CARBON DIOXIDE LEVELS AND DYNAMICS IN ELEMENTARY SCHOOLS: RESULTS OF THE TESIAS STUDY

RL Corsi[1,2*], VM Torres[1], M Sanders[1,2] and KA Kinney[1,2]

[1]Texas Institute for the Indoor Environment, Center for Energy & Environmental Resources, The University of Texas at Austin, TX, USA
[2]Department of Civil Engineering, The University of Texas at Austin, TX, USA

ABSTRACT
The Texas Elementary School Indoor Air Study (TESIAS) involved several phases, including single-day continuous monitoring of carbon dioxide (CO_2) in 120 randomly selected classrooms in two school districts. The median time-averaged and peak CO_2 concentrations were 1,286 ppm and 2,062 ppm, respectively. The time-averaged CO_2 concentration exceeded 1,000 ppm in 66% of the classrooms. The peak CO_2 concentration exceeded 1,000 ppm in 88% of the classrooms and 3,000 ppm in 21% of the classrooms. Mean and peak occupied CO_2 concentrations were statistically different ($\alpha = 0.05$) between the two districts, and peak CO_2 concentrations were statistically greater in classrooms that employed packaged terminal air conditioning (PTAC) systems. Statistically significant differences in both mean time-averaged and peak CO_2 concentrations were not observed for portable vs. traditional classrooms, classrooms with outside vs. inside entries, or when data were separated amongst teacher responses to questions related to classroom odors.

INDEX TERMS
Carbon dioxide, Elementary schools, Measurement, Questionnaire

INTRODUCTION
The U.S. General Accounting Office (1995) estimated that one in five U.S. schools has significant indoor air quality (IAQ) problems, a troublesome assessment given that children spend approximately 7,000 hours in classrooms between the levels of K-5 (kindergarten through 5th grade). Daisey and Angell (1999) reviewed over 450 publications related to IAQ in schools, and concluded that many classrooms are not adequately ventilated. Inadequate ventilation can lead to an accumulation of bio-effluents from room occupants, and various gaseous and particulate pollutants associated with building materials, classroom activities, and general housekeeping. For cost savings, many schools have opted to reduce fresh (ventilation) air provided to classrooms, and/or to reduce the frequency of ventilation system maintenance (Casey *et al*., 1995). In some cases, student occupancy of classrooms significantly exceeds that for which the classroom was designed.

Carbon dioxide (CO_2) is often used as a surrogate for evaluation of the adequacy of classroom ventilation, particularly as related to the dilution of pollutants emitted from human metabolic activity (Casey *et al*., 1995; Daisey and Angell, 1999; Smedje and Norback, 1999). Levels of CO_2 greater than 1,000 ppm (or 700 ppm above outdoor background) are generally assumed to be indicative of inadequate ventilation.

[*] Contact author email: corsi@mail.utexas.edu

Daisey and Angell (1999) reported that CO_2 concentrations were often > 1,000 ppm in portable classrooms with no outdoor intake or with ventilation systems switched off. Amongst 44 NIOSH Health Hazard Evaluation Reports, 32% of classrooms were reported to have CO_2 concentrations > 1,000 ppm. Smedje and Norback (1999) studied CO_2 in 181 classrooms in 40 schools in Uppsala, Sweden. They observed CO_2 concentrations > 1,000 ppm in 40% of classrooms, with a median CO_2 concentration of 950 ppm.

In this paper we present data related to recent monitoring for CO_2 in 115 elementary school classrooms in Texas. Data were collected as part of a larger Texas Elementary School Indoor Air Study (TESIAS), for which data analysis continues at the time of this writing.

METHODS

Two school districts agreed to participate in the TESIAS study. District B is located in the Rio Grande Valley of Texas, along the Texas-Mexico border. District G is located in Central Texas. The study was limited to elementary schools in each district. Thirty schools were randomly selected, 10 in District B and 20 in District G.

Approximately 1,350 staff (900 teachers) in the 30 participating schools completed a questionnaire intended to better understand staff personal characteristics, the nature of classroom environments (water damage, use of candles in classroom, etc.), detection and type of odors, perceived environmental quality of rooms, and health symptoms amongst staff and their students. In this paper we consider only the question of whether teachers are bothered/irritated by odors in their classroom.

A total of 120 classrooms (40 in District B and 80 in District G) were randomly selected for further analysis from amongst the approximate 900 classrooms in which a teacher had submitted a questionnaire. For each of these classrooms, CO_2, CO, relative humidity, and temperature were monitored over the course of one day. All classrooms in District B were monitored between October 23rd and December 1st, 2000. All classrooms in District G were monitored between November 8th, 2000 and January 14th, 2001.

Real-time, non-dispersive infrared CO_2 analyzers with data-loggers were placed in classrooms approximately 15 to 30 minutes prior to student/staff occupation in the morning. The analyzers were switched off approximately 30 minutes or more after students and teaching staff vacated classrooms at the end of the day. Care was taken to place analyzers approximately 0.8 to 1.2 m above the floor and 1 m from walls, and in locations that would not be directly impacted by the breath of individual children. Anecdotally, data were lost for five of the 120 classrooms by inquisitive students who tampered with the instruments, as evidenced by sharp spikes in CO_2 concentration (from student breath) immediately prior to the cessation of data recording. Analyzers were calibrated using zero and 1,000 ppm span gases in accordance with manufacturer specifications. Outdoor CO_2 concentrations varied from 340 to 410 ppm over the entire study.

A detailed visual survey was made of each classroom, including information related to classroom dimensions, operability of windows, and more. A detailed analysis of the type and nature of HVAC systems that served each classroom was also completed.

In this paper we have presented cumulative distribution plots for time-averaged and peak CO_2 concentrations. Time-averaged values are based on the comprehensive data set, i.e., including times when students were not in the classroom. Actual mean CO_2 concentrations during student occupation were higher. However, the period of data logging before the start, and after the end, of the school day were short and generally had less affect on the mean CO_2 concentration than did lunchtime vacancy of classrooms. Hypothesis testing was completed on the equality of mean and peak CO_2 concentrations ($\alpha = 0.05$; variances unknown and not necessarily equal).

RESULTS

For illustrative purposes, example CO_2 profiles for three classrooms are presented in Figure 1. In each case, t = 0 corresponds to the start of data logging and not student occupation. Variations in CO_2 concentrations are a function of activities that required students to vacate the room, sometimes with the door open and sometimes with the door closed during vacancy. For example, students in CR-1 engaged in a 45-minute physical education period (outside of room) shortly after initial room occupancy and left the room for lunch period from approximately t = 260 to 290 minutes. For classrooms (CR) 1, 2, and 3, the mean time-averaged CO_2 concentrations were 1,180 ppm, 1,653 ppm, and 2,857 ppm, respectively. Peak concentrations were 1,828 (CR-1), 2,570 (CR-2), and 3,337 (CR-3) ppm. A summary of time-averaged and peak CO_2 concentration statistics for all 115 classrooms is presented in Table 1. Statistics are also provided for the 36 and 79 classrooms in Districts B and G, respectively, for which data were successfully logged. Cumulative distribution plots for time-averaged and peak CO_2 concentrations are presented in Figure 2.

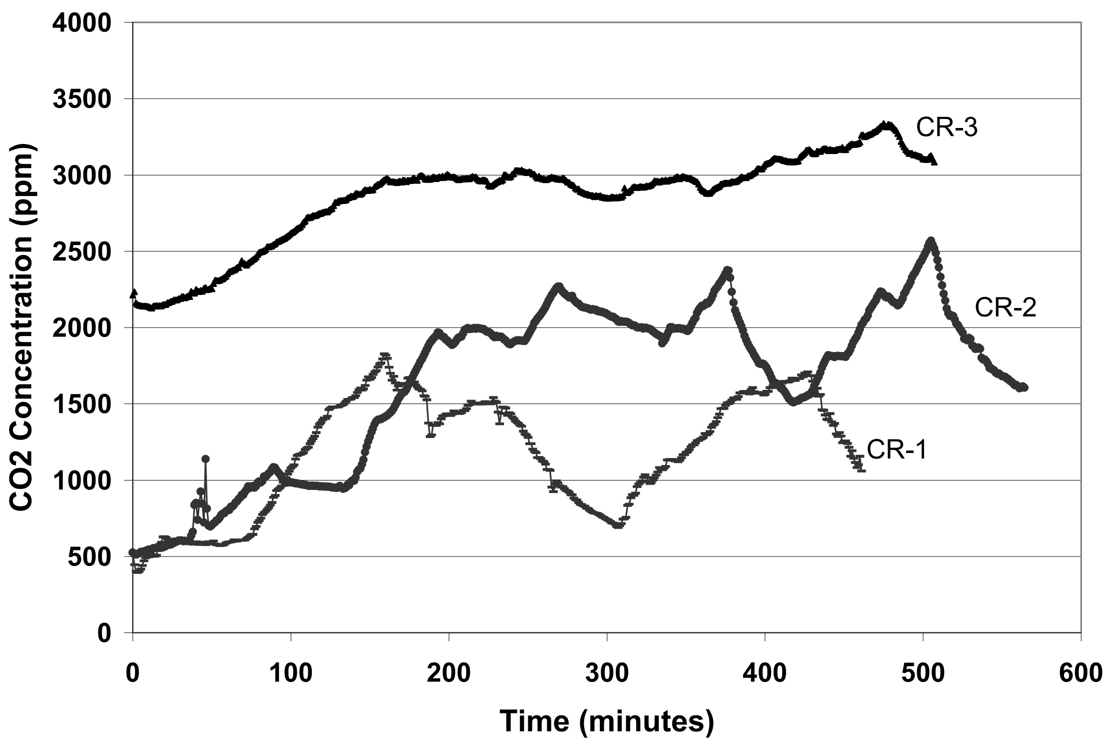

Figure 1. Carbon dioxide profiles as a function of time for three different classrooms.

DISCUSSION

The three CO_2 profiles shown in Figure 1 are illustrative of the dynamic and unique nature of CO_2 profiles in individual classrooms, an observation that has important practical implications. For example, the authors are aware that many consultants in Texas employ short-term, e.g., 10-minute, CO_2 "spot checks" as a means of assessing the adequacy of classroom ventilation. This approach is clearly prone to false conclusions if care is not taken to collect measurements after prolonged student occupation of the classroom. In the case of CR-3 a spot-check measurement anytime after t = 150 minutes would actually provide a reasonable estimate of time-averaged and peak CO_2 concentrations. The same would not necessarily be true for CR-1 and CR-2.

Table 1. Summary statistics for 115 elementary school classrooms in two districts

	All Schools	District B	District G
Time Averaged			
n	115	36	79
Range (ppm)	529-3,112	818-3,112	529-2,899
Mean (ppm)	1,440	1,763	1,292
Median (ppm)	1,286	1,794	1,155
σ (ppm)	642	661	580
Peak			
n	115	36	79
Range (ppm)	744-4,969	998-4,969	744-4,536
Mean (ppm)	2,178	2,657	1,960
Median (ppm)	2,062	2,755	1,854
σ (ppm)	995	1,009	915

n = number of data points; s = standard deviation.

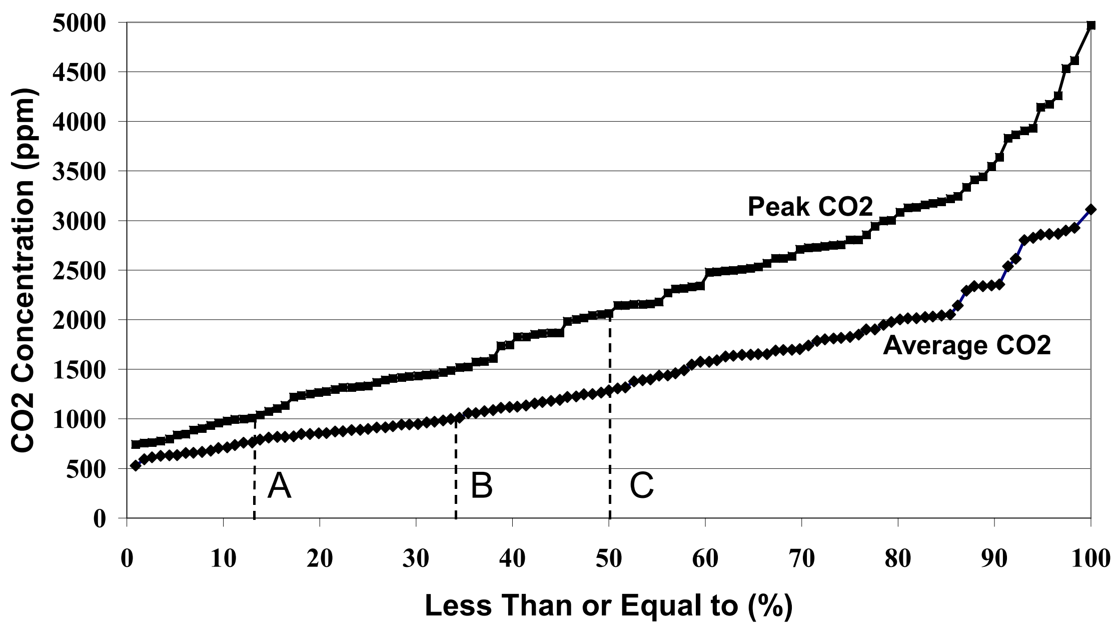

Figure 2. Cumulative distribution plots for time-averaged and peak CO_2 concentrations in classrooms (vertical lines represent % of peak less than 1,000 ppm (A), % of average less than 1,000 ppm (B), and median average and peak CO_2 concentrations (C)).

The dynamic profiles in Figure 1 were largely affected by classroom activities, building design, and design, control, and maintenance of the respective HVAC systems. All three classrooms were served by split system HVAC units that were switched off at night and on weekends. The HVAC systems for CR-1 and CR-2 served only one zone. CR-3 was served by one of four systems that were employed to provide ventilation and comfort for a very large two-story building in which supply air was split between the two floors. The building had no windows. All classrooms on the second floor were designed as an "open environment", divided only by conventional office partitions. There were no exterior doors on the second floor. The ceiling on the second floor was very tall. The outdoor fresh air intake that served the corner of the building where CR-3 was located was purposely blocked.

Classroom CR-1 had an exterior door that remained open during physical education and lunchtime activity periods and following end-of-day departure, hence the rapid decrease in CO_2 concentrations during these periods. CR-2 had an interior door that was also kept open during similar activity periods and was characterized by significant reductions in CO_2 during these periods. Similar responses were not observed for CR-3 during activity periods due to connectivity of classrooms and staggered activity periods between classrooms. The high CO_2 concentrations in CR-3 prior to initial student occupation are a reflection of very poor building ventilation and little decay during the nighttime period. Sampling was completed mid-week. The relatively low increase in CO_2 during the daytime occupation period, despite poor ventilation, was likely due to the large volume (capacity) associated with the second floor of the building.

Sixty-six percent of classrooms were observed to have time-averaged CO_2 concentrations above 1,000 ppm, a percentage that exceeds those reported by Daisey and Angell (1999) and Smedje and Norback (1999). In this study, 20% of classrooms had time-averaged CO_2 concentrations in excess of 2,000 ppm. Peak CO_2 concentrations exceeded 1,000 ppm and 2,000 ppm in 88% and 54% of classrooms, respectively. Peak CO_2 concentrations exceeded 3,000 ppm in 20% classrooms and 4,000 ppm in 5% of classrooms.

The mean time-averaged and the mean peak CO_2 concentrations were both significantly greater in District B than in District G. During walkthrough surveys, we noted that a much higher percentage of outside air intakes that served single zones were blocked in District B classrooms relative to single-zone units in District G. Interestingly, teacher responses to questionnaire issues related to comfort conditions (T, RH, air movement), odors, and classroom environmental quality were not significantly different between the two districts.

Of the 115 classrooms that were monitored, only 8% (10 classrooms) were classified as being within portable buildings. The mean and median time-averaged CO_2 concentrations for the 10 portable classrooms were 1,582 ppm and 1,281 ppm, respectively. The mean and median time-averaged CO_2 concentrations in 105 non-portable (traditional) classrooms were 1,462 ppm and 1,297 ppm, respectively. It was not possible to reject the hypothesis of equality of mean time-averaged CO_2 concentrations between portable and traditional classrooms. A similar result was obtained for mean peak CO_2 concentrations.

Of the 115 classrooms that were studied, 31% had packaged terminal air conditioning (PTAC) units, 25% in District B and 34% in District G. All 36 of the PTAC units were wall-mounted. On average, the equality of both mean time-averaged and peak CO_2 concentrations were rejected when classrooms were separated into those with and without PTAC units, and the alternative one-sided hypothesis of greater mean CO_2 concentrations in rooms with PTAC units was accepted.

Sixty-eight percent of classrooms had entry doors that opened into enclosed hallways that served other classrooms, with nearly identical percentages in District B (69%) and District G

(67%). The equality of mean time-averaged CO_2 concentrations for rooms with and without outside doors could not be rejected. The same was true for peak CO_2 concentrations.

Thirty-six percent of teachers indicated that objectionable odors affect their work in the classroom (35% in District B and 41% in District G). However, 38% of teachers who completed the questionnaire in District G did not answer this question, as opposed to only 5% in District B. We have not been able to determine the reason for the large difference in response rate for this singular question. Interestingly, there was no statistical difference in either mean time-averaged or mean-peak CO_2 concentrations for classrooms in which teachers complained of odor problems, i.e., relative to non-complaint rooms.

CONCLUSIONS AND IMPLICATIONS

The findings presented here represent one component of a much larger study intended to better understand indoor air quality in elementary schools in Texas. The results clearly suggest a cause for concern related to inadequate ventilation of elementary school classrooms. However, the reasons for inadequate ventilation vary considerably from school-to-school and even from classroom-to-classroom. The value of this assessment is two-fold. First, we have quantitatively addressed a problem that was previously suspected based on a sparse dataset. Second, we now have a benchmark that will allow for an assessment of progress if the participating school districts are able to take action to improve classroom ventilation in the future. We are continuing to analyze data to investigate relationships between CO_2, HVAC system design and operation, and staff questionnaire responses. The results presented herein and also obtained through other components of the TESIAS study strongly suggest an immediate need for more research of, and attention to, indoor air quality problems within elementary schools in Texas.

ACKNOWLEDGEMENTS

The TESIAS study was funded entirely by the Texas Higher Education Coordinating Board. The Texas Department of Health provided assistance with questionnaire development and an additional CO_2 analyzer when needed. We thank Dr. Quade Stahl for each. The authors thank staff of the two participating school districts. Joel Banks and Steven Orwick of the Center for Energy and Environmental Resources at The University of Texas at Austin spent considerable time assisting with field monitoring and HVAC surveys.

REFERENCES

Casey ME, Braganza EB, Shaughnessy RJ, *et al*. 1995. Ventilation improvement in two elementary school classrooms. *Proceedings of the 1st Specialty Conference on Engineering Solutions to Indoor Air Quality Problems*, pp 270-284.

Daisey JM, and Angell WJ. 1999. Indoor air quality, ventilation and health symptoms in schools: an analysis of existing information. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate – Indoor Air '99*, Vol. X, pp 1-6. Edinburgh: Indoor Air 1999.

Smedje G, and Norback D. 1999. Factors affecting the concentrations of pollutants in school buildings. *Proceedings of the 8th International Conference on Indoor Air Quality and Climate – Indoor Air '99*, Vol. X, pp 267-272. Edinburgh: Indoor Air 1999.

U.S. General Accounting Office, 1995. School facilities: condition of America's schools, U.S. GAO, Washington, D.C., GAO/HEHS-95-61.