building was found to be 0.95 ppm. This value is significantly greater than the acceptable concentration of 0.1 ppm.

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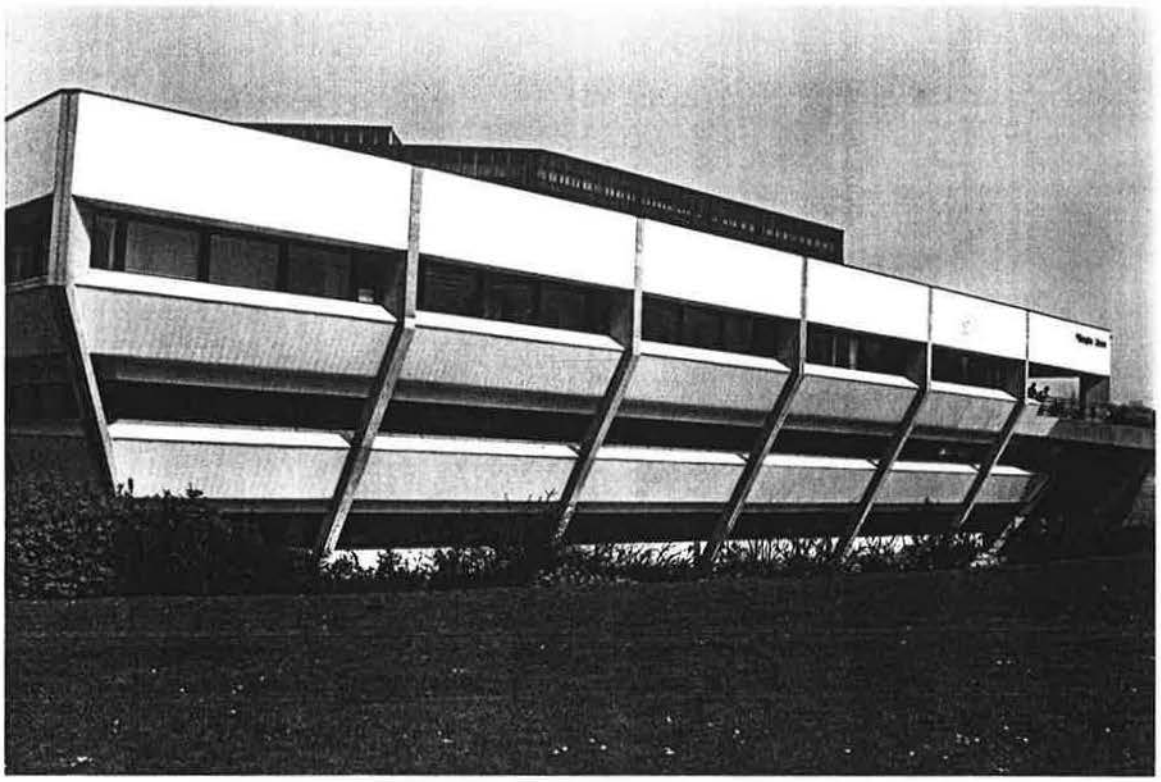
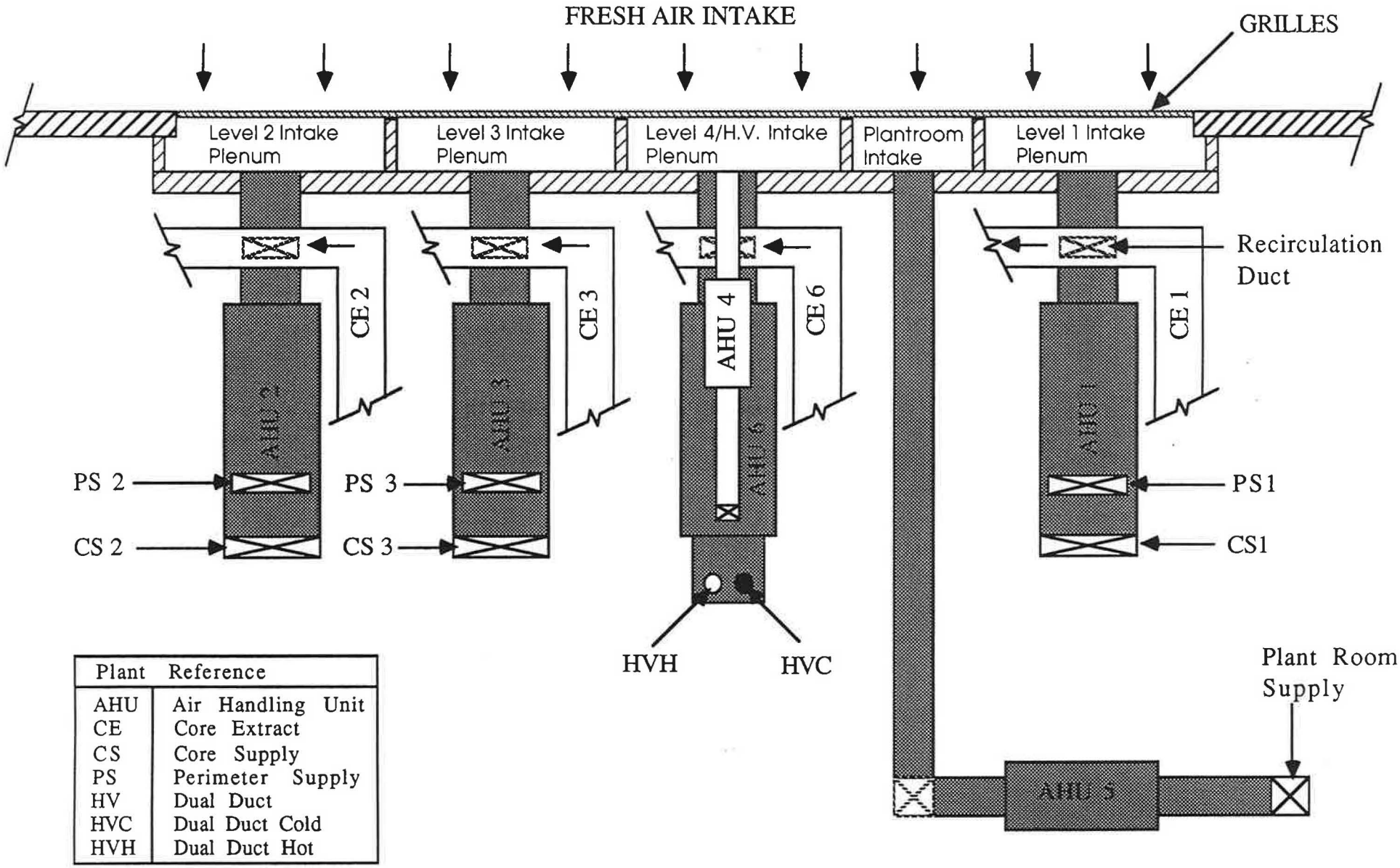


Figure 1 Photograph of the Pilkington Library



Plant	Reference
AHU	Air Handling Unit
CE	Core Extract
CS	Core Supply
PS	Perimeter Supply
HV	Dual Duct
HVC	Dual Duct Cold
HVH	Dual Duct Hot

Figure 2 Schematic of air handling units

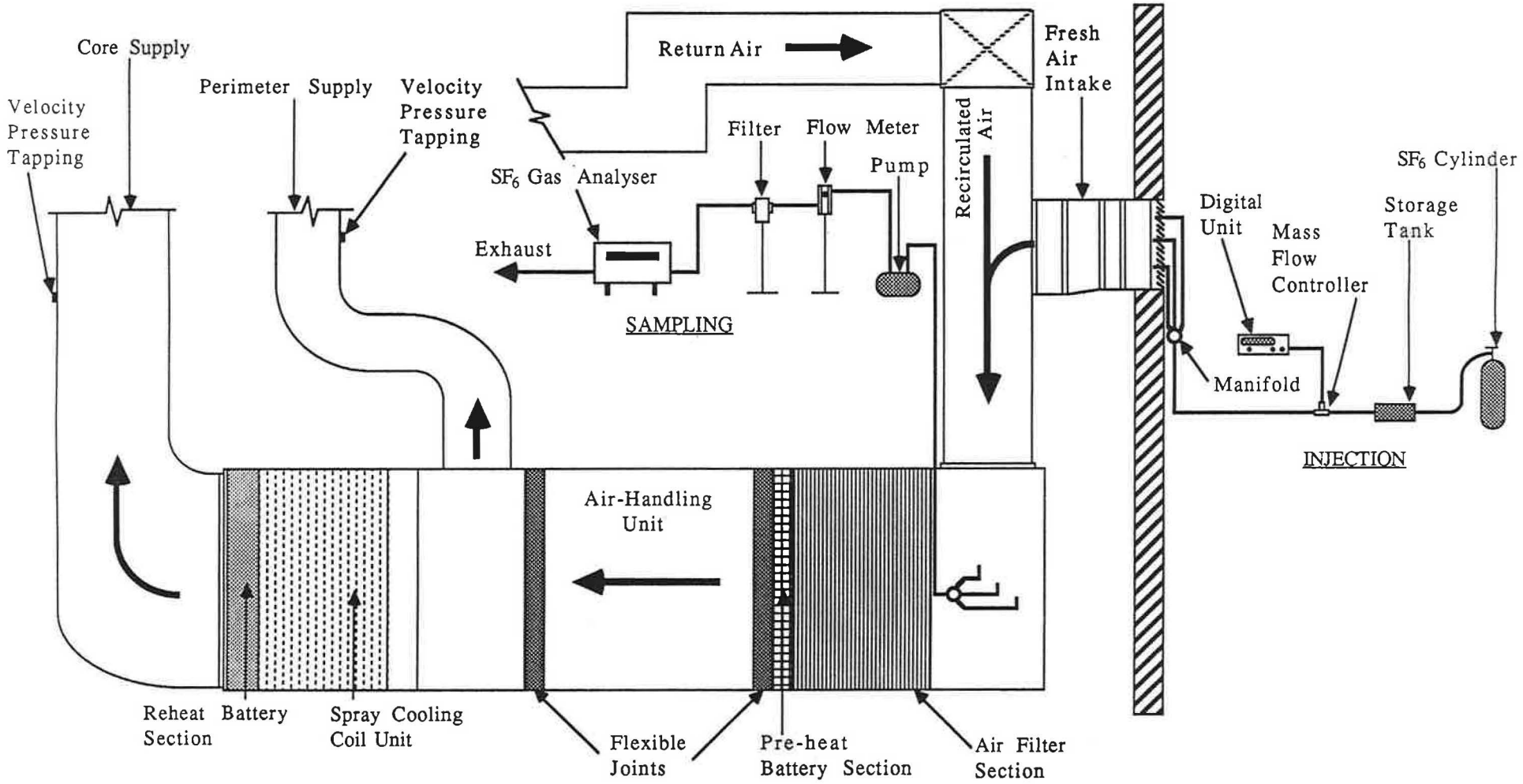


Figure 3 Instrumentation for the constant-injection tracer-gas technique to measure air flow in air handling unit

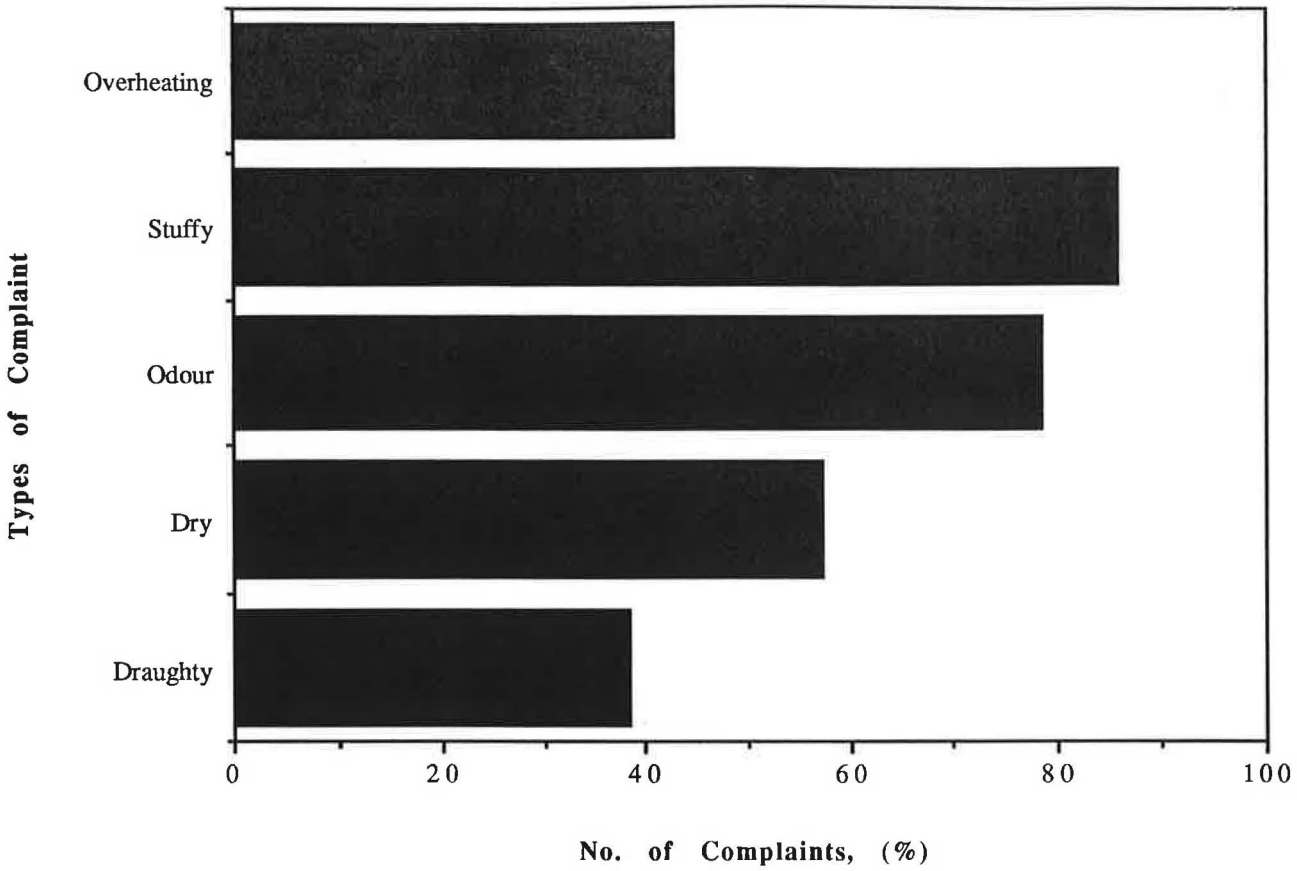


Figure 4 General complaints from staff

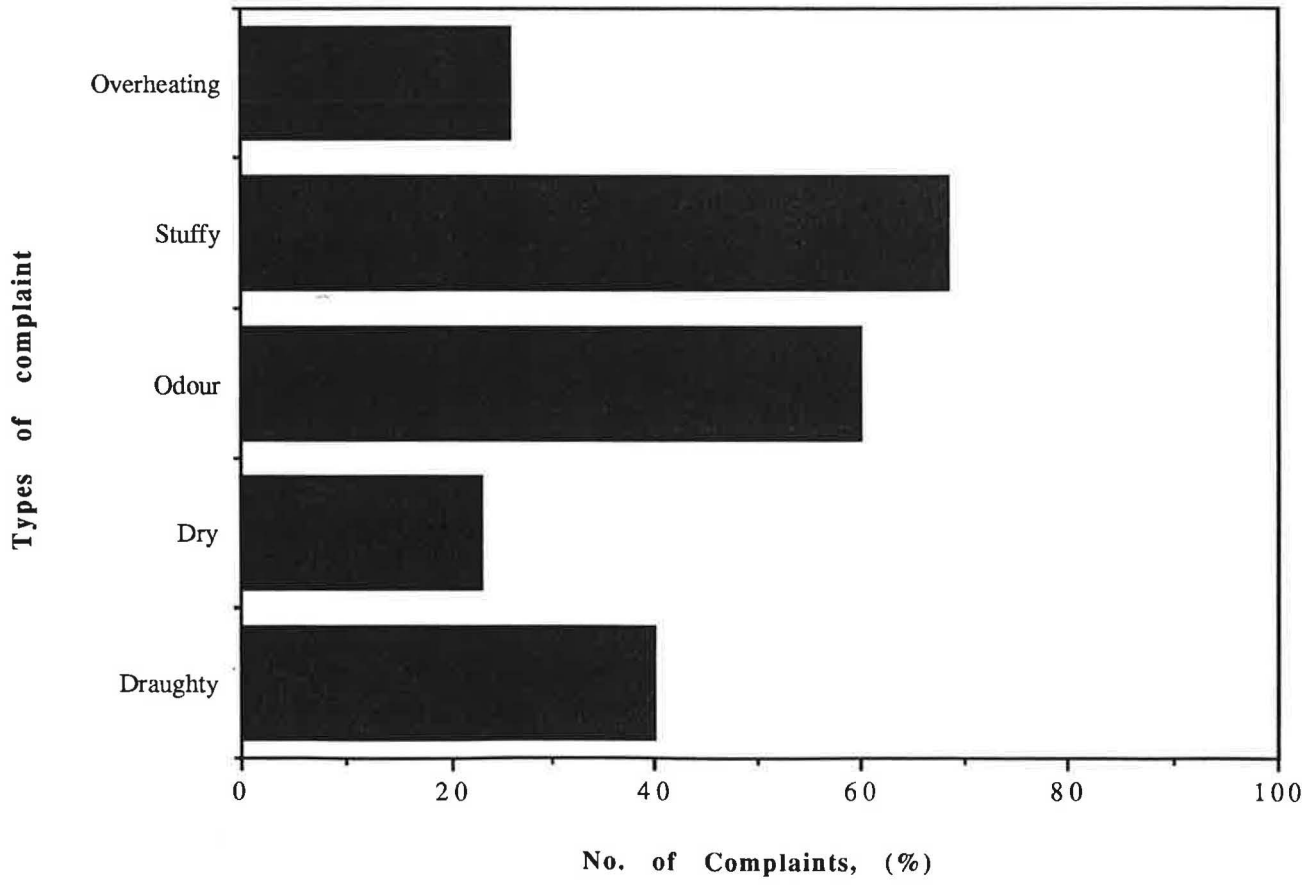


Figure 5 General complaints from library users

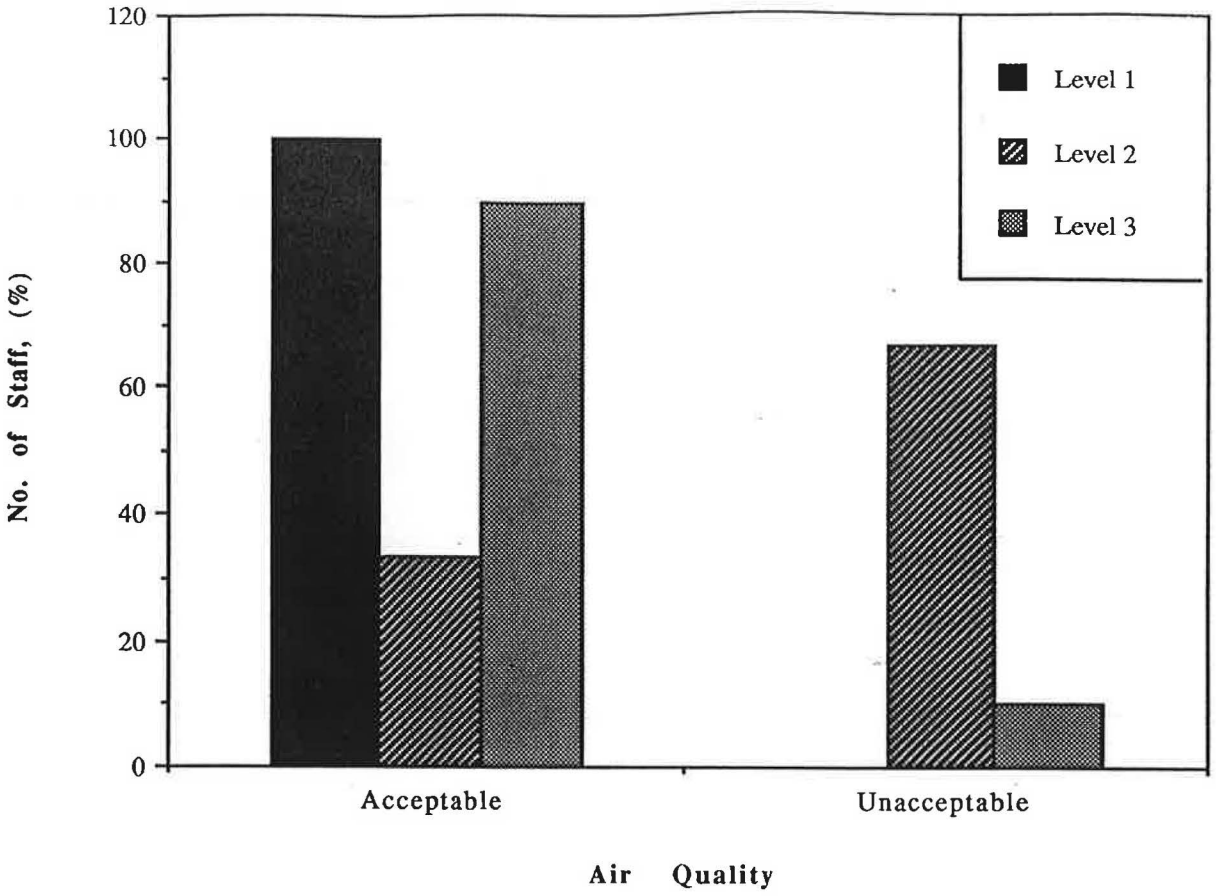


Figure 6 Distribution of air quality, (Staff)

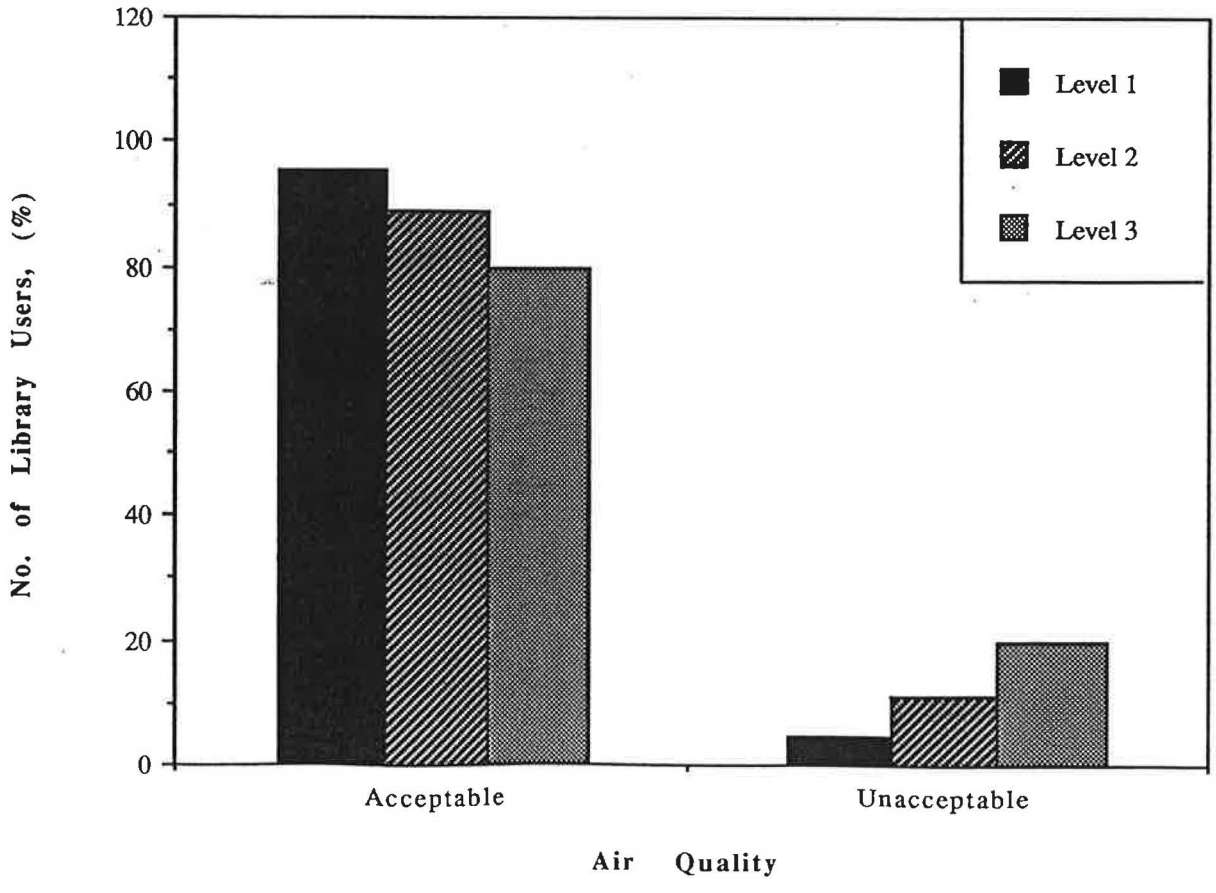


Figure 7 Distribution of air quality, (Library users)

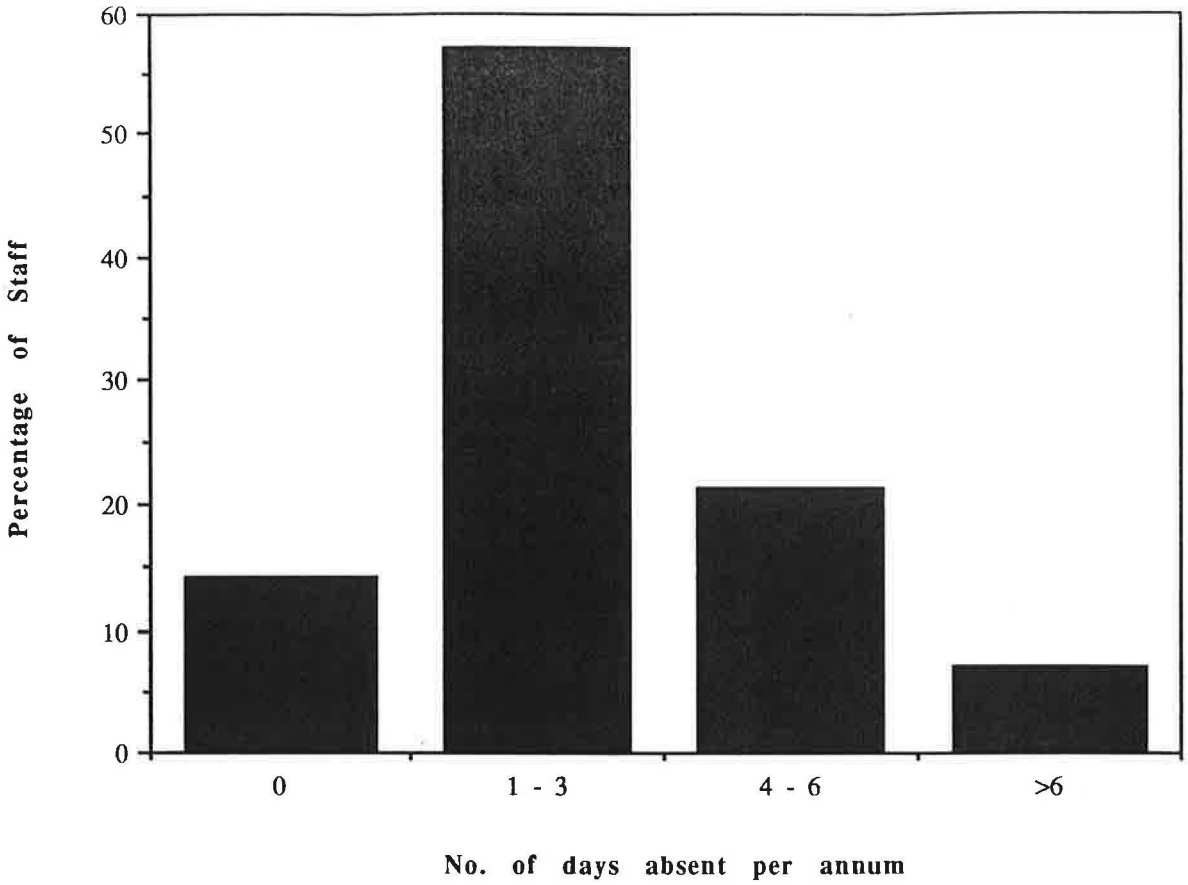


Figure 8 Distribution amongst staff of days absent from work per annum

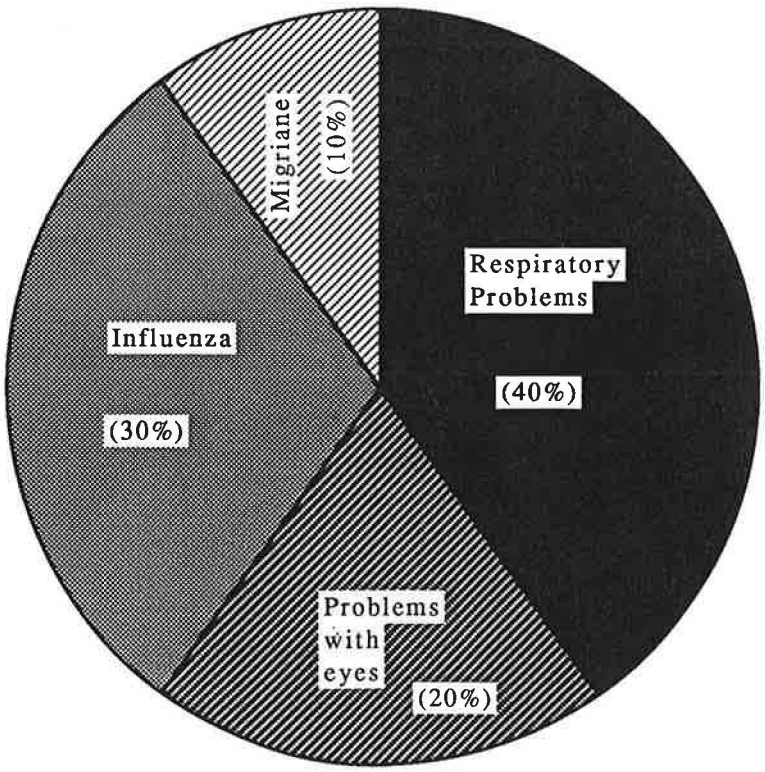


Figure 9 Types of illness

APPENDIX A

QUESTIONNAIRE ON THE ANALYSIS OF SICK BUILDING SYNDROME FOR THE LIBRARY BUILDING[6]

I. GENERAL INFORMATION

1. Sex : _____ 2. Age : _____
3. Do you smoke?
   ( ) a. Yes ( ) b. No

II. NATURE OF WORK

1. How is your position?
   _____
2. What types of work are you handling?
   _____
3. Where is your location of work?
   _____
4. Do you need to sit in the same area during office hours?
   ( ) a. Yes ( ) b. No
5. How many years have you been working in the present location?
   _____
6. What is your rating for the stress in work?
   ( ) a. Very high ( ) c. Average
   ( ) b. High ( ) d. Low ( ) e. Very low
7. Do you like your work?
   ( ) a. Yes ( ) b. No

III. THERMAL COMFORT

1. How do you feel about the ambient air temperature?
   ( ) a. Very cold ( ) c. Cool ( ) e. Warm
   ( ) b. Cold ( ) d. Satisfactory ( ) f. Hot ( ) g. Very hot
2. Do you experience draughts?
   ( ) a. Yes ( ) b. No
3. How do you feel about the room air?
   ( ) a. Too dry ( ) b. Satisfactory ( ) c. Too wet
4. Do you have control over the air temperature for your working area?
   ( ) a. Yes ( ) b. No

IV. AIR QUALITY

1. What is your feelings towards the ambient air?
   ( ) a. Very Stuffy ( ) b. Stuffy ( ) c. Fresh ( ) d. Very fresh
2. Do you sense the presence of any odour?
   ( ) a. Yes ( ) b. No
3. Where does the odour come from if it exists? (more than one answer is possible)
   ( ) a. Cigarettes ( ) e. Ceiling tiles
   ( ) b. Papers or books ( ) f. Furniture
   ( ) c. Other occupants ( ) g. Wall finishes
   ( ) d. Carpet ( ) h. Others (Please specify : _____)
4. How do you feel about the odour?
   ( ) a. Unacceptable ( ) b. Acceptable
5. What is your overall rating for the indoor air quality?
   ( ) a. Unacceptable ( ) b. Acceptable

V. HEALTH

1. What is the average number of days per year that you are absent because of illness?
   ( ) a. 0 ( ) b. 1-3 ( ) c. 4-6 ( ) d. >6
2. What type(s) of illness did you suffer in those absent days? (more than one answer is possible)
   ( ) a. Respiratory problems ( ) c. Problems with nose
   ( ) b. Allergic problems ( ) d. Problems with eyes
   ( ) e. Others (Please specify : _____)
3. Have you experienced the following symptom(s) during office hours only and they disappear or alleviate quickly after leaving the office? (more than one answer is possible)
   3.1 Problems with nose
   ( ) a. Dryness ( ) c. Stuffy nose
   ( ) b. Itching, stinging sensation ( ) d. Running nose
   3.2 Problems with eyes
   ( ) a. Dryness ( ) c. Watering eyes
   ( ) b. Itching, stinging sensation ( ) d. Reddening of eyes
   3.3 Problem with skin
   ( ) a. Dryness ( ) c. Reddening of skin
   ( ) b. Itching, stinging sensation
   3.4 Neurotoxic symptoms
   ( ) a. Reduced memory ( ) d. Headache
   ( ) b. Tired or sleepy feeling ( ) e. Dizziness, Intoxication
   ( ) c. Reduced power of concentration ( ) f. Nausea or feeling of vomiting

VI. OVERALL SUBJECTIVE RATING FOR THE WORKING AREA

1. What is your feeling towards the working area?
   ( ) a. Very comfortable ( ) c. Acceptable
   ( ) b. Comfortable ( ) d. Uncomfortable ( ) e. Very comfortable
2. Do you like the internal environment?
   ( ) a. Yes ( ) b. No
3. Do you find that some/all of the symptoms you experienced as stated in VIII (3) above also occurred in the past during office hours?
   ( ) a. Very often ( ) c. Seldom
   ( ) b. Sometimes ( ) d. Never
4. Do you find that these symptoms are more obvious at the beginning of a week e.g. on Mondays and Tuesday?
   ( ) a. Yes ( ) b. No
5. Do you have any other comments on the internal environment e.g. air temperature, air quality, lighting, noise etc?

Thank you for completing this questionnaire. EnCoQ(S)