SICK BUILDINGS:
Case Studies of Tight Building Syndrome and Indoor Air Quality Investigations in Modern Office Buildings

E.M. Sterling

E.D. McIntyre

C.W. Collett

Theodor D. Sterling Limited
70-1507 West 12th Avenue
Vancouver, B.C., V6J 2E2

T.D. Sterling

Faculty of Interdisciplinary Studies
Simon Fraser University
Burnaby, B.C., V5A 1S6

J. Meredith

British Columbia Buildings Corporation
3350 Douglas Street
Victoria, B.C., V8W 2T4

INTRODUCTION

Hundreds of "Sick Buildings" have been investigated throughout North America since the mid 1970's. Investigators have included both government and private organizations. Most investigations were motivated by complaints from occupants of symptoms including irritation of the eyes, nose, throat, upper respiratory system, headaches, and general fatigue. This complex of symptoms, when experienced among occupants of modern office buildings has been termed "Tight Building Syndrome" by the public health community (Hicks, 1984).

The term "Sick Building" is often used to describe buildings in which a large number of occupants experience symptoms of "Tight Building Syndrome" for which no specific cause can be determined. The majority of these sick buildings have been constructed in the past 10 years, are well sealed, mechanically ventilated and air conditioned and have few, if any, operable windows. In general, investigators have discounted health complaints and perceptions of occupants, instead concentrating on indoor measures of various pollutants and environmental parameters. If monitored at all, the performance of building systems have been obtained from plans and specifications. In some cases spot measures have been made, but for the most part systems have been assumed to be functioning as designed. Typical of investigations of this type is a large Federal government office complex in Hull, Quebec that houses 5,300 public servants of which 49% experience nose irritation, 46% eye irritation and 83% headaches. After taking random measures over the course of one year, researchers still could not identify any specific causal agent nor could they recommend effective control measures (McDonald, 1984).

Many sick buildings have now been studied by qualified investigators. Although most studies were inconclusive, there now exists a substantial archive of data in the form of both published and unpublished reports. Much can be learned from a review of these reports regarding what has been done and found by the investigators. Such a review was initiated by us. We have collected nearly all written reports of these sick building investigations (nearly 250), extracted the data from the reports and loaded them into a computerized Building Performance Database (BPD) (Sterling *et al.*, 1985)* These data include such parameters as air quality, ventilation, lighting, acoustics and reported effects on the health and comfort of occupants as well as research protocol and instrumentation. From our review of these data in addition to experience gained from numerous investigations we have undertaken in Canada, the U.S. and Great Britian a practical, systematic strategy on how to proceed or where to look to diagnose a sick building, identify the cause of problems and prescribe a course of action designed to correct the situation has been developed. Our investigative protocol includes: use of a standard questionnaire to collect occupant health and comfort perceptions; an industrial hygiene walk-through; evaluation of architectural/engineering plans and specifications (verified by spot on-site inspections) combined with a comprehensive measurement program.

This strategy is described through two case studies of sick Canadian buildings. The first case illustrates a comprehensive program of measuring air quality, ventilation and thermal conditions as well as monitoring the performance of the heating, ventilating and air conditioning systems. The second illustrates use of a standard survey questionnaire with back up field monitoring of environmental parameters.

CASE STUDY 1: DIAGNOSING AN INDOOR ENVIRONMENT PROBLEM

The first case is an evaluation of the indoor environment of a three-storey building located in Ottawa and constructed in the 1970's, Building A.

*Information about use of and access to the Building Performance Database can be obtained by contacting the author at Theodor D. Sterling Ltd., #70 - 1507 W. 12th Avenue, Vancouver, B.C., V6J 2E2, (604) 733-2701.

The building contains approximately 30,000 sq. ft. of office space on three floors and is connected by two stairwells and two elevators with underground parking. Air cooling and ventilation are controlled by a Variable Air Volume (VAV) mechanical system. Heat is provided by radiant baseboard hot water units located along the perimeter curtain wall. A separate mechanical system supplies ventilation air to the parking garage.

The study was undertaken at the request of the building tenant. The building has a history of occupant health and comfort complaints. A survey of building occupants conducted by the tenant indicated that 86% experienced headaches, 53% report dry throat, 51% dry nose and 44% dry skin. In addition, temperature control was felt to be inadequate. A preliminary walk-through inspection of the building identified photocopiers and leakage of fumes from an underground parking garage as possible causes of health complaints.

Tests were conducted to monitor:

1. Leakage of pollutants from the garage to the office space.

2. Humidity and temperature in the office space.

3. Generation of pollutants in the office space by office equipment.

4. Supply of outside air to interior office spaces.

The results of monitoring conditions in Building A are presented in two parts: The first part was undertaken to verify leakage of garage pollutants into the office space. The second part was general monitoring of air quality and thermal conditions in the office space.

Results

Part 1 Garage Testing:

There are two obvious pathways through which garage pollutants can enter the occupied office space, the stairwells and elevator shafts connecting the garage to the main building envelope. Part 1 tested for infiltration through these pathways and included:

1. Smoke pencil tests to determine the pattern of air movement.

2. CO measurements to determine the extent to which combustion fumes drift through the building, and

3. Tracer gas tests to verify the pattern of air flow through the stairwells.

Smoke pencil tests showed that under certain conditions air movement from the parking garage into occupied office floors could occur through the stairwells connecting the parking garage to the office space. Measurements of carbon monoxide concentrations (Table 1) confirmed that garage air containing emissions from vehicle exhaust was transported through the stairwells into the occupied office space. However, no significant infiltration of garage air into the office space was found through the elevator shafts. (Not shown here.)

...The term "Sick Building" is often used to describe buildings in which a large number of occupants experience symptoms of "Tight Building Syndrome"...

Infiltration of garage air into the occupied office space was verified by release of SF6 tracer gas into the garage and subsequent measurements of SF6 levels in the garage, stairwells and office space. Results of tracer gas tests presented in Table 2 show infiltration occurs through both the east and west stairwells. (Tracer gas released into the parking garage was also detected in office space on the second and third floors.)

TABLE 1

Carbon monoxide concentrations in parking garages and east and west stairwells (ppm)
December 3, 1984

Floor Level:	Garage		Main Floor		Second Floor		Third Floor		Outdoor Ambient
Stairwell:	East	West	East	West	East	West	East	West	
Pass1 9:05-9:30	11	30	4	14	9	9	4	8	4
Pass2 10:01-10:18	4	21	3	15	3	13	3	11	3

Part 2 Office Space Testing:

Temperature, humidity, ozone, formaldehyde and CO2 were measured in the office space. Temperature and humidity measurements indicate the ability of the building to provide thermal conditions suitable for human comfort. CO2 measurements indicate the ability of the mechanical ventilation system to remove human generated contaminants. Tracer gas measures the effectiveness of fresh air ventilation and smoke pencils determine the performance of ventilation diffusors.

Table 3 shows temperature measured on all three occupied office floors. On all but the Main floor, temperature was within the range of 19C to 26C currently recommended by the American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE, 1981).

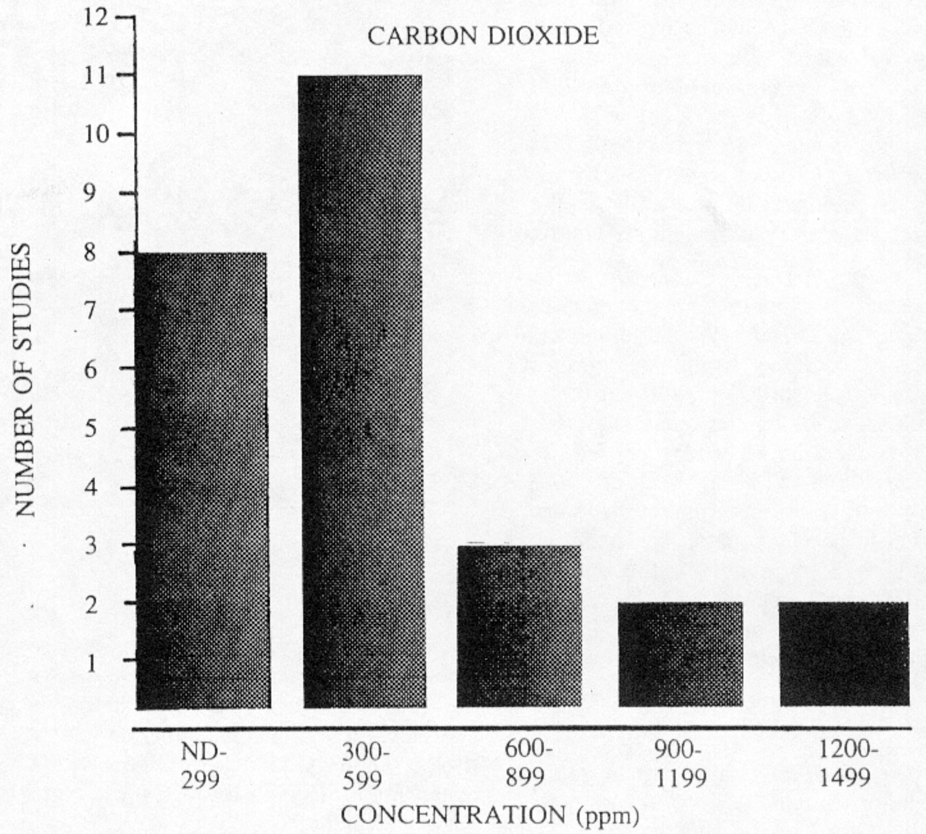
Humidity levels in the Building ranged between 25-33% Rh. This is within the 20-90% RH range recommended by ASHRAE (1981). However a review by the Authors for Health and Welfare Canada which was subsequently published by ASHRAE suggests narrowing this range to between 40 and 60% to protect occupants from both direct and indirect effects of water vapour (Sterling *et al.*, 1984, 1985a). The humidity range measured in Building A was well below the 40-60% recommended by us.

Ozone and formaldehyde concentrations were measured both indoors and outdoors. Although higher levels occurred indoors than outdoors, all formaldehyde concentrations were very low and were not likely to present a health hazard to building occupants.

Carbon dioxide concentrations measured at selected locations on all occupied office floors are presented in Table 4. Carbon dioxide levels are higher than those normally found in similar air conditioned office buildings. For example Figure 1 is a graph of the distribution of CO2 levels measured in 26 office buildings contained in the Building Performance Database (Sterling *et al.*, 1985b). The concentration of CO2 measured in Building A is higher than that found in the majority of buildings.*

The dramatic increase ofCO2 concentrations measured in Building A over the workday indicates an inability of the mechanical ventilation system to control metabolic produced contaminants. Although CO2 concentrations are all below the 2500 ppm level recommended by ASHRAE (1981a), all levels measures are above the concentration of 600 ppm at which sensitive individuals begin to feel discomfort (Rajhans, 1984, Sterling *et al*, 1984a).

FIGURE 1: Graph of Carbon Dioxide Ranges Measured in 26 Building Studies



...systematic strategy on how to proceed or where to look to diagnose a sick building, identify the cause of problems and prescribe a course of action designed to correct the situation has been developed...

Tracer gas was released into the HVAC system fresh air intakes and measured at selected supply air diffusers to evaluate effectiveness of ventilation. Tests indicated uneven distribution of air to the office environment.

Performance of the variable air volume supply diffusers was evaluated by smoke penciltests. Although the ventilation system had been cleaned and balanced the previous year and a maintenance contract was in effect, nearly one third of all diffusers were found to be malfunctioning or not supplying air at all.

Conclusions (Case Study 1)

1. Garage generated pollutants infiltrate the office space.

2. Ventilation in the office space is inconsistent due to malfunctioning of the supply air diffusors.

3. Increasing CO2 concentrations during the workday demonstrates inadequate control of human metabolic byproducts by the existing ventilation system, as operated, and

4. Humidity levels are low in comparison to recommended levels.

Extensive modifications to the ventilation and air conditioning systems are being undertaken based on the results. When complete, similar tests will be undertaken to determine if the problems that were identified have been solved.

*Incidentally, this type of comparison demonstrates one very practical use of our Building Performance Database.

CASE STUDY 2: HOW SICK IS A SICK BUILDING?

The second case study was an investigation of office conditions conducted during the winter months 1984/1985 in two buildings in Victoria, British Columbia. One building had no such history and was used for control. The investigation consisted of two parts. For *Part 1* an 'Office Work Environment Survey' questionnaire was administered to the occupants of both buildings, and For *Part 2* environmental measurements were taken throughout both buildings.

Building S (the study building) is a low rise (4 floor) sealed, mechanically ventilated and air-conditioned office building constructed approximately ten years ago. Tempered, ventilating air is supplied by means of a central air-conditioning system to the building core and by heat pump units to the perimeter office areas. Lighting is provided by flourescent lamps.

Building C, (the control building) is also a low rise (4 floor) office building. It is approximately 50 years old and is equipped with operable windows for ventilation and radiators for heat. At the time of the investigation there were an equal number of occupants housed in both buildings, performing similar types of work.

Results

Part 1 Questionnaire Survey:

A self-administered Work Environment Survey Questionnaire (previously tested on a large number of office workers in a number of different buildings) was administered to occupants of both buildings (Sterling *et al*, 1984b). The questionnaire requested data in four information categories: demographic characteristics of the respondent, subjective evaluation of the office environment, health impairment symptoms experienced at work and degree of control of occupants over environmental conditions.

Comparison of the populations of study and control buildings showed a similarity in various charactristics. These include age, sex, job types, smoking habits, number of hours worked in the building and use of office equipment, such as typewriters, VDT's and photocopiers. Despite the similarity between the two building populations, further examination of responses indicated major differences in health and environmental conditions.

...Despite the similarity between the two building populations, further examination of responses indicated major differences in health and environmental conditions...

Tables 5 and 6 summarize the responses to questions related to environmental conditions and health complaints of occupants of both buildings. Each table shows the percent of staff reporting that they *usually* experienced a particular condition or complaint in their work location. Differences between the distribution of responses among occupants of the two buildings were statistically analyzed.

Table 6 compares responses related to environmental conditions within the two buildings. Statistically significant differences were found for six of the fourteen environmental parameters. Over 75% of respondents felt that the study building had too little air movement, that the air was too dry and too stuffy, 48% found the air to be too smokey. The results show a high level of dissatisfaction in the study building with ventilation, thermal conditions, noise levels and glare from work surfaces.

Table 6 shows the frequency of response for symptoms of tight building syndrome related to irritation of the mucous membrane. The differences between the two buildings are statistically significant for all symptoms except eye irritation. Twice as many respondents from the study building indicated symptoms of sore and irritated throat, nose irritation, skin dryness, rash or itching, and respiratory problems compared to the control building. It is interesting that the most frequent complaints in both study and control buildings are those of eye irritation. While the difference in fequency of eye irritation is not significant (measured by statistical criteria) it must be emphasized that eye irritation is the most pervasive health and comfort complaint.

TABLE 2

Tracer GAs (SF 6) contcentrations (ppm) east and west stair wells, garage level 2, main and third floors

Floor Level:	Garage		Main		Third	
Stairwell:	East	West	East	West	East	West
Pass1 8:40-9:04	30.71	10.6	12.7	5.1	.6	.6
Pass2 9:149:38	39.6	7.7	23.0	6.4	10.1	6.0

Table 7 shows the distribution of response for non mucous membrane irritation symptoms related to tight building syndrome. Occupants of the study building experienced a significantly higher level of headache, fatigue and nausea than did occupants of the control building.

Table 8 shows the frequency of response for muscular symtoms, including aches of the arms, hands and wrists, chest pain and tightness, back ache and neck ache. There are no significant differences in these symptoms between the two buildings. Since occupants of both buildings use the same type of equipment and furnishings, these data suggest that the differences in symptoms of tight building syndrome shown in Tables 6 and 7 between occupants of the study and control buildings are likely due to environmental factors such as ventilation and thermal performance.

Part 2 Environmental Measurements:

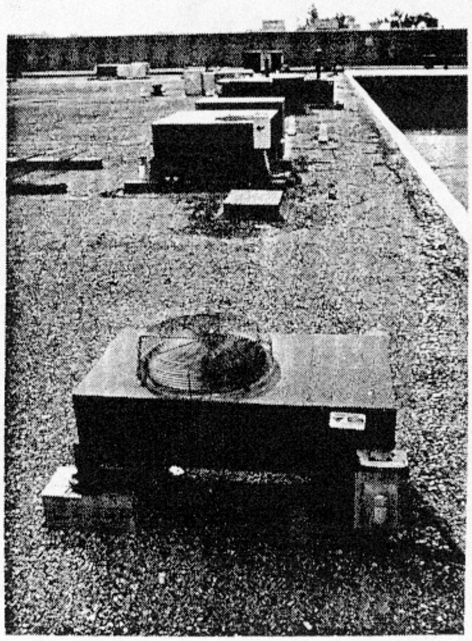
In conjunction with the administration of the questionnaire, carbon dioxide, temperature and relative humidity were measured. Spot measurements were taken twice a day at a number of locations on each floor of the study building for a two week period between December 5 to December 21. For comparison, similar measurements were taken at selected locations in the control building and outside on the roof of the study building. Table 9 shows the range and mean values of carbon dioxide, temperature and humidity measured inside Buildings S and C and outside.

...The cause is not the same for all buildings...

The results show a strong similarity between the study and control buildings for CO2 concentrations and temperature. However, the relative humidity was substantially lower in the study building with a mean value of only 22.3% RH compared to the control building with a mean value of 29.8 RH.

Conclusions (Case Study 2)

1. There is a higher incidence of reported problems with the environment among occupants of the study building.



2. There is a higher incidence of symptoms of Tight Building Syndrome reported by occupants of the study building, but especially of symptoms of irriated mucus membranes that may be related to low humidity levels.
3. The relative humidity is substantially lower in the study building.

Discussion

In the coming years public health inspectors will be increasingly requested by office building occupants to investigate complaints of Tight Building Syndrome. We have demonstrated in the preceeding case studies that a systematic approach to investigations of sick buildings can provide researchers with the clues necessary to determine the cause and define an effective control strategy. We have also seen that the cause is not the same for all buildings. In building A the ventilation system was malfuncting. The exhaust fans in the parking garage were operating in reverse, while in the office space 30% of the supply air vents were stuck in the closed position. Building S, even though located in the very moist coastal climate of British Columbia, provides very dry air to occupants. This building requires the addition of a humidification system while building A requires repairs and adjustments.

The following suggestions may provide some guidance for public health inspectors investigating a suspected problem building.

1. Listen to occupant perceptions of environmental conditions. If possible, use a survey questionnaire for which base line data is available. (For example, the survey questionnaire used in Case Study 2 has been administered to nearly 4,000 office workers in Sick Buildings and, for comparison, 1,200 office workers in buildings with no history of complaints.)
2. Review the building and mechanical system plans and do a walk through site visit keeping in mind the features common to sick buildings. (Sterling et al, 1983).
3. Develop a measurement strategy based on what can be learned from building occupants and seen from a site and plan inspection.
4. Because measurments can be very expensive and often not very enlightening, there ought to be a reason for all measures taken. Also, keeping in mind the purpose of a building evaluation is often more practical than scientific. The intent ought to be to *solve* a problem rather than to *study* a situation.

TABLE 3

Range of average temperature measured on main, second and third floors
October 25 - November 6, 1984

Floor	Low	High
Main	63.6	69.0
Second	69.5	74.6
Third	72.2	73.8

Continued on Page 18.

Continued from Page 15.

TABLE 4

Carbon dioxide concentrations (ppm) at selected locations main, second and third floors

	Main	Second	Third	Outdoor Ambient
Pass 1 11:18-11:50	-	770	700	355
Pass 2 13:00-14:16	680	697	730	330
pass 3 14:29-14:58	730	.900	810	370
Pass 4 15:00-15:28	900	830	800	-
Pass5 15:30-15:58	860	1,040	840	-
Pass 6 16:00-16:25	1.020	910	900	350
Pass 7 16:29-16:58	775	690	590	-

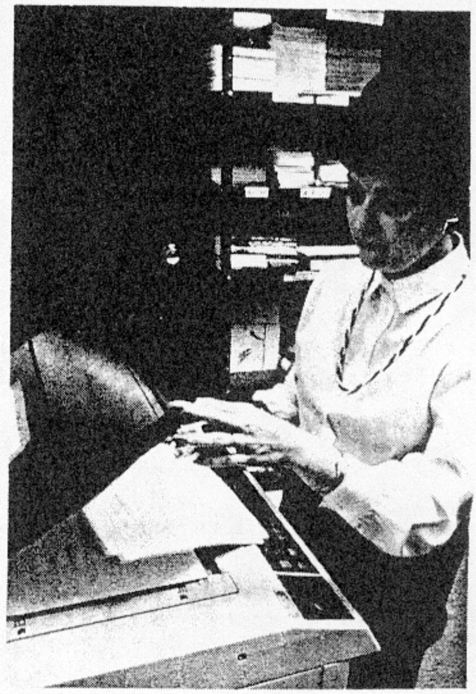


TABLE 5

Percent of occupants of study and control buildings rating environmental conditions as usually occurring

Environment Complaint	Study Building (N=129)	Control Building (N=118)
Too little air*	76.6	48.7
Too much air	19.4	20.5
Too dry*	76.7	37.6
Too moist*	3.1	8.6
Too hot	58.9	49.6
Too cold	55.8	65.8
Too bright	27.1	33.3
Too dim	19.4	23.9
Glare on work surface	43.4	43.6
Too noisy	62.0	69.0
Too quiet	3.1	5.1
Smoky*	48.8	35.0
Stuffy*	84.5	46.2
Unpleasant odors*	46.5	35.0

* Differences between study and control buildings are statistically significant.

TABLE 6

Percent of occupants of study and control buildings reporting symptoms related to irritation of mucous membranes

	Study Building	Control Building
Respiratory problems*	12.4	1.7
Sore and irritated throat*	39.5	18.8
Nose irritation*	43.4	21.4
Skin dryness or itching*	33.3	18.0
Eye irritation	47.3	41.9

*Differences between study and control buildings are statistically significant.

BIBLIOGRAPHY

1. Hicks J. B., Tight building syndrome. *Occupational Health and Safety Magazine* (January):1-12, 1984
2. McDonald J. C., Investigation of Employee Health Complaints at Les Terrasses de la Chaudiere. *Final Report to TB/PSAC Steering Committee, Treasury Board of Canada, Contract TB/CRT-REQ B8059,1984.*
3. Sterling E.M., Steeves J.F., Wrigley C.D., Sterling T.D., Weinkam J.J. "Building Performance Database." *Proceedings, International Conference of Building Use and Safety Technology, March 12-14, 1985.*
4. ASHRAE Standard ANSI/ASHRAE 55-1981, Thermal Enivronmetal Conditions for Human Occupancy, *American Society of Heating, Refrigating and Air Conditioning Engineers, Atlanta, 1981b.*
5. Sterling, Theodor D. Ltd.: Criteria for Residential Exposure to Water Vapour, *Criteria Section, Environmental Health Directorate, Health and Welfare Canada, Contract 1032.*
6. Sterling E.M., Arundel A., Criteria for human exposure to humidity in occupied buildings. *Transactions, American Society of Heating, Refrigerating and Air Conditioning Engineers, 1985a.*

7. Sterling E.M., Sterling T.D., "Pollution concentration in buildings." *Proceedings AIA Research & Design '85, Los Angeles, CA., March 14-18, 1985b.*
8. ASHRAE Standard 62-1981, Ventilation for Acceptable Indoor Air Quality. *American Society of Heating, Refrigerating and Air Conditioning Engineers, Atlanta, 1981a.*
9. Rajhans, G.S.: Indoor air quality and CO2 levels. *Occupational Health in Ontario. 4(4):160-167, 1983.*
10. *Sterling, Theodor D. Ltd., Criteria for Residential Exposure to Carbon Dioxide, Criteria Section, Environmental Health Directorate, Health and Welfare Canada, Contract 1032.*
11. Sterling E.M., Sterling T.D., "Baseline data: Health and comfort in modern office buildings." *Proceedings, 5th AIC Conference "The Implementation and Effectiveness of Air Infiltration Standards in Buildings," Reno, Nevada, October 1-4, 1984b.*
12. Sterling E.M., Sterling T.D., McIntyre D., New health hazards in sealed buildings. *American Institute of Architects Journal,* (April):64-67, 1983.

TABLE 7

Percent of occupants of study and control buildings reporting symptoms related Building Illness (not including symptoms of mucous membrane irritation)

	Study Building	Control Building
Headache*	52.7	40.1
Dizziness	19.4	12.0
Fatigue*	61.2	42.7
Nausea*	14.7	6.8

*Differences between study and control buildings are statistically significant.

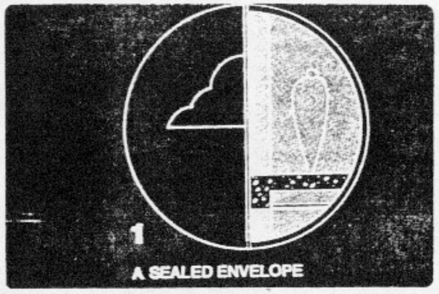
TABLE 8

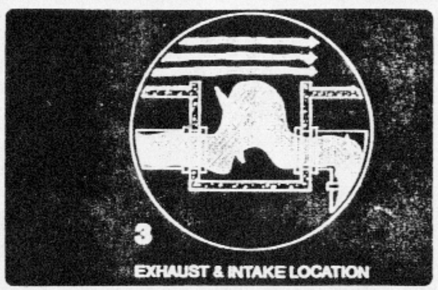
Percent of occupants of study and control buildings reporting muscular complaints

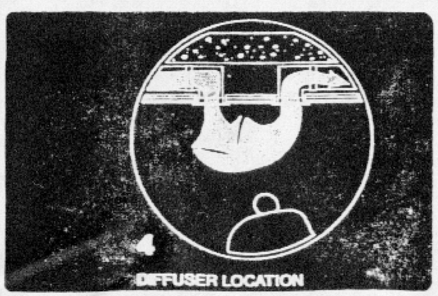
	Study Building	Control Building
Aches of arm, hands, wrists	15.5	16.2
Chest pains or tightness	6.24	4.3
Back ache	35.7	36.8
Neck ache	34.9	41.0

TABLE 9 Carbon dioxide, temperature and humidity measured in buildings S and C.

	BUILDING S		BUILDING C		OUTDOOR	
Environmental Parameter	Range	Mean	Range	Mean	Range	Mean
Carbon Dioxide (ppm)	291.7-666.7	514.6	250-791.2	515.2	83-302.9	302.9
Temperature (°C)	19-23	21.4	19-23	21.0	3-10.5	6.3
Relative Humidity (%)	7-39	22.3	19-43	29.8	9-81	50.6







SUMMARY OF CHARACTERISTICS COMMON TO SICK BUILDINGS

E.M. Sterling and E.D. McIntyre

Theodor D. Sterling Ltd.
#70 - 1507 West 12th Avenue
Vancouver, B.C. V6J 2E2

From case studies as well as other research, nine features common to Sick Buildings have been identified:

1. A sealed building envelope

Generally, the amount of fresh air drawn into a sealed, mechanically controlled building is minimized as it is energy efficient to recirculate as much of the building air as possible.

2. Mechanical heating, ventilation and air conditioning

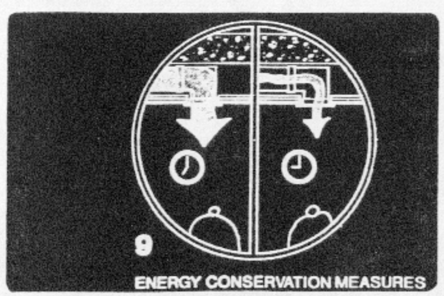
The mechanical system aids dispersal throughout a building of the many irritants and pollutants generated by materials and equipment. The system may also incubate and spread fungi, bacteria and viruses. (A mechanical ventilation system was in part responsible for spreading Legionnaire's Disease, which caused 21 deaths in the Belleview Stratford Hotel.)

3. Location of vents and exhausts

Air supply vents can introduce outdoor contaminants into a building. For example, supply vents located overlooking a busy street or transit stop are often the source of entry for autó or diesel exhaust. Also, poor placement of supply and exhaust vents can prevent exhaust from escaping. Exhaust air may even be introduced directly back into the air supply.

4. Location of ventilation diffusers

Both inlet and exhaust diffusers are commonly located in the ceiling. This often creates stratification and short circuiting of supply at the ceiling level resulting in dead air and poor circulation.



5. Lack of individual control over environmental conditions

All people are not equally comfortable in the same environment. Elimination of the possibility to modify the environment tends to contribute to discomfort, stress, strain and minor health problems.

6. Use of new materials and equipment

Synthetic materials and modern office equipment, as well as industrial soaps, detergents and waxes used for maintenance, generate many irritating and sometimes toxic fumes and dusts including formaldehyde, hydrocarbons, amines, ozone and respirable particulates.

7. Fluorescent lamps

The new popular sunlight simulating type as well as the standard fluorescent lamp emanates ultraviolet light. These lamps may provide energy for photo chemical reactions among pollutants, thus creating indoor smog (Sterling *et al*, 1984c).

8. Parking garages, restaurants and other non-office space use

Many large office developments also contain within the same building parking garages, access to transportation (such as buses and subways), restaurants, health clubs, laundry and recreation facilities. These spaces may add substantial amounts of combustion by-products and industrial chemicals including carbon monoxide, oxides of nitrogen, carbon dioxide and diesel exhaust to the indoor environment.

9. Energy conservation methods

Energy conservation methods usually involve reduction of fresh air ventilation rates. Reduction of the fresh air supply increases the rate of accumulation of pollutants by reducing the volume of air exhausted. The efficiency of standard air filters and their ability to control contaminants is reduced substantially as the velocity of the ventilation air is lowered. Many buildings now use a Variable Air Volume system. This VAV only introduces fresh air when cooling or heating is required, not when vent is required. Occupants of buildings with the VAV system often complain of stale, stuffy air, an indication of insufficient ventilation.