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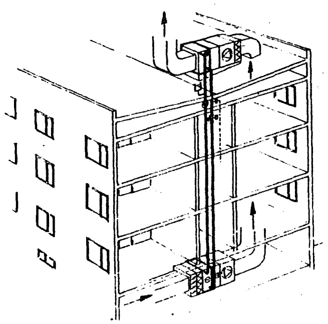

Fig. 1 Example of the installation of a liquid-coupled heat recovery system.

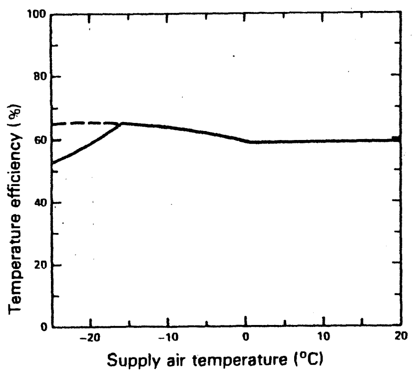

Fig. 2 Variation of the temperature efficiency as a function of the supply air temperature upstream of the heat exchanger. (The efficiency is reduced at about -17 °C in order to avoid frosting.)

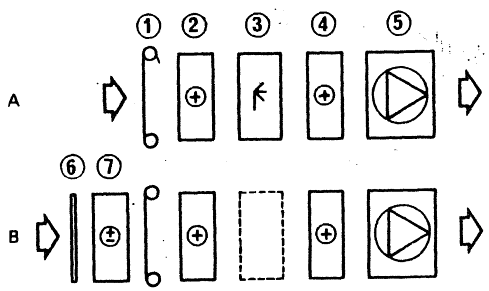

Fig. 3 Supply air system in Example 1. A: original design, B: after the installation of the heat recovery system. 1) roll filter, 2) preheating coil, 3) humidifier, 4) reheating coil, 5) supply air fan, 6) panel filter, 7) heat recovery coil.

Indoor Air Quality in Energy-Efficient Buildings

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Summary

The relationship between ventilation rate and indoor air quality is being investigated with a mobile laboratory designed specifically for studies of indoor air quality and energy utilization in buildings before and after energy conservation retrofits, and in new buildings incorporating energy-efficient designs. The characterization program includes measurement of infiltration rate (continuous C_2H_6 and N_2O tracer gas method), CO, CO_2, NO, NO_2, SO_2, O_3, formaldehyde, total aldehydes, radon and particulate mass and chemical composition. Results of the initial phases of this program indicate that the concentrations of some air pollutants in the built environment are higher than outdoor levels and in some cases even exceed recommended health and comfort criteria when infiltration and ventilation rates are reduced.

Qualité de l'air á l'intérieur de bâtiments éfficients du point de vue énergétique

Résumé

La relation entre les taux de ventilation et la qualité de l'air intérieur est etudiée avec un laboratoire mobile construit spécialement pour les études de qualité de l'air et d'utilisation d'énergie dans les immeubles existants, avant et après certaines mesures pour économiser l'énergie, et dans les immeubles nouveaux, à haute éfficience énergétique. Le programme de caractérisation se compose de mesures des taux de renouvellement d'air (méthode à injection continue des gaz traceurs C_2H_2, H_2, N_2O), des taux de CO, CO_2, NO, NO_2, SO_2, O_3, aldéhyde formique, aldéhyde totale, radon, et la masse et la composition chimique des particules en l'air. Les résultats de la phase initiale de ce programme indiquent que les concentrations de quelques polluants dans l'environnement intérieur dépassent les niveaux extérieurs et parfois ils excèdent même les critères recommandés de santé et confort, surtout quand les taux de renouvellement d'air et de ventilation sont réduits.

Introduction

Reduced infiltration and ventilation rates in buildings can lead to elevated levels of indoor generated air contaminants (1). Chemical and biological contaminants released into indoor environments are undesirable but often unavoidable by-products of human activity, building materials and/or furnishings within enclosed spaces. Typical indoor contaminants include gaseous and particulate pollutants from indoor combustion processes (such as cooking, heating, tobacco smoking), toxic chemicals and odors from cooking and cleaning activities, odors and viable microorganisms from humans, odor-masking chemicals used in several activities, and a wide assortment of chemicals released from indoor construction materials and furnishings. Table 1 lists some of the major indoor air pollutants in residential buildings and their sources.

When these contaminants are generated in indoor environments in excessive concentrations, they may impair the health, safety, or comfort of the occupants. Building occupants are normally protected from the accumulation of undesirable indoor air contaminants in two ways: the random introduction of outdoor air by infiltration (through cracks in the building envelope); or regulated introduction by natural ventilation (opening windows and doors) or mechanical ventilation (fan and duct systems of varying complexity). In institutional and commercial buildings, the primary engineering control for the maintenance of indoor air quality is mechanical ventilation, i.e., the use of controlled flows of air. The levels of indoor air contaminants can be lowered by 1) dilution with fresh outside air; 2) the use of recirculation systems incorporating chemical and physical contaminant control devices; or 3) a combination system employing both dilution and recirculation.

The United States has begun to examine its energy consumption because of rising concern about the availability of conventional energy resources. It is clear that we have entered a period in which increasing attention will be devoted to discovering new methods of conserving energy. Because of this increased energy conservation awareness, measures are being taken to make buildings more energy-efficient. These include tightening the building envelope to reduce exfiltration and infiltration, improving insulation, and reducing ventilation. As these measures are implemented and less fresh air is introduced into buildings, the quality of the indoor air may deteriorate. Unfortunately, there is little agreement in the United States or elsewhere, on the level of fresh air required for the health, safety and

Table 1 Indoor Air Pollution in Residential Buildings

SOURCES	POLLUTANT TYPES
OUTDOOR	
Ambient Air	SO_2, NO, NO_2, O_3, Hydrocarbons, CO, Particulates
Motor Vehicles	CO, Pb
INDOOR	
Building Construction Materials	
Concrete, stone	Radon
Particleboard, Plywood	Formaldehyde
Insulation	Formaldehyde, Fiberglass
Fire Retardant	Asbestos
Adhesives	Organics
Paint	Mercury, Organics
Building Contents	
Heating and cooking combustion appliances	CO, SO_2, NO, NO_2, Particulates
Furnishings	Organics, Odors
Water service; natural gas	Radon
Human Occupants	
Metabolic activity	CO_2, NH_3, Organics, Odors
Human Activities	
Tobacco smoke	CO, NO_2, HCN, Organics, Odors
Aerosol spray devices	Fluorocarbons, Vinyl Chloride
Cleaning and cooking products	Hydrocarbons, Odors, NH_3
Hobbies and crafts	Organics

comfort of building occupants.

Ventilation standards for buildings with different functional uses have been in existence for over a half century. In general, they do not take energy conservation requirements into account and, since they have been established by a variety of groups, they frequently vary for the same application. A comprehensive effort is now underway in several laboratories in the United States and Europe to establish a scientific basis for all such existing standards, to measure the actual levels of indoor air contaminants in several classes of buildings, and to provide a consistent set of recommendations for the establishment of energy-efficient ventilation standards in residential, institutional and commercial buildings.

The ultimate objective is to reduce energy consumption as much as possible without impairing the health and comfort of the occupants. Currently, there is incomplete information for determining indoor air quality criteria. These criteria are required for establishing ventilation requirements in buildings. This information gap is due in large measure to the complex nature of indoor air pollution. In particular, the complex biological, chemical and physical mix of indoor air pollutants has been recognized only very recently. Most studies of indoor air pollution have largely assumed that indoor pollution arises from and is directly related to outdoor sources. Recently, it has been recognized that a number of indoor air contaminant sources can be traced to the built environment itself.

In order to establish criteria for setting energy-efficient ventilation standards, the Lawrence Berkeley Laboratory (LBL) under contract to the U.S. Department of Energy is involved in a comprehensive assessment of indoor air quality in several building types under a variety of infiltration and ventilation conditions. LBL and its subcontractors are assessing a significant number of the pollutants shown in Table 1. The general parameters are:

- temperature and relative humidity
- odors
- toxic chemicals (gases and particulates)
- microbial burden

Experimental Methods

The Energy Efficient Buildings (EEB) Mobile Laboratory (2) is designed to facilitate both field indoor air monitoring efforts and research studies of ventilation requirements and energy utilization in residential, institutional and commercial buildings.

The laboratory contains sampling, calibration and monitoring systems which provide an index of the overall air quality in a building. Air exchange rates are measured using a tracer gas system (3) developed at LBL in which either nitrous oxide or ethane is injected into the building and monitored continuously at various sampling sites in the building under controlled conditions. Tracer gas concentrations and other continuously-monitored parameters are recorded on a microprocessor-controlled floppy disk. The recorded information is transmitted back to LBL by telephone or by sending the floppy disks back to LBL where they may be read into the LBL computer system.

The EEB Mobile Laboratory is positioned outside the building to be studied. Air is drawn through teflon sampling lines from four locations within the structure into the mobile lab for analysis. By sequentially

sampling the lines (one of which is used to monitor outdoor ambient air), the air quality can be monitored in several rooms. The four lines are sequentially sampled for ten-minute intervals to allow monitoring of the gas concentrations (CO, CO_2, NO, NO_2, SO_2 and O_3) in all four locations; consequently, ten-minute samples are taken from each site every forty minutes.

For some pollutants, grab sampling techniques are used. The size distribution of the particulate matter in the sampled air is measured by means of an optical scattering instrument and automatic dichotomous air samplers; the latter are also used to collect particulate matter for chemical analysis. The dichotomous air samplers (4), developed at LBL, separate the aerosols into respirable and non-respirable fractions (below and above 2.5 micron size respectively) using a flow-controlled virtual impaction system, which deposits the particulate matter on teflon filters. The particulates collected on the filters are analyzed at LBL using beta-ray attenuation to measure mass concentration, and x-ray fluorescence to determine chemical composition for 27 elements. Some of the contaminants must be collected with gas bubblers and other sampling techniques requiring subsequent laboratory analysis. These contaminants include formaldehyde, total aldehydes, other selected organic compounds, radon and airborne microbes.

Results and Discussion

LBL is monitoring indoor air quality at several hospitals and educational facilities in the United States before and after energy-conserving retrofits are implemented. In addition, prototype energy-efficient residential, institutional and commercial buildings are being studied as possible models for energy conservation practices in future building design.

The first four sites to be included in the LBL indoor air quality field monitoring program are an air-conditioned high school in Concord, California; occupied and unoccupied Minimum Energy Dwellings (MED) in Mission Viejo, California; the Naval Regional Medical Center in Long Beach, California; and the Iowa State University Energy Research House (ISU-ERH) in Ames, Iowa.

The indoor air quality at the MED and ISU-ERH houses is of considerable interest because these residential buildings were constructed to have low air infiltration. Air change rates measured at the unoccupied MED house, using a simple exponential decay-rate method, yielded values of approximately 0.2 air changes per hour (ach). Infiltration rates at the ISU-ERH were measured using the N_2O continuous tracer gas system. The infiltration rate varied from about 0.15 ach to 0.75 ach with an average of about 0.3 ach.

Preliminary results from these field monitoring sites show that the pollutants studied fall into three major classes, those for which the primary sources are indoors (e.g., CO_2, HCHO), those for which the primary sources are outdoors (e.g., O_3), and those for which the sources are combustion processes in either the indoor or outdoor environment (e.g., CO, NO_2). Substances in the first class have indoor concentrations which increase and may present health risks as buildings are tightened and ventilation rates reduced, while substances in the second class tend to be shielded from the indoor environment as ventilation rates are reduced.

Figure 1 shows a histogram of ten-minute nitrogen dioxide (NO_2) concentrations both indoors and outdoors at the occupied MED house. These concentrations are higher indoors since NO_2 is a combustion product of natural gas used in cooking. The NO_2 indoor levels, however, are significantly below the U.S. Environmental Protection Agency annual average NO_2 air quality standard of 50 ppb and the proposed short-term (1 hour) standard of 250 ppb (1). Figure 2 shows histograms of the ozone (O_3) concentrations indoors and outdoors at the occupied MED house site. In the case of this pollutant, the house serves to shield the occupants from the O_3 produced in the outdoor environment. The short-term (1 hour) air quality standard for O_3 is 120 ppb.

Total aliphatic aldehydes have been measured (as formaldehyde) at the occupied and unoccupied Minimum Energy Dwellings (MED) in Mission Viejo, California; at the Naval Regional Medical Center in Long Beach, California; and at the Iowa State University Energy Research House in Ames, Iowa. Preliminary results indicate that the average concentration of aldehydes in the occupied MED house with an air exchange rate of 0.2 ach is about 116 ppb compared to 38 ppb in the unoccupied MED house and 14 ppb in outdoor air. The well-ventilated hospital in Long Beach had low levels of aldehydes (typically <30 ppb) and no significant differences between indoor and outdoor aldehyde levels were observed.

Figure 3 is a histogram showing the range of total aliphatic aldehydes and formaldehyde during the monitoring at the Energy Research House in Ames (air exchange rate ∿0.3 ach). The concentrations of total aliphatic aldehydes were between 109 and 186 ppb (133 ppb average) when unoccupied. Simultaneous sampling of outdoor air yielded an average aldehyde concentration of 13.5 ppb with a maximum value of 30 ppb and a minimum value of 2 ppb. The formaldehyde fractions of the indoor samples were between 51

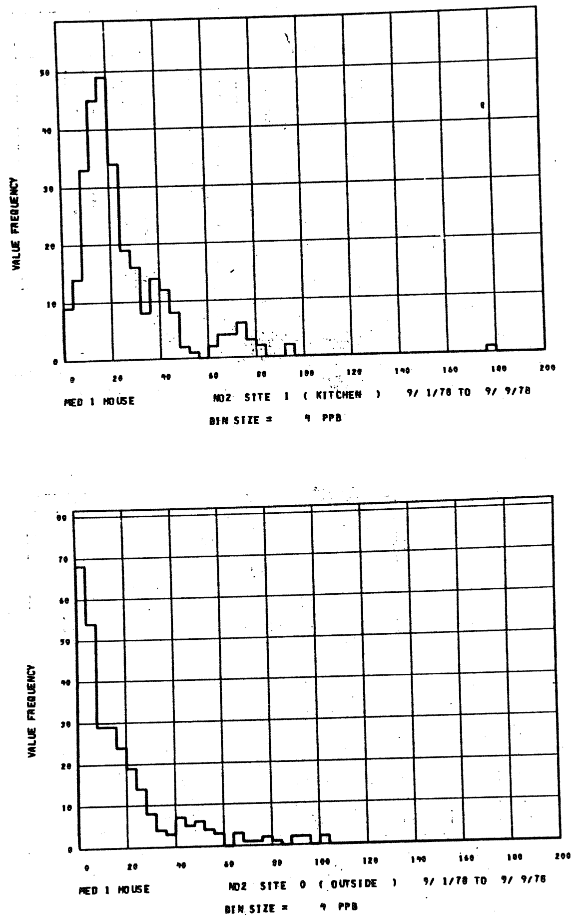

Figure 1. Indoor/Outdoor Nitrogen Dioxide

and 125 ppb and averaged 74 ppb. The outdoor formaldehyde concentrations were below 5 ppb for the entire sampling period.

These results indicate that, in general, indoor air has higher formaldehyde/aldehyde concentrations than outdoor air. The concentration of aldehydes often exceed the recommended U.S. and European formaldehyde standards (100 ppb) (1) for indoor air in residential buildings. Common building materials such as plywood and particleboard constructed with urea-formaldehyde resin are possible indoor formaldehyde/aldehyde sources.

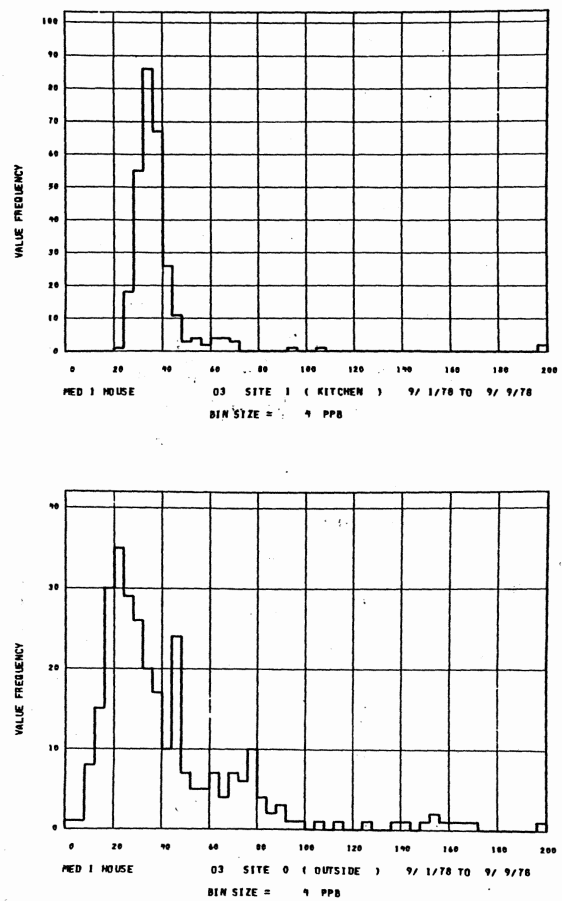

Figure 2. Indoor/Outdoor Ozone

In addition, the activities of the building occupants, e.g., cooking, smoking and cleaning, also generate significant amounts of aldehydes.

Preliminary results from the California school indicate that the fresh air ventilation rate could be substantially reduced without compromising the health or comfort of the occupants. The air quality in two classrooms, in a corridor, and outdoors was monitored under three ventilation rates in the school. The first ventilation rate, 22.6 m^3/h of outside air per occupant was the normal operating mode, with roof dampers in the full

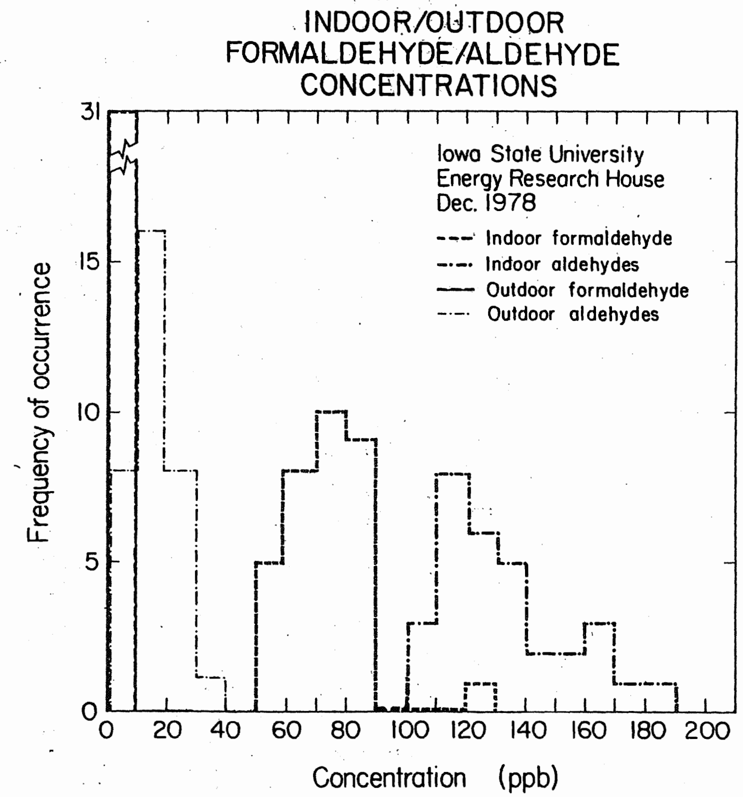

Figure 3. Indoor/Outdoor Formaldehyde/Aldehyde

open position. The second and third rates (4.3 m^3/h and 2.6 m^3/h, respectively) restricted the total fresh air vented into the school. The decision to restrict the fresh air to 2.6 m^3/h was not made until it had been established that the indoor air quality at 4.3 m^3/h was still very good.

Data collected at these three ventilation rates indicated that carbon dioxide was the only pollutant detected in significant concentrations inside the school. This is not surprising, since there were no obvious indoor sources of pollution other than the occupants themselves. The school borders on a main road and during rush-hour periods when increased levels of nitrogen oxides and ozone were present outside, smaller but measurable concentrations were observed indoors. Indoor concentrations of these pollutants actually decreased as the "fresh" air ventilation rates were reduced. Although CO_2 concentrations inside the classroom increased as ventilation rates were lowered, at no time did they exceed 2000 ppm, and only occasionally did they exceed 1500 ppm. This should be compared to the eight to ten-hour maximum values of 5000 to 10,000 ppm recommended by various U.S. health agencies (5).

In order to assess the potential reaction of the students to the changes in ventilation rates, a questionnaire on the quality of the indoor environment was distributed to the classroom occupants. The students' subjective judgment of odor level at various ventilation rates was of particular terest since odor control is probably the basis for current ventilation requ ements in schools. The questionnaires were filled out every other day at same time. Results of this survey showed no deterioration of student com caused by decreased ventilation rates.

The California ool was also one of the two sites included in the biological field moni ng project. The results at the school do show that decreasing the ventila n rate did not increase the microbial burden in the classrooms.

In summary, results of the field mo ring project at the California school indicate no significant change as a lt of decreased ventilation in any of the parameters measured, with the excep of carbon dioxide. In fact, the air quality improved in the school for some rameters (nitrogen dioxide and ozone) when the ventilation rate was red d. Although indoor CO_2 levels increased, they were still far below those evels considered to be a health hazard.

Since the amount of outside air entering the school could be decreased without any adverse effect on the health, safety or comfort of the occupants, substantial energy savings could be achieved by lowering the fresh air ventilation rates at the school. Total energy use for this 700-student high school, including gas and electricity (used for space conditioning, lighting and hot water) costs about $40,000 per year. If the ventilation rates were changed from 22.6 m^3/h per occupant to 2.6 m^3/h, it is estimated that savings would be $3500 to $4000 per year or 9% of total annual energy costs for the building.

Conclusions and Recommendations

Because of increased energy prices, there are financial incentives to reduce air exchange rates and thereby reduce heating and cooling loads. Nevertheless, measures presently under consideration that would reduce infiltration and ventilation rates could significantly increase exposure to indoor contaminants and perhaps have adverse effects on occupant comfort and health.

Preliminary results from the LBL field monitoring program indicate that the indoor levels of several pollutants exceed the levels found outdoors; however, in general (except for aldehydes), the levels are still within limits established by air quality standards. It is expected that an extensive field monitoring program in a number of energy efficient buildings, wherein pollutant levels and air exchange rates can be determined over a range of occupancy conditions, will allow us to delineate more precisely the sources of indoor pollutants, the effects of conservation measures on indoor pollutant levels, and the health and comfort effects of such changes.

Indoor pollution levels are strongly affected by human activities in a building and by the manner in which materials are incorporated into a building, as well as other aspects of the building design, particularly the infiltration or ventilation rate. There are several building design options that might be adopted specifically to limit increases in indoor air pollution. Options include a careful selection of building materials; the use of integrated mechanical ventilation/heat exchanger systems in residential buildings to allow moderate ventilation, while recovering heat losses from air exchange; the use of contaminant control devices; and the coating of various building materials with sealants to reduce emissions of potentially harmful pollutants.

Acknowledgements

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Room temperatures as the basis for heating charges in apartment houses - energy saving and consumer reactions

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Room temperature as the basis for heating charges has been tested in 78 apartments with a control group of the same size. The system is proposed as an alternative to direct energy metering, which does not give a fair distribution of heating costs. The signals from a temperature sensor, mounted at a central place in the apartment, are transformed to pulses by means of conventional electronics, and the pulses are feeding a small electromechanical counter. The energy saving are estimated to 10-15% for the heating season, which corresponds to a room temperature reduction in the order of 2 °C. Consumer reactions, surveyed just after the introduction and at the end of the test period, indicate however that the room temperature is hard to concieve as the "natural" basis for heating charges.

Choix de la têmperature ambiante comme base de tarification des charges de chauffage dans des immeubles collectifs a usage d'habitation. Economies rêalisés - reaction des locataires.

Le systême a êté têstée dans 78 appartements et sur un groupe de contrôle de la même importance. Celui-ci est destinê a remplacer les mesures directes de consommation, qui ne donnent pas une rêparation êquitable des charges. Les signaux êmis par une sonde thermique montêe au milieu de l'appartement sont transformês en impulsions qui sont enrêgistrêes par un computeur êlêctromêcanique. Les êconomies rêalisêes sont estimêes â 10-15% pendant la pêriode de chauffage, ce qui correspond â une rêduction de la tempêrature ambiante d'environ 2 °C. La rêaction des locataires êtudiêe d'une part juste aprês l'introduction et d'autre part â la fin de la pêriode du test, indiquent les difficultês de comprendre la tempêrature ambiante comme base "naturelle" de tarification des charges de chauffage.

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