The CO_2 Riddle: Precision & Savings?

By Leonard A. Damiano, *EBTRON, Inc.* March 2016

We cannot efficiently maintain prescribed minimum ventilation rates using CO_2 inputs alone.

By 'efficiently,' I mean allowing as much outdoor air as you need, but no more and no less. In theory, we want to satisfy professional ventilation standards and code requirements for occupant health and productivity; and at the same time avoid excess ventilation to minimize or eliminate energy waste during operation. The savings objectives can only be obtained through greater control 'precision' with dynamic ventilation controls. As long as the minimum ventilation rates are exceeded, codes and standards do not care by how much.

Most in our engineering and construction community believe in CO_2 control inputs primarily because the lone set point control concept is easy to understand. It's very much like a thermostat with a single set point. Instead of maintaining space temperature, you try to maintain a predetermined interior or differential CO_2 concentration. Unfortunately, the random comparison of differential CO_2 set point to measured airflow rates happens very rarely and without sufficiently accurate reference measurements, so deviations can be explained away, minimized or ignored.

A REVEALING ARGUMENT IN FAVOR OF CO_2

Designers and decision makers are often misled by unsupported linkages that have been made between interior CO_2 concentrations and ventilation rates. The perceived convenience in using CO_2 sensors for ventilation control and the expectation of both first-cost and long term savings are usually the tie-breakers in design decisions. This is more meaningful when weighed against a limited number of ventilation control options for variable occupancy spaces. The perceived simplicity of interior CO_2 sensing has helped the decision-making process but has probably not improved the results from the decisions.

At issue now are concepts that attempt to rationalize the use of a single CO_2 set point and/or a lone CO_2 control input to provide variable ventilation control. Supporters of the lone-input theory are bolstered by statements like those made at an ASHRAE Regional CRC Technical Program, and quoted below. The argument was detailed in a web-posted slide presentation. Try to follow the logic, note the terminology but avoid biting the hook. Comments and explanation follow the quote.

- *"Since* [the] *building is probably NOT at steady-state, CO_2 concentration* [alone] *cannot be used to determine* [the] *number of occupants or their pollutant source strength or the actual cfm/person*
- *However, CO_2 concentration still tracks bioeffluent concentration and it is bioeffluent concentration you are trying to control*
- *Cfm/person rates were determined based on steady-state chamber studies*
- *Conclusion: Steady-state equation can be used to determine CO_2 setpoint and actual CO_2 concentration can be used to control actual ventilation rate"*

Outdoor Air Control and Demand Controlled Ventilation, ASHRAE Region VI CRC, Chicago 2007 Track III: Session 2

My interpretation of these bullet-points goes something like this:

- CO_2 DOESN'T WORK THE WAY WE WERE TOLD AND CANNOT BE USED TO DETERMINE THE VARIABLES CRITICAL TO COMPLIANCE WITH CODES AND STANDARDS.
- HOWEVER, ALL THAT MAKES NO DIFFERENCE BECAUSE WE CAN IGNORE VENTILATION CODES AND STANDARDS IF WE TRACK BIOEFFLUENTS INDIRECTLY WITH CO_2.
- WHEN ALL ASSUMPTIONS ARE SATISFIED, THE STEADY-STATE EQUATION RESULTS IN CFM/PERSON AIRFLOW RATES, WHICH ARE ONLY ONE PART OF THE COMPLIANCE REQUIREMENTS. WE CANNOT GIVE YOU ANY EXPLANATION HOW TO USE

IT IN DETERMINING SET POINTS TO CONTROL BIOEFFLUENTS, EXCEPT TO SAY THE SAME THING ABOUT THE STEADY-STATE EQUATION OFFERED BY APPENDIX C IN 62.1.

- THE USE OF "ACTUAL" TO DESCRIBE CO_2 CONCENTRATION MEASUREMENTS IMPLIES THAT THE DETERMINATION IDENTIFIED THE CO_2 CONCENTRATION PERFECTLY. THERE WAS NO SAMPLING ERROR, NO SENSOR ERROR AND NO OTHER CONTRIBUTION TO MEASUREMENT ERROR WHEN USING CO_2.

Bioeffluent levels are only **one of many** contaminants that the ventilation rates are intended to dilute, mitigate and/or flush from the space. Bioeffluent reductions are neither the stated purpose nor the operational target of any compliance procedure in the standard. Not all bioeffluents are unacceptably odorous and not all indoor odors are due to bioeffluents. The common core in human bioeffluents includes 13 chemical constituents. Yet, we are expected to make the leap of faith to conclude that "*CO_2 concentration still tracks bioeffluent concentration"* to a significant and meaningful level of consistency. In statements like this quote, we begin to see the linkage that is trying to be established, with CO_2 as the answer to all of our ventilation control problems.

Regardless of how well CO_2 does or does not track bioeffluents, Dr. Andrew Persily of the BFR Lab at NIST summarized the critical deficiency of this indirect means of ventilation control in a 1996 paper:

> "And while maintaining CO_2 concentrations within 1250 mg/m3 of outdoors should provide acceptable perceived air quality in terms of human body odor, **it does not necessarily imply adequate control of other pollutants**."
>
> Persily, A. K. 1996. *The Relationship Between Indoor Air Quality and Carbon Dioxide*, Build '96.

This effectively reflects the position that the ASHRAE 62.1 committee has taken on CO2 for the past 20 years. Yet, it is also puzzling to think that a standard intended to establish minimum ventilation rates, with "not less than" mandates and operational requirements does not contain a single reference to the needed performance level at which these rates are to be maintained over time. Performance is rarely addressed. However, we are provided with part of the equation, defining the difference between IAQ effectiveness and energy efficiency standards.

"Not less than" requirements in 62.1 establish an undisputable -0% tolerance, yet the previously referenced Chicago ASHRAE presentation neglected to account for the many sources of measurement error: likely sampling errors, the tendency for CO_2 to stratify, and that 'actual' ventilation rates cannot be controlled indirectly (due to significant control uncertainty) without frequent or continuous verification (measured directly). The usage of "actual" when describing CO_2 concentrations and ventilation rates is misleading. It is more significant within 62.1, the Steady-State Equation and IMC§403 when referring to occupied space <u>population.</u> CO_2 cannot determine population without integrating calculations using ventilation rates. Otherwise "actual" in this context may require a clarifying definition to be understood.

This ASHRAE CRC technical session material is typical of the rationalization that some designers and equipment manufacturers use to justify design decisions. Is this because most non-engineers are considered not to be very bright? As a result of the rationalization, it becomes more difficult for operations staff to understand or question their recommendations. It is quicker and easier to pass responsibility to the 'expert' upon whom they originally relied to make decisions.

I have heard this CO_2 argument before. The proponents appear to like the uncertainty that the use of CO_2 creates, masking the ventilation rates actually being supplied. They propose control of CO_2 concentrations based on several required assumptions (with high uncertainties and very weak connectivity relating the interior CO_2 concentrations to theoretical intake rates), and then operate the system based on calculations. Then, when readjustments are typically made, they are justified with the new assumptions.

ASHRAE 62.1 and CO_2 – BACKGROUND

The use of the *Steady-State* equation referenced in the Appendix to the ASHRAE ventilation standard since 1989 has led to much disagreement and has been used to justify concepts contrary to both the intent of this informative appendix and insufficient to insure compliance to the rate requirements in the standard. The conversion of this rate-justification for use as a control strategy may well have been commercially motivated and satisfied the design need for a simple-but-inaccurate solution to variable ventilation requirements. For the *Steady-State* equation details, see ASHRAE 62.1-2013, Appendix C and any of the papers referenced here.

Proponents also tend to argue that the 62.1 standard is intended for design calculation and not to indicate how the systems in question is to be operated. For code enforcement at the planning stage, this may be the reality of the process.

However, since 2001, Standard 62 was has been classified an "operational" standard with specific operating and maintenance requirements, together with requirements for compliance self-verification (§7.2.2). Other than California's Title 24 ventilation "police," most enforcement of operational violations is outside the authority of the code officials. However, disincentives will still be provided by civil courts and utility rates.

Although the 62.1 standard does not prohibit anyone from over ventilating; our societal, legal and governmental priorities should. Because we have been consistently denied specific guidance or validating research on how to efficiently use CO_2 to meet the *Ventilation Rate Procedure* of the standard, engineers are left to reinvent the wheel from design firm-to-design firm, with the likelihood of most failing to achieve compliant ventilation designs and operating goals. The industry 'standard' for DCV by default is said to be: mount a CO_2 wall sensor and modulate the outdoor intake damper based on a single predetermined CO_2 concentration set point. Yet, we all know this is WRONG and does not comply with minimum ventilation codes or professional standards.

The original 1936 research which formed much of the scientific basis behind the ventilation rate tables according to a follow-up study in 1970, was very clear on the use of CO_2 concentrations to control ventilation rates. It was republished in the ASHRAE Journal in 2011.

> "Further work was carried out by Yaglou, Riley and Coggins on the subject of correlating odor intensity production to ventilation flow rates. Among the more significant conclusions arrived at by these researchers were the following:
>
> 1. Outdoor air requirements can be determined by gauging the odor produced.
> 4. Recirculated air can be rendered relatively odor-free by the process of washing, humidifying, cooling and dehumidifying.
> 9. <u>Carbon dioxide concentration is an unreliable index of adequate ventilation</u> because its concentration is not proportional to the odor intensity produced. "
>
> Original research
> C.P. Yaglou, E.c. Riley and D.I. Coggins, 1936, *Ventilation Requirements,* ASH&VE Transactions, Vol. 42, p.133, 1936.
> Summarized in

Klauss, A.K., R.H. Tull, L.M. Roots and J.R. Pfafflin, 2011. *History of the Changing Concepts In Ventilation Requirements*. First published 1970 ASHRAE Journal, American Society of Heating, Refrigeration and Air-conditioning Engineers, Inc., Atlanta, and republished ASHRAE Journal, vol. 53, no. 2, February 2011.

IMC 2015, Chapter 4 - Ventilation

Our primary model mechanical code, the IMC, covers ventilation issues mostly in Chapter 4. §403 and 405 cover the intake rate tables, calculations and ventilation controls. Most of §403 has been modified over the last few years to reflect the same formulae and calculation process as required in the *Ventilation Rate Procedure* in ASHRAE 62.1-2013. After several years of harmonizing, almost all of the occupancy categories between the two documents are now synchronized. Most significantly §403.3.1.3 *System Operation* goes to the central issue of minimum rate determination:

> *"…shall be permitted to be based on the rate per person indicated in Table 403.3.1.1 and the actual number of occupants present"*

This IMC requirement eliminates the possibility of using population estimates or averages, other than the design maximum or current actual. CO_2 alone is not capable of controlling ventilation rates to the precision necessary to comply with the "not less than" mandate (without intentional severe over ventilation) and cannot be used alone to 'count' occupants with any reasonable confidence.

For more information and alternatives to CO_2-based DCV, you may want to check some of the references for this including *Reduction of Errors in Ventilation Rate Determinations* in ASHRAE Transactions 2010 Volume 116, Part 2; and *The Relationship between CO_2 Levels and Ventilation for DCV Applications – Multiple Zone Recirculating Systems,* January 13, 2010 by David S. Dougan.

The Real Riddle – Why do CO_2 design proponents believe this single input method works despite many obvious issues?

Here are some challenges to the justifications for the CO_2 lone-input DCV method.

1. **CO_2 *directly* addresses only the people component of 62.1 rate tables and has no direct and normally no indirect relationship to the area component**. To use CO_2 in these circumstances, first requires the acceptance of large uncertainties in control; together with deliberate over ventilation as populations change (through theoretical calculations or "worst-case" assumptions). Excess ventilation is needed as a safety margin to avoid violating not-less-than minimums during operation and to cover a smaller fixed ventilation component for floor area because CO_2 does not respond to building-generated contaminants. This excess tends to be poorly controlled and disconnected from the requirements of 62.1 or the IMC.

   For the single-input DCV justification to be valid a provision must be made for intentional excess. To further complicate the relationship, this additional 'floor area' requirement forces the relationship between CO_2 and ventilation rates to vary nonlinearly with changes in population. The CO_2 set point requirement is unique to the size and type of occupancy of each space involved. Providing "less [outdoor air] than that required" by the *Ventilation Rate Procedure* is almost a certainty under some operating conditions. This forces the use of a "worst-case" assumption or some type of nonlinear algorithm using multiple set points, with a different set point for every space monitored then individually written into custom controller software.

In establishing this algorithm, consideration must also be made for additional ventilation to compensate for all sources of potential measurement error (indoor sensor error, fixed outdoor CO_2 concentration uncertainty, and estimated occupant activity level), in an attempt to prevent the intake rate from falling below the prescribed minimums stated in the Standard. At the upper end of the range, intake rate performance will still be limited to the cumulative measurement and hardware errors of the CO_2 sensors, together with the uncertainties related to the application.

2. **CO_2 can be used to estimate space population in steady-state or transient conditions provided that dynamic outdoor air intake rates and zone supply rates are also known** (Mumma 2005, Dougan 2008, et.al.). Population determination with CO_2 should not be excluded due to the lack of steady-state conditions, but rather due to the lack of input on the additional variables needed to address all of the relationships required to calculate population – namely outdoor air intake rates and/or zone supply air rates – depending on the method selected and the type of system involved.

   Multi-zone control with ventilation reset for a variable population is possible, but not without more precise airflow inputs. There are at least three potential methods (EBTRON 2004). All of these multiple input control methods carry the uncertainties associated with CO_2 concentration measurement, but modeling has shown them to be far superior in ventilation control performance than CO_2 inputs alone.

   CO_2–based reset may be used for variable ventilation control, however imprecise. However, there are applications where CO_2 is the best or only choice available to indicate changes in population. It can be argued that CO_2 alone is simply not capable of determining either the "actual" ventilation rates or the population(s) in variable occupancy situations. Control acceptability with CO_2 inputs alone and code compliance to minimum rates not-less-than a fixed value, are totally different animals. They cannot be equated easily.

3. **The cost for CO_2 sensors, wiring, installation and control software is likely to exceed the cost of much simpler and more reliable alternatives (time schedules, binary occupancy sensors, etc.).** The single input CO_2 control method may effectively increase the engineer's risk and extend his liability if the system does not operate as reliably or efficiently as expected. There are many examples which are not appropriate for discussion here.

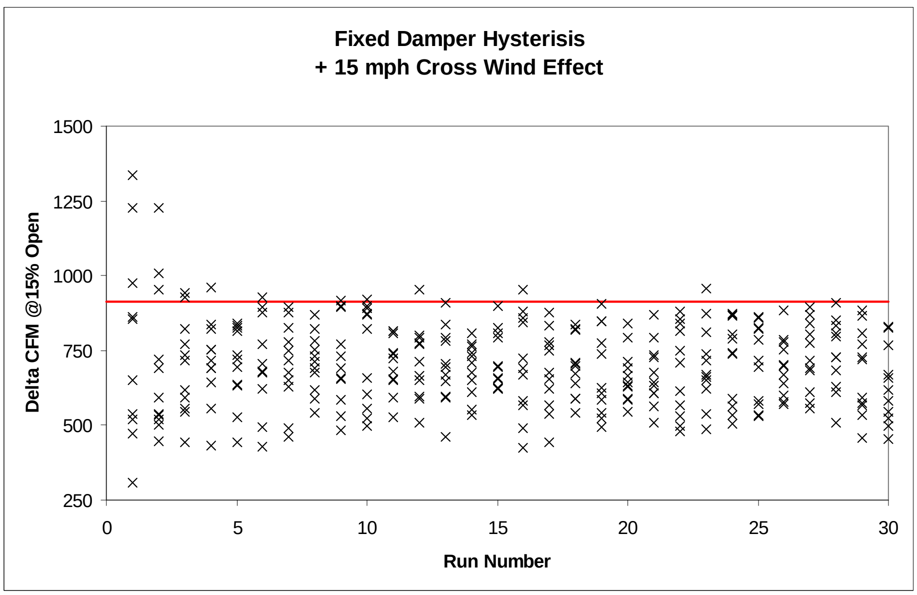
4. **Central to the issue is the conclusion that *controlling bioeffluents* is a valid objective of the Standard (62.1) and that bioeffluents/odors may be equated to or at least parallel changes in dilution ventilation rates.** The original chamber studies in the 1930's did focus on odor control, but only to establish a range of intake rates required to dilute it. By extension, those rates were assumed to also dilute other indoor contaminants. Without some direct measure we can never be sure that the calculated design rate will be sufficient for compliance with rate-based standards and codes during operation. The lack of any odors is not evidence of satisfying the *Ventilation Rate Procedure* in ASHRAE 62.1-2013, and the measurement of CO_2 alone does not satisfy the *IAQ Procedure*. Although, there is a subjective opinion component to the IAQ Procedure which polls occupants for IAQ acceptability. Notwithstanding a subjective survey in a limited procedural situation, the purpose of the standard has always been "to specify minimum ventilation rates" as stated in its published Purpose, since 1989. The Purpose has never been to limit indoor bioeffluents or odors.

1663 Hwy. 701 S. • Loris, SC 29569 • USA
Toll Free: 800.2EBTRON (800.232.8766) • Local Phone: +1.843.756.1828 • Fax: +1.843.756.1838
Internet: www.EBTRON.com • e-Mail: ebtron@EBTRON.com

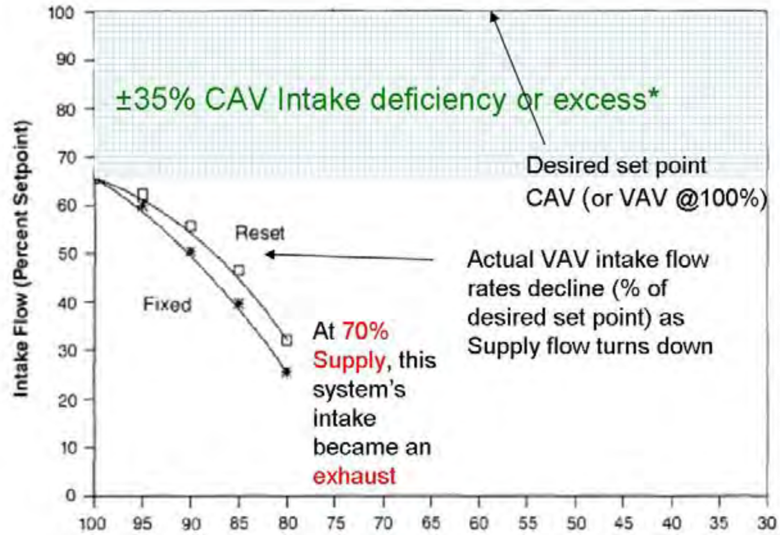
The interpretation expressed in the ASHRAE CRC presentation referenced earlier, unacceptably stretches the linkage between odors and dilution as an indirect measurement for ventilation rate sufficiency. Resulting conclusions cannot be considered valid for use in code compliance. To do so would require wholesale changes to be made to the Purpose and Scope of our ventilation standard – away from "breathing zone rates" and closer toward "interior CO_2 concentrations".

5. **Currently, the minimum, worst-case, airflow rate is allowed to be determined with a one-time manual measurement and a predetermined fixed position on a 2-position damper.** Neither of the component variables in this determination (field traverse measurement and airflow across a fixed orifice) is sufficiently repeatable to the degree of certainty needed. This is especially true considering the effect of damper/actuator hysteresis and actuator resolution.

   It was demonstrated in full-scale testing with high-quality aluminum airfoil dampers that a 30% – 50% change in flow rate was possible based solely on damper system linkage hysteresis (EBTRON 1999). These findings were later verified in full-scale system testing with full instrumentation (EBTRON 2008).



The possible effects on fixed intake damper control variations, was modeled and published in an *ASHRAE Journal* article shortly thereafter, by comparing the difference in performance at start up to operation, (Solberg, ASHRAE Journal, Jan 1990).



The industry eventually accepted the vulnerability of varying flow rates to the use of fixed intake dampers on VAV systems with the following added by addendum "u" of ASHRAE Standard 62-2001, Section 5.3 *Ventilation System Controls*, in Jan. 2002:

> *"The system shall be designed to maintain minimum outdoor airflow as required by Section 6 under any load condition.* ***Note:*** *VAV systems with fixed outdoor air damper positions must comply with this requirement at minimum supply airflow.*

The note highlighted the operating penalty required to use a fixed damper in the future due to these changes. This section was retained in nearly identical language until amended in the 2010 parent document. An approved addendum (62.1 's' in 2011) makes the same point on fixed damper control even stronger, but removed the note. This change was published in the 2012 Supplement of approved addenda to the 2010 Standard and has survived through to the soon-to-be current 2016 version.

> ***5.3 Ventilation System Controls.*** *Mechanical ventilation systems shall include controls in accordance with the following:*
>
> ***5.3.1*** *All systems shall be provided with manual or automatic controls to maintain no less than the outdoor air intake flow (V_{ot}) required by Section 6, under all load conditions or dynamic reset conditions.*
>
> ***5.3.2*** *Systems with fans supplying variable primary-air (V_{ps}) or variable mixed-air flow, including single-zone VAV and multiple-zone-recirculating VAV systems shall be provided with one or more of the following:*
>
> *a. Outdoor air-intake, return air dampers or a combination thereof that modulate to maintain no less than the outdoor air intake flow (V_{ot})*
> *b. Outdoor-air injection fans that modulate to maintain no less than the outdoor air intake flow (V_{ot})*
> *c. Other means of ensuring compliance with Section 5.3.1*

This ANSI-approved addendum places the requirement directly in the body of the standard, giving it the full normative force of the standard and any codes that follow it. The standard <u>requires</u> dynamic intake systems using modulating dampers or modulating fans in VAV systems. Fixed position intake dampers, by definition, are static devices and effectively prohibited by these changes. They are unacceptable in all situations but those using the most conservative worst-case design assumptions needed to satisfy 5.3.1.

The big question to be asked now is "What inputs can be used most effectively to control those components for continuous dynamic system changes or environmental changes?"

6. **Good indoor air quality has never yet been equated to specific indoor CO_2 levels.** In 1989, the ASHRAE 62 committee specifically warned users in Interpretations and addenda attempting to overcome much of the confusion initiated in 62-1989 regarding the acceptable use of CO_2 control.

> "*FOREWARD* (not part of standard) *… Addendum 62f addresses a lack of clarity in ANSI/ASHRAE Standard 62-1989 that has contributed to several misunderstandings regarding the significance of indoor carbon dioxide (CO_2) levels. The Standard led many users to conclude that CO_2 was itself a comprehensive indicator of indoor air quality and a contaminant with its own health impacts, rather than **simply a useful indicator of the concentration of human bioeffluents**.*"

Human bioeffluents have not been mentioned in the standard since addendum (f) to 62-1999, except as an informational mention within the scientific rationale for the origin of the ventilation rates included in the tables (Appendix C).

Based on newly published European studies (2016) on the effects of interior CO_2 levels on human cognitive performance, by Chinese and Danish researchers, there may be reason to reconsider at least a recommended maximum CO_2 indoor level. Time and additional research will help us to understand the potential of CO_2 as a contaminant in its own right. Unless hidden health effects are discovered, it is not likely that these findings will substitute for the need and utility of minimum ventilation in occupied spaces and that CO_2 is an inaccurate determinant of ventilation rates.

Conclusions

Demand Controlled Ventilation is NOT synonymous with the use of CO_2 concentration sensing. CO_2 is merely one of several possible inputs that can be used to indicate a change in population. The latest version of 62.1 includes a revised section on Dynamic Reset (§6.2.7) which includes Demand Controlled Ventilation. It defines DCV as: *"any means by which the breathing zone outdoor air flow (V_{bz}) can be varied to the occupied space or spaces based on the changing number of occupants and/or ventilation requirements of the occupied zone*." Please refer to section 6.2.7 in the standard for details.

The indirect control of intake rates, regardless of the proxies used, are loaded with compounding uncertainties that make the controlled variable (OA intake rates) nearly impossible to regulate efficiently. The indirect variable, in this case CO_2 and the bioeffluents it is assumed to track, **should never be confused with the purpose of the standard and its primary compliance determinant – minimum ventilation rates**. A control method should not be tolerated because of the convenience it may provide the user, if it also carries excessive uncertainties. These uncertainties can circumvent the intent of the Standard and the energy inefficiencies that are sure to follow during operation.

DCV is required for high density spaces in Standard 90.1 and can help to satisfy CA Title 24 energy code in specific high-density situations. However, it cannot be reasonably used as the sole input to control ventilation in a multi-zone building. Private studies and ASHRAE Research have both indicated that probability. Its usage does not relieve the engineer from the responsibility of finding ways to satisfy BOTH energy and IAQ objectives simultaneously, in single and multi-zone systems.

Only with inappropriate assumptions or some very creative rationalizations, can one conclude that CO_2-based DCV can satisfy Standard 62.1 without periods of gross over ventilation. It is the HVAC engineer whose stamp is on the plans that becomes a willing accomplice by accepting those assumptions. Because the engineer assumes responsibility for the performance of the design, few are likely to question an air system's poor performance during operation; at least not until someone is harmed or damage is claimed.

BIBLIOGRAPHY

ASHRAE Handbook-2013 Fundamentals, American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Atlanta, GA., p. 36.16. 2013.

ASHRAE Standard 62.1 *Users' Manual,* 2010. American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Atlanta, GA., Section 5. 2010

ANSI/ASHRAE Standard 62.1-2013, *Ventilation for acceptable indoor air quality.* American Society of Heating, Refrigerating and Air-Conditioning Engineers*, Inc.* Atlanta: 2013.

ASHRAE. 2013. ANSI/ASHRAE/IESNA Standard 90.1-2013, Energy Standard for Buildings Except Low-Rise Residential Buildings. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc.

ASHRAE. 90.1 User's Manual - ANSI/ASHRAE/IESNA Standard 90.1-2010. Atlanta: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. 2011

ASHRAE Standard 189.1-2014,. American Society of Heating Refrigeration and Air Conditioning Engineers, Inc., Atlanta, GA. 2014

Curtiss, P.S., J.F. Kreider 1992. "Laboratory Test of the Nonlinearity of Outdoor Air Percentage as a Function of Damper Position and Induced Inlet Pressure," *ASHRAE Transactions* V. 98, Pt. 1. 1992

Damiano, Leonard A. 2010. Reduction of Errors in Ventilation Rate Determinations. *ASHRAE Transactions*, Volume 116, Part 2, American Society of Heating, Refrigeration and Air-Conditioning Engineers, Inc.: Atlanta, 2010. and Seminar AB-10-C007, ASHRAE Conference 2010 – Albuquerque, NM, June 27, 2010

Dougan, D.S. and L.A. Damiano, 2004. "$C0_2$-based Demand Controlled Ventilation: Do Risks Outweigh Potential Rewards?" *ASHRAE Journal,* October 2004.

Dougan, D.S., 2003. "Airflow Measurement for HVAC Systems – Comparing Technologies," May 2003. EBTRON Inc. Loris, South Carolina. Downloaded September 20, 2011 from http://ebtron.com/Web_Pdfs/SPSync/Vertical%20Marketing/White%20Papers/Airflow_Measurement_Technologies_1.pdf

Fisk, W.J., Faulkner, D., & Sullivan, D.P. 2006. *Accuracy of CO_2 sensors in commercial buildings: A pilot study.* Berkeley, CA: Lawrence Berkeley National Laboratory. Retrieved from http://eetd.lbl.gov/ie/pdf/LBNL-61862.pdf.

Ke, Y, S.A. Mumma. 1997. "Using carbon dioxide measurements to determine occupancy for ventilation controls." *ASHRAE Transactions* 103 (2) :365-374.

Mumma, S.A., Y.M. Wong 1990. *Analytical Evaluation o/Outdoor Airflow Rate Variation vs. Supply Airflow Rate Variation in Variable Air Volume Systems When the Outdoor Air Damper Position Is Fixed, ASHRAE Transactions* AT90-17-2, 1990

Mumma, S.A., Y.P. Ke, 1997. "Using carbon dioxide measurements to determine occupancy for ventilation controls." ASHRAE Transactions 103(2):365–374. 1997

Mumma, S.A., 2004. "Transient Occupancy Ventilation by Monitoring CO,," *IAQ Applications,* Winter 2004, p.22. 2004

National Building Controls Information Program (NBCIP), 2009. *Product Testing Report, Wall Mounted Carbon Dioxide (CO) Transmitters,* Iowa Energy Center, Energy Resource Station, Ankeny, IA. Research funded by California Energy Commission and Iowa Energy Center, June 2009.