Simple methods to measure air exchange rates and detect leaks in display and storage enclosures

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Abstract

Industry-standard measurement techniques of air exchange using tracer gas decay have been adapted for use with low cost gas detectors and portable tracer gas delivery systems. The experimental and practical application has led to the production of a recommended protocol and data analysis spreadsheet freely available on the Internet. Using these tools it is relatively simple to calculate the air exchange rates of display cases, picture frames and storage units. A range of leak detection equipment has been evaluated to support the use of low air exchange enclosures as an important preventive conservation tool.

Keywords

air exchange, tracer gas, leak detection, half time, leakage

Introduction

The air exchange or ventilation rate of display cases, picture frames and storage enclosures has a significant effect on their effectiveness as tools for preventive conservation. Well-sealed enclosures provide a buffer against external humidity variations and reduce the ingress of externally generated pollutants and particulates. Where internally generated pollutants are a concern, deliberate ventilation of the enclosure may be an appropriate mitigation measure. When a buffer such as silica gel is to be added to enhance relative humidity (RH) stability the air exchange rate (AER) of the enclosure is a key variable (Thomson 1977). In the authors' experience it is difficult to determine an approximate AER of an enclosure from visual inspection, and AER in enclosures ranging from less than 0.1 to greater than 50 air changes per day (ac/d or acd^{-1}) are common (Table 1). This makes the routine use of 1 ac/d for a well-sealed display case in buffer calculations (Thomson 1977) difficult to justify (Weintraub 2002) and explains why buffering works very well for some (Guichen and Gai 1984) but not others (Ashley-Smith and Moncrieff 1984).

Low-cost gas detectors and innovative gas delivery methods were used for a research project to investigate the impact of ventilation on internally generated pollutants (Calver 2001). Subsequent use during several enclosure installations suggested that it would be useful to further investigate the technique and produce a standard protocol.

Measurement of air exchange rate

Tracer gas techniques have previously been used to measure the AER of museum enclosures. Early studies involved the loss of water vapour (Padfield 1966, Thomson 1977). The disadvantage of water vapour is that any moisture absorbent material will attempt to buffer the change in concentration. Brimblecombe and Ramer (1983) purged cases with nitrogen, introducing carbon dioxide as a tracer and also measuring the ingress of oxygen, monitoring the concentrations with gas–liquid chromatography. Cass et al. (1989) used sulphur hexaflouride (SF_6) and electron capture gas chromatography, Daniel and Maekawa (1992) measured the ingress of atmospheric oxygen (O_2) using an oxygen analyser. Cassar and Martin (1994) commissioned the UK Buildings Services Research Information Association (BSRIA) to develop a test for the AER of display cases (Potter 1998) which uses dinitrogen oxide (nitrous oxide, N_2O) as a tracer. It is now common in the UK to include a target AER in

Table 1. Selection of air exchange rates measured with a PM3010 nitrous oxide detector 2000–2004

Enclosure type	Specification	Measured ac/d	Measured ac/d post-modification (if applicable)	Notes
Test display case 2	Unknown	0.5	0.11	Base sealed and vertical joint taped with aluminium tape
Capital Concerns display case	Unspecified	2.0	0.25	Baseboard sealed with Marvelseal
World City Gallery transport display case	0.25	2.2	0.37	Infill panel installed and top glazing sealed
Creative Quarters display case	Unknown	0.6	0.4	Lock covered with aluminium tape
Demonstration demountable acrylic case	Unspecified	0.45		Test of sample case
World City Dickens display case	0.25	0.59		
World City Gallery Guys Hospital display case	0.25	1.2		
High specification storage unit	Unknown	0.65		
London Before London prototype display case	0.25	1.5		Not properly sealed 'aesthetic' prototype only
Standard metal storage cabinet		2.4		Glass-fronted unit
Outside display case	Unspecified	3.0		
New Dynasty display case	Deliberately vented	32 (vented)	3 (vents sealed)	Case used to monitor impact of ventilation on internally generated pollutants
Roman display case 5	Deliberately vented	6.0	4.4 (vents sealed)	Case used to monitor impact of ventilation on internally generated pollutants
Tudor display case T19	Deliberately vented	97	30	Obvious vents sealed to test leakage
Tudor display case 22	Vented	>1000 (sic)		Installed above an air conditioning return air duct

specifications for enclosures (Reed 1999, Bacon and Martin 2000) validated by this commercial test. However, the service is relatively expensive (about €1500 for two enclosures or 10–50 per cent of enclosure purchase price). Therefore, only a small sample of enclosures is tested during an installation (Bacon and Martin 2000). Furthermore, during a busy installation schedule the results are often not available in time to rectify defective enclosures (Erimen and Tate 1999).

Demystifying air exchange

In the past few years several users, also experimenting with low costs gas detectors, have contacted the authors. It was felt a standard measurement protocol for these detectors plus an accompanying data analysis spreadsheet to make air exchange calculations a simple exercise would be useful.

There is some dispute over whether air exchange per unit time has any valid scientific meaning (Brimblecombe and Ramer 1983, Stanley et al. 2003). It is argued that in an enclosure a complete air change or loss of tracer gas never occurs, following a process of exponential decay the concentration will approach but never reach the external value. Thomson (1977) gives a good description of exponential decay and demonstrates that for most practical purposes the mathematical argument is irrelevant in real-world applications. When a tracer gas is introduced into an enclosure, it is mixed with the air and the change in concentration is used to model the movement of air into and out of the enclosure. By adding a tracer gas with similar characteristics to air, we can measure the transfer of external air (a mixture of air, gaseous pollutants, particulates, water vapour) into and out of an enclosure. This movement is driven by a combination of infiltration (convection) through cracks and holes, diffusion through smaller cracks and holes and permeation through enclosure materials. When the exchange is due to diffusion we should account for the molecular mass of the tracer gas compared with air (Brimblecombe and Ramer 1983). The various driving forces for air exchange and their contribution to leakage are described by Michalski (1993) in a comprehensive review.

Figure 1. Sam Calver adds tracer gas to a test case using a whipped cream dispenser (without the cream). Inside the case, three PM3010 N_2O gas detectors are tested together

Measurement of air exchange by tracer gas decay

Of the various tracer gas techniques used for measuring ventilation in buildings (Liddament 1996), the most practical for museum enclosures is single zone concentration decay (ISO 2000, ASTM 2000). After introduction into a sealed enclosure, the concentration of the gas will decrease as air enters and leaves. If the driving forces for air exchange remain constant, the concentration of the tracer gas is found to decay exponentially against time. Plotting the natural logarithm of the exponential decay curve against time should result in a straight line, the slope of which is the AER in air changes per unit time (Figure 3). For this article all measurement are reported as number of air changes per day.

The exchange rate (N) of a particular gas is driven by the difference in concentration of the gas inside and outside the enclosure. Thus it is important to monitor and subtract the background measurements for atmospheric gases such as CO_2, O_2 and H_2O. For example, the apparent air exchange using the oxygen sensor in Figure 6 would be 0.43 ac/d rather than 0.18 ac/d if the background were ignored.

The general form of the equation for calculating air exchange per unit time is given in Equation 1:

$$N = [\ln(C_{\text{int}}{}^{t0} - C_{\text{ext}}) - \ln(C_{\text{int}}{}^{t1} - C_{\text{ext}})]/(t^1 - t^0) \quad (1)$$

where

N = number of air changes
$C_{\text{int}}{}^{t0}$ = internal concentration of tracer gas in enclosure at start
C_{ext} = external concentration of tracer gas in room
$C_{\text{int}}{}^{t1}$ = internal concentration of tracer gas in enclosure at end
t^0 = time at start (days)
t^1 = time at end (days)
ln = natural logarithm.

Where the half time ($t_{1/2}$) for a particular gas is a more relevant measure, for instance to determine the half time for water vapour to aid buffer calculations or the ingress of oxygen in anoxic enclosures, the relationship is calculated by dividing the exponential rate constant by the AER (Thomson 1977) (Equation 2):

$$t_{1/2} = 0.693/N. \quad (2)$$

Figure 2. Air exchange measurement equipment case includes gas detector PM3010, Cream whipper and N_2O chargers, external battery and charger. Portable computer also required for analysing data

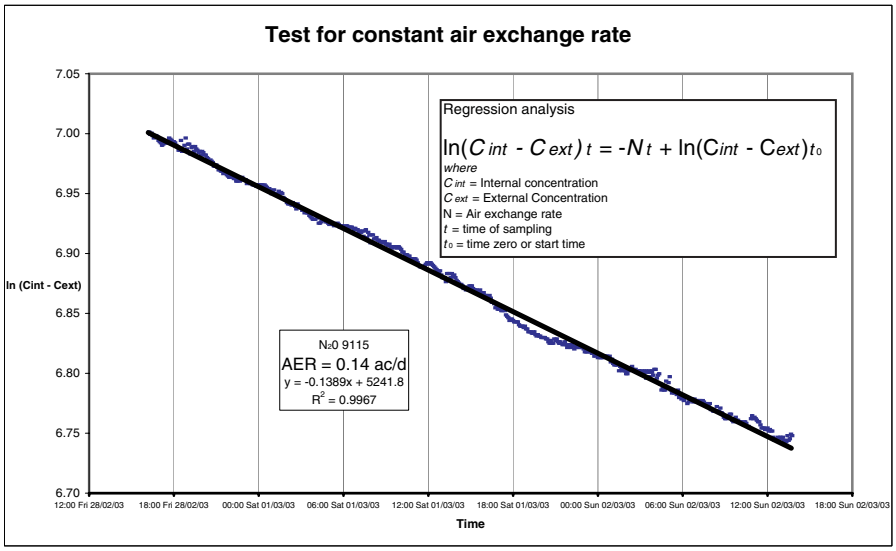


Figure 3. Test for constant air exchange. The graph shown is from the data analysis spreadsheet with field data. The general form of the regression equation is shown (ISO 2000) modified to allow for the background subtraction of atmospheric gases. The data presented here are from a comparison with a BSRIA test case at the V&A Museum of Childhood. The test was undertaken for 48 h immediately after a BSRIA test with a PM3010 N_2O detector. The calibrated AER is the slope of the linear regression trend (0.1389x) rounded to 0.14 ac/d. The result from the BSRIA test undertaken earlier was 0.1 ac/d. For the measurement period, the external RH was 45 ± 2 per cent and temperature was 18 ± 2° C

Measurement with low cost gas detectors

The high-precision gas analysers used commercially cost in the region of €10,000–30,000. However, in the past five years lower-cost detectors have been developed for CO_2 (for ventilation studies) and N_2O (for personal monitoring in anaesthesia). We have experimented with N_2O and CO_2 detectors with integral data loggers that cost less than €1600. Using readily available catering supplies of nitrous oxide and carbon dioxide the equipment is easily portable (Figure 2).

Equipment selection

The gas detectors tested by the authors are listed in Table 2. A range of the equipment tested is shown in Figure 4. Selection was based on the following criteria:

- tracer gas safe to use with objects and users (Table 3)
- relatively low cost gas analysers with data logging capability
- no modifications to enclosures required (small and battery powered to fit inside common enclosures).

Calculating the air exchange rate

The use of start and finish concentrations alone, as in Equation 1, does not give any indication if the measured AER was constant over the measurement period or highlight any instrumental errors (for example, see Figure 5). In practice, the concentration is logged at intervals and imported into a spreadsheet and linear regression analysis of this data is calculated with the slope of the line giving AER (Figure 3). The confidence level of the data is calculated following the method outlined in the ISO 12569 standard (ISO 2000). For instance, in Figure 7 the AER for the CO_2 is 0.128 ac/d $\pm$ 0.0118.

Table 2. Characteristics of gas analysers

Gas detected and model	Cost (€)[1]	Sensor type	Measurement range/accuracy [2]	Battery life (h) (standard/ extended)	Calibration method	Comments
Nitrous oxide Medigas PM3010	1590	Non-dispersive infrared (NDIR)	0–1000 ppm 0–100 ± 10 ppm[3] 100–1000 ± 25 ppm or 10% reading	6/18 plus	Factory or user	Integral pump. Extended battery requires user modification[4]. Closed cell allows use of sensor with sampling tubes for small enclosures such as picture frames. Avoid use of auto-calibration mode[6]
Carbon dioxide Air Watch PM1500	830	NDIR	0–50,000 ppm	6/18	Factory or user	Integral pump. Extended battery requires user modification[4]
Carbon dioxide Vaisala GM 70 GMP222 probe	1300	NDIR	0–10,000 ppm ± 20 ppm plus 2% of reading	8/720	Factory or user (1 or 2 point)	Optional pump. Extended battery life in auto off mode with reduced accuracy
Carbon dioxide Telaire 7001	440		0–10,000 ppm ± 20 ppm	80+	Unknown	Requires optional data logger[5](s) range then restricted to 4000 ppm
Oxygen Crowcon Gasman II	450	Chemical cell	0–25%	Up to 1 year	Optional calibration adapter	1 year lifetime for chemical cell
Water vapour Hanwell Humbug	330		0–100% RH	2 years plus	Factory or user	Not suitable if moisture reservoir present

[1]Average retail price in UK at November 2004, at current exchange rates (£1 = €1.42).
[2]Data supplied by manufacturers.
[3]Tests have shown poor results at low AER below 400 ppm.
[4]The method required to add an external battery is described in the user protocol.
[5]Range then restricted to 2500 ppm or 4000 ppm depending on input voltage range of logger.
[6]The PM3010 has an autocalibration mode designed to correct for drift. In practice, this mode has been found to not function when a concentration decay is measured, leading to erroneous results.

Figure 4. Selection of gas detectors, gas delivery devices and leak detectors. Top left to bottom right: (a) Medigas PM3010 N_2O detector with additional battery; (b) N_2O chargers 'whippets'; (c) aerosol cream whipper; (d) pressurized 'air duster' – source of halocarbon RJ 134a for leak detection; (e) D-Tek detect IR halogen leak detector; (f) Hanwell Radiotelemetry RH/T sensor; (g) Crowcon Gasman II O_2 detector; (h) CO_2 cycle tyre inflator and cylinder; (i) Vaisala GM 70 and GMP222 probe, CO_2 detector; (j) UE Systems WTG-1 ultrasonic warble tone generator; (k) Ultraprobe ultrasonic leak detector; (l) Tif 5600 halogen leak detector

Table 3. Characteristics of tracer gases

	Nitrous oxide[1] (N_2O)	Carbon dioxide (CO_2)	Oxygen (O_2)	Water vapour (H_2O)
Relative molecular mass	44	44	32	18
Background concentration	0.03 ppm	350–400 ppm[3]	209,000 ppm (20.9%)	Variable
Target concentration	1000 ppm	5–10,000 ppm	50,100,000 ppm (5–10%)	30–50% above/below ambient levels
Typical occupational exposure limits	100 ppm OES (UK), 50 ppm PEL (USA). Exceeded inside enclosure only	5,000 ppm LTEL (UK) 15,000 ppm STEL (UK)	None established. To avoid asphyxia maintain concentrations above 195,000 ppm (19.5%)	
Health and safety notes	OEL will not be exceeded in normal use assuming operator is not inside enclosures. Avoid direct inhalation and use in ventilated environment. Mild narcotic (used in aesthetic gas mixtures). Oxidizing agent and supports combustion. Explosive at high temperatures (600 °C)	OEL will not be exceeded in normal use assuming operator is not inside enclosures	Avoid inhalation of low concentrations in enclosures	
Adverse object reactivity	Unreactive at normal room temperatures (Mattson et al. 2001)	Possible reactions with some materials[4,5]	Explosive at high concentrations, non-flammable at recommended concentration	Avoid very high levels if objects present
Supply and delivery methods	Catering gas chargers, aerosol cream whippers (without cream)	Catering gas chargers and soda siphon (no soda), cycle tyre inflation devices	Purge enclosure with inert gas such as nitrogen until concentration reaches target.	Humidifier, ultrasonic mister
Remarks	Powerful greenhouse gas. Catering N_2O is synthetic but it estimated the total production of N_2O used in the food industry amounts to only 0.0002% of emissions from other sources	Powerful greenhouse gas, commercial sources normally reclaimed as by-product of industrial processes	Requires sufficient inert gas to purge case	Only suitable if no moisture absorbents present or for measuring the hygrometric properties of enclosures

[1]Dinitrogen oxide (IUAPAC name).
[2]Relative molecular mass of moist air at 50% RH at 20 °C = approximately 28; for discussion on the influence of molecular mass and diffusion see Brimblecombe and Ramer (1983).
[3]Human occupation can raise background concentrations to more than 1500 ppm, depending on ventilation and occupancy rate.
[4]Production of carbonic acid. Carbon dioxide is in equilibrium with carbonic acid on a surface, although the level of CO_2 is elevated for the test period the equilibrium concentration of carbonic acid potentially formed would be less than would be expected from acetic acid levels commonly recorded in display cases.
[5]Carbonaceous materials are in equilibrium with the carbon dioxide vapour. Basic lead carbonate has been reported to convert to lead carbonate at carbon dioxide concentrations above 1500 ppm. The concentrations used for measurements are above this level so an experiment was designed to determine if this would occur. Basic lead carbonate powder was exposed to 20,000 ppm of CO_2 for 7 days. The powder was analysed by using FTIR on a diffuse reflectance accessory (DRIFTS) which is extremely sensitive to impurities on the surfaces of powders. Experiments with mixtures of lead carbonate and basic lead carbonate had indicated that less than 1 per cent of lead carbonate could be detected by examination of the absorption band at 1050 cm^{-1} with this method in basic lead carbonate. No lead carbonate was detected in the exposed sample.

Method

The protocol developed is based on ISO 12569 (ISO 2000). Each gas detector has particular characteristics, which are included in the protocols.

Basic procedure

1. Monitor RH and temperature of enclosure and exterior during test.
2. Check calibration and/or zero gas detector in tracer free air at same temperature as test conditions.
3. For atmospheric gases, measure external concentration at start.
4. Add target concentration of tracer gas to enclosure.
5. Test for a minimum of 12 h for fabrication checks, 24–48 h for performance validation.
6. For atmospheric gases, measure external concentration at end. For non-atmospheric gases, record any sensor drift in tracer free air at same temperature.
7. Download data and import into data analysis spreadsheet to calculate AER.

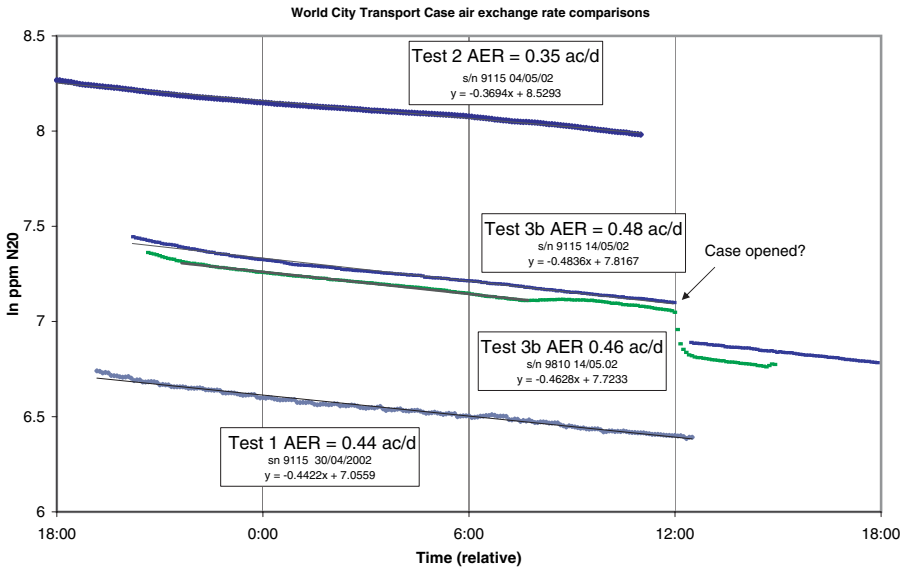


Figure 5. Comparison of AER measured on the same enclosure undertaken over a two week period during the gallery installation. Note that the linear regression trend lines are not perfectly straight, for example test 1. The tests were done with the same PM3010 gas detector (apart from test 3b when a comparative test with another PM3010 was also used). The different AER readings are likely to result from changes in the external environment and different configuration of door seals as the cases are opened and closed. Note a sudden drop in the tracer gas concentration for tests 3a and 3b. This was due to the case being opened during the test without the author's knowledge. This demonstrates the inherent danger of not plotting the data. Taking the start- and end-points only would have resulted in a much higher AER. Thus it is important to undertake the regression analysis shown in Figure 3 and plot all the data points as this highlights any

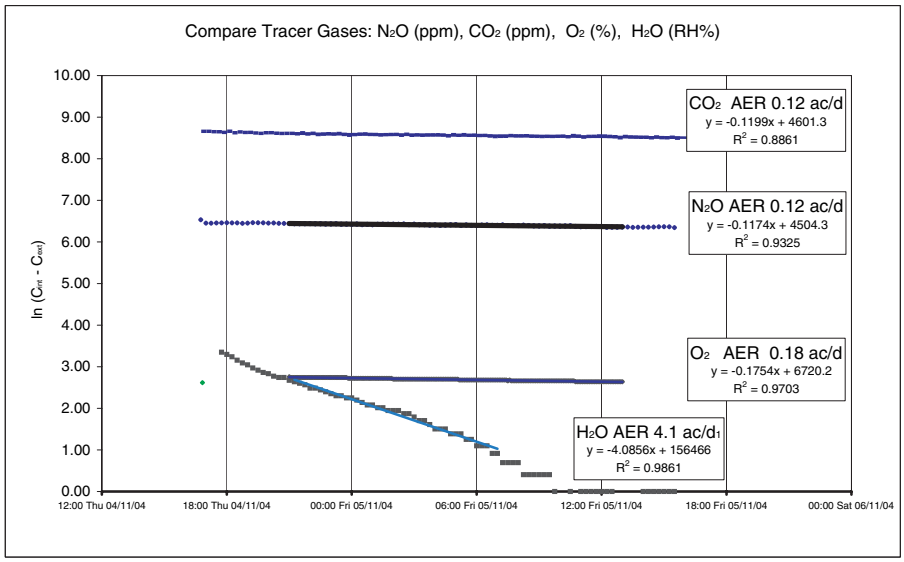
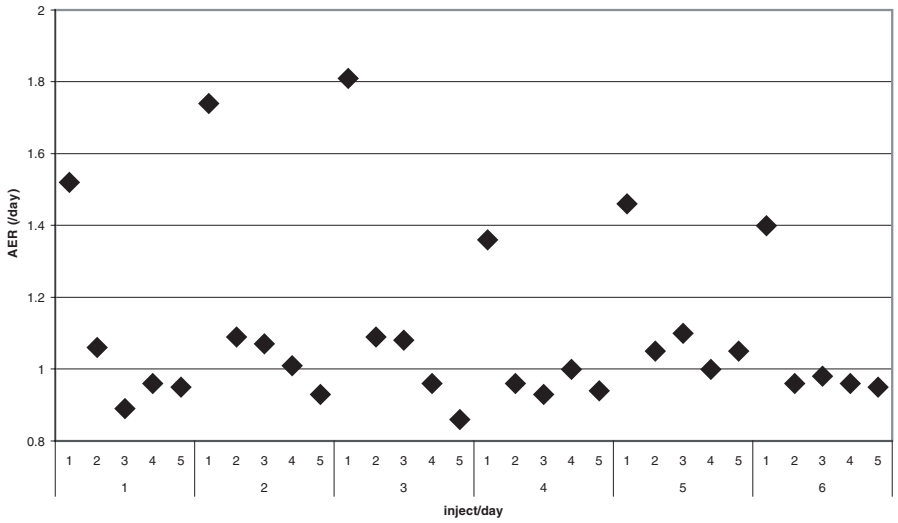


Figure 6. These are the results from a simultaneous test monitoring the decay of the two standard tracer gases used (N_2O and CO_2) and comparing the result with the ingress of oxygen method (Raphael 2004). The case was purged with oxygen-free nitrogen until the oxygen level reached 5 per cent. The ingress of oxygen was monitored with a Crowcon Gasman II oxygen detector (see Table 2 and Figure 4). The nitrogen was dry and thus the RH reduced compared with the external value. The RH increased as water vapour leaked into the enclosure and this data was also used to calculate an AER. Note that the N_2O and CO_2 are in good agreement and that O_2 would diffuse into the case faster than the other gases diffused out. By Graham's law (Brimblecombe and Ramer 1993) the correlated AER_{O2} is 0.16, closer to agreement with the other values. No calibration data were available for the O_2 detector. Note the rate shown for AER_{H2O} is very much higher. The case had a medium density fibre-board (MDF) baseboard. This was covered with an acrylic sheet; even so it seems that the MDF base released sufficient moisture to make a dramatic impact on the AER_{H2O} value

Table 4. Reproducibility of air exchange measurement



To determine the reproducibility of the measurements, CO_2 was used to measure air exchange rates in a Perspex case over 30 consecutive days. Fresh CO_2 (approximately 10,000 ppm) was injected into the case by opening the door every 5 days. A Vaisala GM70 was used as the analyser in extended battery mode. The first measurement after injection is consistently and statistically significantly higher (1-tailed *t*-test at 95 per cent confidence levels) than the rest of the measurements. This is with a CO_2 concentration above 5000 ppm. This is possibly due to the increased pressure caused by the high concentration of CO_2. Excluding these measurements, the reproducibility is 11 per cent between readings, with an average AER of 0.99 ac/d. To reduce the influence of changing door seal seating a further series of measurements (not shown) was done with the CO_2 injected through a valve, which reduced the variation to 7 per cent.

Table 5. Characteristics of leak detectors

Analyser type	Cost (€)[1]	Type	Source/delivery mechanism	Usability	Comments
Helitest helium leak detector	8550	Selective Ion Pump Detector	Helium/commercial balloon gas	Detection has a 10 s delay during operation. Identifying the position of a leak or gap can be difficult.	Quantitative recording possible. Equipment is sensitive (1 ppm). Expensive but can be hired. Useful application could be to measure leakage rate of known leaks or enclosure manufacturers to test prototype seal, locks, and so on.
Inficon D-TEK™ Select	430	Infrared	Halocarbons/ pressurized air duster (containing RJ 134a)[2]	Sensitive and provides semi-quantitative results with audible readout.	User needs to scan sensor between the suspected leak and the surface of the case. Concentration is relative to average concentration in environment.
TIF 5600	180	Heat cell type detector	Halocarbons/ pressurized air duster (containing RJ 134a)	Difficult to qualify results: alarm and LED display difficult to interpret.	User needs to scan sensor between the suspected leak and the surface of the case. Now superseded.
UE Systems Ultraprobe ultrasonic leak detector	1970	Solid-state hybrid heterodyne receiver	Detector is supplied with WTG-1 ultrasonic warble tone generator	Instantaneous result. Sensitive: volume on receiver can be adjusted. Warble tone generator needs to be placed inside enclosure.	Need to 'zero' the receiver for transmitted sound through enclosure materials before scanning: the correct detection volume can then be set. Can be used in incomplete enclosures and to test room size enclosures, door and window seals.

[1]Average retail price in UK at November 2004 at concurrent exchange rates (£1 = €1.42).
[2]Kenair pressurised air duster.

Suitability of tracer gases

Common building tracer gases are hydrogen sulphide (H_2S), helium (He), SF_6, ozone (O_3), N_2O and CO_2. N_2O, CO_2 and O_2 can be safely used with objects (Table 3) and low-cost gas detectors are readily available. So far, several gas detectors have been tested by the authors (Table 2). The first experiments were with a prototype CO_2 air quality monitor, further tests were undertaken with Medigas PM3010 N_2O detectors to allow comparison with the BSRIA technique in the field (N_2O detectors are cross sensitive to CO_2 and BSRIA were understandably reluctant to compromise any commercial tests).

Experimental

To validate the basic operational method two PM3010 N_2O sensors were tested in a chamber connected to a mass/flow meter with a measurable flow rate. The average air flow for the chamber was 572 cm^3/min (6.59 ac/d) compared with calibrated rates of 6.16 and 6.46 ac/d for the PM3010 detectors which suggested the method and equipment used warranted more study.

Further measurements have compared the repeatability of tests on the same enclosures at different times and using different measurement techniques. The regression line is often S-shaped rather than a straight line (Figure 5), suggesting that the AER is not constant over time (Calver 2001, Ligternik et al. 2001). Significant variation has also been noted between repeat measurements which are difficult to explain by differences in external forces alone (Michalski 1993) and are likely to result from actual differences caused by slightly different gasket configurations each time an enclosure is opened and closed. Originally, the tracer gas was mixed with enclosure air using a battery-powered fan, timed to run for 30 min, but tests have shown that mixing is not normally required.

To test the repeatability of measurements on the same enclosure, a series of measurements was made over a period of 30 days (Table 5). Concurrent tests were also undertaken using the CO_2 and N_2O detectors used by the authors, and finally a simultaneous comparison was made with four gases including ingress of oxygen (Raphael 2004) and RH techniques previously reported (Figure 6).

Relative humidity tests

The use of water vapour (as RH) as a tracer has a certain elegance. Detectors are readily available and a key reason to measure the AER is for the control of RH. A glass case was constructed without the use of any moisture absorbent materials and the AER measured using H_2O vapour as a tracer. The experiment was carried out in a dehumidified room with a stable RH (30 ± 4 per cent) and the RH in the enclosure raised to over 80 per cent with an ultrasonic humidifier. The concentration decay curves for one sensor are shown in Figure 7. Test 1 gave AER_{H2O} for three concurrent RH sensors of 0.92, 1.09 and 1.11 ac/d. Test 2, including a N_2O detector for comparison, gave AER_{H2O} measurements of 1.20 and 1.18 ac/d and an AER_{N2O} rate of 2.06 ac/d. The estimated crack dimensions suggest diffusion-controlled concentration decay. By applying diffusion coefficients calculated from Graham's law (Brimblecombe and Ramer 1983). The adjusted value for the AER_{N20} measurement is 1.32 ac/d, close to the AER_{H2O} values. Test 3 simulates an enclosure with organic components. The base was covered with a MDF sheet and a softwood batten added to simulate a wooden object. The concentration decay curve is much steeper (Figure 7) demonstrating how moisture is rapidly absorbed. The AER_{N2O} measurement was 1.4 ac/d and the apparent AER_{H2O} measurement was 15–40 ac/d. After stabilization, the apparent moisture exchange rate was calculated as 0.014 ac/d, which gives a half time for the enclosure of 50 days (by Equation 2). A further test was undertaken in another case where an attempt had been made to seal the moisture baseboard but the results were still very disappointing (Figure 6).

Although these tests confirm that water vapour is an unreliable tracer gas in many practical applications, combined with one of the other methods it is the tracer of choice to determine the hygrometric performance and permeability of enclosures.

Comparison with commercial tests

Attempts were made to compare the PM3010 N_2O detector with the equipment used by BSRIA by testing enclosures concurrently. Unfortunately, at the sub-300 parts per million (ppm) levels used by BSRIA, the PM3010 was found to be unreliable. However, a test on the same case immediately afterwards but at the gas concentration of 1000 ppm recommended yielded a more promising result. The BSRIA measurement was 0.10 ac/d and the PM3010 value was 0.14 ac/d (Figure 3).

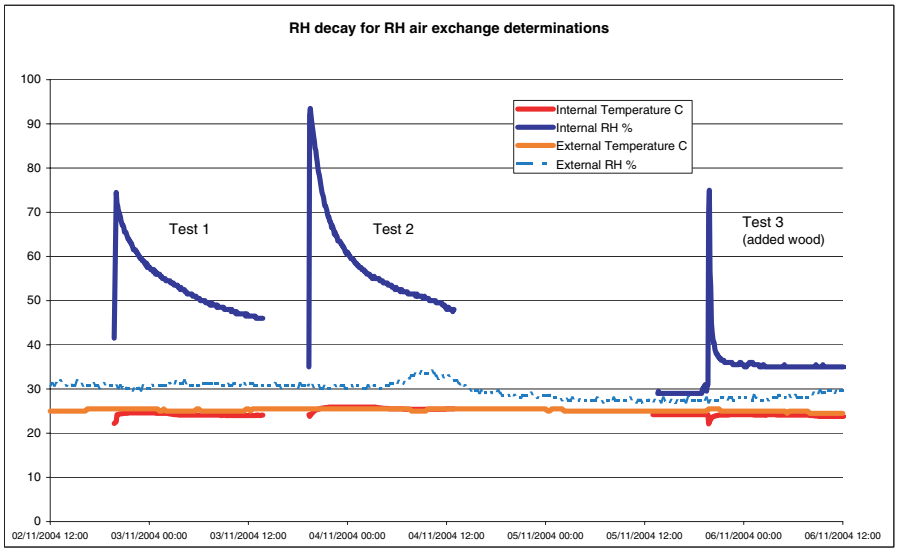


Figure 7. Concentration decay of water vapour (expressed as per cent RH) in a glass test case constructed without moisture-absorbent materials. Test 1 gave an AER_{H2O} of 1.11 ac/d, test 2 including an N_2O detector for comparison gave a AER_{H2O} measurement 1.18 ac/d and a AER_{N2O} rate of 2.06 ac/d. Test 3 simulates an enclosure with organic components. The base was covered with an MDF sheet and a softwood batten added to simulate a wooden object. As can be seen concentration decay curve is much steeper, demonstrating how moisture is rapidly absorbed. The apparent AER_{H2O} measurement was about 15–40 ac/d whereas the comparative AER_{N2O} measurement was 1.4 ac/d

Gas delivery

Conventional industrial cylinders are difficult and hazardous to transport. The catering industry uses N_2O as a propellant for whipped cream; CO_2 is used in soda siphons, and small disposable cylinders are readily available. Using cream and soda dispensers was found to be a very effective way to deliver the small quantities of gas required (Figure 1). Small quantities of carbon dioxide are also easily available as cycle tyre inflators. A selection of the equipment is shown in Figure 4.

Practical applications

The N_2O and CO_2 detectors have been used in several practical studies and have been particularly useful during the construction of enclosures (Stanley et al. 2003). For instance, the technique can be performed overnight to test whether a display case meets the specification, with the results available the next day while the installer is still on site and able to make modifications. Results from gallery projects undertaken by the Museum of London and English Heritage have shown that testing during installation is a very effective way of improving quality control.

Leak detection

To minimize the AER or locate manufacturing or assembly defects, a means is required to identify the leakage paths. By knowing the AER and the geometry of the case, it is possible to use the tables in Michalski (1994) to estimate the hole or crack dimensions that could contribute to the leaks. However, experience has shown that it is not always easy to spot leaks (Stanley et al. 2003). Manufacturers of display cases commonly use a smoke test to determine leakage points. Unfortunately, most smoke-producing materials leave a residue and the technique cannot be used with objects.

Refrigerant leakage detectors designed to detect halogen compounds are commonly used to check for leakage in anoxic pest control (Daniels 1997). Recently, leak detectors based on infrared (IR) absorption sensors which are

more sensitive and have a longer detection cell life have come to replace the heated chemical cell types. For this work, an IR halogen leak detector (Inficon D-TEK Select) was compared with a heated cell type detector (TIF5600). Rather than using chlorinated solvents as the source, it was found that the propellant in pressurized air dusters is a common refrigerant gas carrier (RJ 134a) to which both detectors are sensitive. This provides a safe, readily available and portable gas delivery system. Hydrogen sulphide and helium are used for very sensitive industrial applications, and a helium gas detector was hired for comparison. Ultrasonic leak detectors are also common in industry. An ultrasonic tone generator is placed inside the enclosure and a detector is used which converts the ultrasound 'leaking out' into the audible range. The detector selected for testing uses a 'warble tone' generator, which was found to offer greater sensitivity when compared with single tone generators.

Figure 8. Andy Holbrook uses the D-TEK select and Sam Calver uses the Ultratone 100 leak detectors as part of a research project at the Museum of London. The case is deliberately vented (6 ac/d): sealing the vents only reduced the AER to 4 ac/d, suggesting most of the air was entering not through the filtered vents but elsewhere. Leaks were found along all door seams and especially around lock positions

Field comparisons

The different detectors were evaluated on test enclosures with defined leakage points and on enclosures in the field (Figure 8). It is important that the operating instructions set out by the manufacturers are followed as each detector works in a slightly different way (Table 3). For instance the refrigerant leak detectors rely on detecting a concentration change: thus they must be slowly moved across suspected leakage paths whereas the helium detector measures absolute values and can be used for sensitive detection of leaks through very small openings such as locks or hinges. For ultrasonic detectors, the tone emitted varies according to wall thickness and density. Leakage is interpreted based on signal strength and it important to distinguish between increases due to low density, such as an uncompressed gasket that maintains a proper seal, compared with actual leakage. The technique gives an instant result, whereas with the gas detectors one has to wait for the gas to diffuse out of through the leaks. Gross leaks can be detected from some distance away, making it very useful where it is not possible to gain access to suspect leakage points, for example underneath a case. Unlike refrigerant leak detectors, ultrasound can also be used in enclosures that are not completely sealed to evaluate specific gasket joints and construction seams during fabrication.

Conclusions

Since experimentation began, we have undertaken over 100 individual AER measurements for pollution research, display and storage enclosure installations and for detector comparisons. We have shown that the AER of enclosures, an important factor for preventive conservation, can be easily calculated using low cost gas detectors. By using a combination of leak detectors and AER measurements during enclosure installation, performance specifications are more likely to be met or any defects rectified more readily. Where compliance with a performance specification is required for contractual purposes, an independent validation of a sample of enclosures is still recommended. It is encouraging that several manufacturers of display cases have expressed an interest in using the test methods, and it is hoped the adoption of these techniques by manufacturers and clients during prototyping, fabrication and installation will ensure greater compliance in the future.

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Materials

Our measurement protocol and data analysis spreadsheet is available by email: acalver@museumoflondon.org.uk or the Indoor Air Quality in Museums and Archives website: http://www.iaq.dk/links.htm.

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Medigas PM3010 infra red Nitrous oxide monitor, PM1500 Carbon Dioxide monitor
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