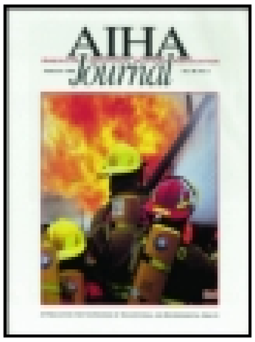


American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: http://www.tandfonline.com/loi/aiha20

VOC Emission Rates and Emission Factors for a Sheetfed Offset Printing Shop

R.A. Wadden , P.A. Scheff , J.E. Franke , L.M. Conroy , M. Javor , C.B. Keil & S.A. Milz

To cite this article: R.A. Wadden , P.A. Scheff , J.E. Franke , L.M. Conroy , M. Javor , C.B. Keil & S.A. Milz (1995) VOC Emission Rates and Emission Factors for a Sheetfed Offset Printing Shop, American Industrial Hygiene Association Journal, 56:4, 368-376, DOI: 10.1080/15428119591016999

To link to this article: http://dx.doi.org/10.1080/15428119591016999

VOC EMISSION RATES AND EMISSION FACTORS FOR A SHEETFED OFFSET PRINTING SHOP

R.A. Wadden
P.A. Scheff
J.E. Franke
L.M. Conroy
M. Javor
C.B. Keil
S.A. Milz

Environmental and Occupational Health Sciences, School of Public Health,
University of Illinois at Chicago, Box 6998, Chicago, IL 60680

Emission rates were determined during production for a sheetfed offset printing shop by combining the measured concentrations and ventilation rates with mass balance models that characterized the printing space. Air samples were collected simultaneously on charcoal tubes for 12 separate 1-hour periods at 6 locations. Air samples and cleaning solvents were analyzed by gas chromatography for total volatile organic compounds (VOC) and 13 hydrocarbons. The average VOC emission rate was 470 g/hr with a range of 160–1100 g/hr. These values were in good agreement with the amounts of VOC, hexane, toluene, and aromatic C_9s determined from estimated solvent usage and measured solvent compositions. Comparison of the emission rates with source activities indicated an emission factor of 30–51 g VOC/press cleaning. Based on the test observations it was estimated that this typical small printing facility was likely to release 1–2 T VOC/year. The methodology also may be useful for the surface coating industry, as emission rates in this study were determined without recourse to a temporary total enclosure and without interfering with worker activities, increasing worker exposure, or increasing safety and explosion hazards.

Offset printing has the potential to release volatile organic compounds (VOC) and particulate matter as fugitive emissions. Since most small- and intermediate-size offset printing operations are not served by local exhaust systems, these emissions directly enter workroom air before being vented outside. Because the releases can occur at various locations on the press and at different times during a press run, the amounts are particularly difficult to quantitate.(1–4)

This study measured VOC concentration patterns and ventilation rates in a sheetfed offset print shop. Several mass balance models were then applied to these data to transform concentrations and air flow rates to emission rates, i.e., mass/time form. By comparing the emission rates with source activities collected simultaneously with the area concentrations, it was then possible to express mass of emissions as a function of one or more operating variables—such as number of printed sheets or length of cleaning periods—that is, as an emission factor.

EXPERIMENTAL METHODS

Test Location

The mass balance approach was applied to a print shop containing four offset sheetfed presses and three spirit duplicators used for imprinting letterheads on stationery and envelopes. The shop consisted of a plate-making room (volume = 16,000 ft^3), the press room (36,000 ft^3), and a storage room (5600 ft^3), for a total volume of 57,600 ft^3 (1646.7 m^3, Figure 1). All these spaces were served by the same ventilation system. A six-color press was located in an adjacent area that was served by a separate ventilation system. However, this space was not included in the present evaluation.

Exhaust air from the press/plate-making rooms passed through the air return duct, was mixed with make-up air, and the mixed air was returned to the rooms through air diffusers. There was no local exhaust. The four presses were a 1977 Miller TP-38A two-color perfecter (Line 1); 1964 Harris LXG-FR one-color (Line 2); 1975 Harris L-129 one-color (Line 3); and a 1969 Miller TP-38 two-color perfecter (Line 4).

Offset printing consists of an inking system that delivers a thin, uniform ink film to a printing plate. An aqueous fountain solution containing small amounts of phosphoric acid and i-propyl alcohol or glycol ethers wets nonprinting areas of the

---

This study was supported in part by the University of Illinois Occupational Safety and Health Educational Resource Center, NIOSH award 2T15OH07104 (Industrial Hygiene) and by a NIOSH-funded research grant, 5RO1OH02804.

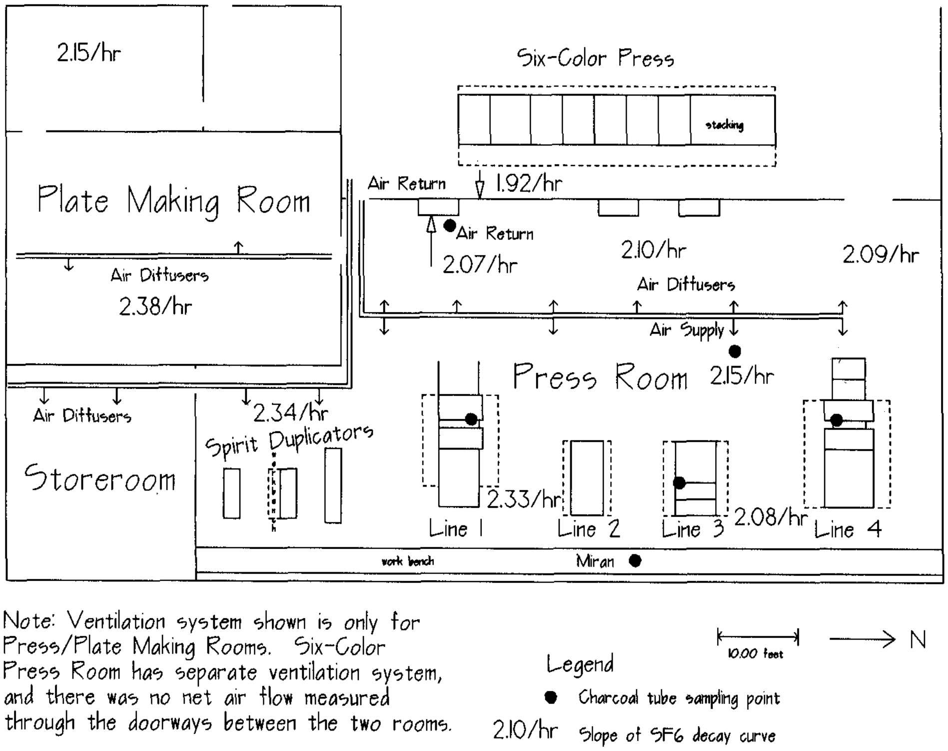


FIGURE 1. Plan view of print shop

plate. The printing plate, positioned on a cylinder, delivers only the inked images to an elastomeric, rubber-covered, multi-tiered lithographic blanket on the blanket cylinder. The blanket, in turn, passes images onto substrate (paper, paperboard), while the impression cylinder controls the force imposed on the substrate to ensure proper transfer of inked images. Inks are formulated to set within minutes of application and generally contain drying oil (linseed, soy), resins and pigments, and petroleum distillates. Blankets and ink rollers need to be cleaned before, during, and after jobs, usually with volatile solvents. Sheetfed printing is a slow process in which individual sheets from a stack are run through a press. The ink is nearly dry as the sheet leaves the press.(1)

Test Conditions

Process observations were carried out for 12 one-hour periods during production over two days (December 17–18, 1991). For each hour, simultaneous concentration measurements were made of organics at the air return register, in the supply air, in the immediate vicinity of three of the presses, and at the workbench on the east side of the press room (Figure 1). The press sampling locations were located 6–8 inches (0.15–0.2 m) above the contact plane between the ink rollers and the image plate. Consequently, since the presses were of different heights, Line 1 and Line 4 samples were 2.1 m above the floor, while Line 3 samples were 1.2 m above floor level. Plan view sampler placement is to scale in Figure 1.

Organic vapor samples were collected on charcoal tubes at calibrated flow rates of 300 mL/min for one hour. Twelve one-hour periods were monitored at each of the sampling locations. As a quality control measure for hydrocarbon sampling and analyses the authors also collected duplicate charcoal tube samples at three of the locations (air return, air supply, and workbench), which were analyzed for VOC by a commercial laboratory. Resources were not available to have the other VOC samples and hydrocarbon speciation done commercially.

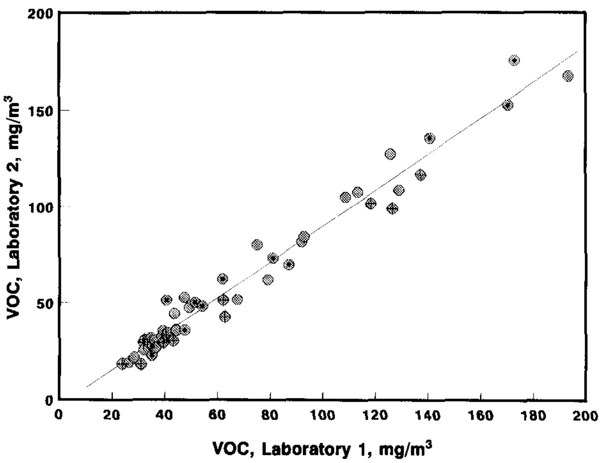
Because an area of interest was to compare emissions to source activities, a continuous measure of concentration was implemented that may more specifically reflect process variability.(5,6) During this study continuous monitoring was carried out at the workbench (Figure 1) with an infrared gas analyzer (Foxboro/Wilks Miran 1A General Purpose Gas Analyzer, Foxboro, Mass.). The Miran was calibrated prior to use with a closed-loop calibration system at a wavelength of 13.9 μm (toluene).

Three of the presses and two of the spirit duplicators were in operation during the test, which was the usual operating procedure. Source activities were recorded at approximately five-minute intervals simultaneously with air sampling. The activity observations included number of sheets printed, number of setup and cleaning periods, number and duration of idle periods, job number, and number and duration of ink addition intervals.

The air supply was measured from the diffusers using an air balancing instrument (Balometer Model 6465, Alnor Instrument Co., Skokie, Ill.). Air return and make-up air flow rates were measured using a thermoanemometer (Model 8350, TSI Inc., St. Paul, Mich.). Cross drafts and flow in and out of doors were determined with smoke tubes and a thermoanemometer. The mixing characteristics of the space were determined by an SF_6 tracer concentration decay test. For a completely but inefficiently mixed system without a source, the decay of an initial concentration because of ventilation will be described by(7)

$$C = C_0 \exp\left(-\frac{kq}{V}t\right) \tag{1}$$

C is the concentration of tracer (ppm) in the space at time, t (hours);
C_0 is the concentration of tracer at t = 0;
q/V is the is the air change rate/hr; and
k is the mixing factor, the fraction of ventilation air that mixes completely with room air.



N = 48; r^2 = 0.969; Lab 2 = 0.929 (Lab 1) - 3.042
Total hydrocarbon determined on basis of hexane FID response.

FIGURE 2. Quality control comparison of duplicate VOC samples

If the air change rate is known, the value of k can be determined from the slope of the SF_6 concentration/time curve. SF_6 was released into the air return ducts. The change in concentration with time was observed at 10 locations. Disposable syringes were used to collect 20 mL samples at each location at various times after release. The samples were analyzed with a gas chromatograph and an electron capture detector optimized for SF_6. The procedure is similar to that recommended by the American Society for Testing and Materials for air infiltration.(8)

Analysis Conditions

The charcoal tubes were extracted with carbon disulfide and analyzed by gas chromatography (Model 5890 Gas Chromatograph, Hewlett Packard, Palo Alto, Calif.) for VOC and for speciation of 13 organic compounds. A 30m × 0.53 mm Supelcowax 10 column was used with flame ionization detection (FID). VOC was defined as the total area under the chromatogram trace, interpreted with the hexane response factor, after the CS_2 peak for an initial interval of three minutes, followed by a program rate of 3°C/min from 40°C to 160°C. (The authors used the designation VOC in the generic sense rather than the regulatory definition, which excludes certain specific halogenated compounds. Some of these, if present, may contribute to the total area under the GC response curve. However, these compounds were not likely to have constituted major contributions to the authors' measurement of VOC). Duplicate VOC samples were collected at the air return, air supply, and workbench and were analyzed by a commercial laboratory using the same procedure for VOC. Nine solvents also were analyzed for organic composition.

RESULTS AND DISCUSSION

Concentration Measurements

Total VOC concentrations are compared for duplicate samples in Figure 2. Agreement was excellent with r^2 = 0.97 for 48 paired samples and a slope of 0.929.

The average concentrations over all 12 hours of monitoring are shown in Table I for VOCs and 13 compounds. The aromatic C-9 category is the total of n-propyl benzene, o- and p-ethyl toluene, and 1,3,5-, 1,2,4-, and 1,2,3-trimethyl benzene. All of

TABLE I. Average VOC Concentrations (Standard Deviations) Based on 12 One-hr Samples

	mg/m³					
Component	*Air Return*	*Work Bench*	*Over Line 4*	*Over Line 3*	*Over Line 1*	*Air Supply*
n-Hexane	1.31 (0.74)	2.06 (0.73)	0.82 (0.45)	1.07 (0.51)	1.37 (0.69)	0.90 (0.47)
i-Propyl-Alcohol and Benzene	3.71 (2.45)	5.09 (3.17)	8.17 (7.38)	4.77 (3.80)	4.21 (2.21)	3.30 (2.12)
Toluene	18.04 (13.46)	23.14 (17.74)	28.84 (32.90)	22.60 (19.09)	22.10 (15.03)	16.54 (14.98)
Ethylbenzene	0.30 (0.40)	0.44 (0.51)	0.84 (0.97)	0.50 (0.57)	0.38 (0.42)	0.27 (0.34)
p-Xylene	0.16 (0.14)	0.22 (0.19)	0.34 (0.30)	0.23 (0.21)	0.21 (0.17)	0.16 (0.18)
m-Xylene	0.32 (0.18)	0.45 (0.26)	0.59 (0.36)	0.39 (0.24)	0.42 (0.24)	0.27 (0.14)
o-Xylene	0.46 (0.28)	0.61 (0.38)	0.85 (0.49)	0.73 (0.41)	0.62 (0.39)	0.41 (0.24)
n-Propyl-Benzene	1.23 (0.79)	1.59 (1.08)	2.52 (1.45)	1.88 (1.22)	1.68 (1.09)	1.14 (0.70)
p-Ethyl-Toluene	5.09 (3.03)	6.53 (4.17)	10.35 (5.60)	7.72 (4.75)	6.98 (4.26)	4.77 (2.72)
1,3,5-Trimethyl-Benzene	1.79 (1.10)	2.29 (1.50)	3.68 (2.02)	2.75 (1.72)	2.53 (1.53)	1.63 (0.99)
o-Ethyl-Toluene	1.15 (0.65)	1.50 (1.06)	2.39 (1.64)	2.02 (1.31)	1.74 (0.97)	0.92 (0.54)
1,2,4-Trimethyl-Benzene	2.45 (1.42)	3.15 (1.96)	5.07 (2.66)	3.75 (2.24)	3.43 (1.99)	2.27 (1.29)
m-Diethyl-Benzene	0.28 (0.17)	0.37 (0.24)	0.58 (0.33)	0.45 (0.28)	0.43 (0.25)	0.25 (0.16)
1,2,3-Trimethyl-Benzene	0.25 (0.16)	0.32 (0.22)	0.53 (0.29)	0.39 (0.25)	0.36 (0.21)	0.23 (0.15)
Aromatic C-9s[A]	11.95	15.38	24.54	18.51	16.70	10.95
Total VOC	55.62 (35.25)	75.50 (48.60)	109.57 (85.20)	77.05 (52.35)	67.14 (42.09)	50.14 (33.45)

[A] Total of n-propyl benzene, o- and p-ethyl toluene, and 1,3,5-, 1,2,4-, and 1,2,3-trimethyl benzene these components were specifically determined. It was not possible to separate benzene and iso-propyl alcohol with the particular chromatography column used for analysis (Supelcowax 10, 1 μm thickness, 30 m × 0.53 mm in a Model 5890 gas chromatograph, Hewlett Packard, Palo Alto, Calif.), so the reported value is a total for the two materials. The air supply concentration represents a mixture of outdoor makeup air and recycled (air return) air from the print shop. The "Over Line" samples represent workstation exposures for Lines 1, 3, and 4. The standard deviation also is shown in Table I for each component to indicate the variation in concentration (but not in sampling or analytical precision) over the 12 test hours.

Solvent compositions are given in Table II. The benzene compositions were determined specifically for the solvents by the commercial laboratory; quantitatively by gas chromatography on a Model 5890 Series 2 with an FFAD 30 m × 0.53 mm column and FID, and identified on a Model 5996 GC/MS system with a 60 m × 0.75 mm Supelcowax 10 column (Hewlett Packard, Palo Alto, Calif.). Resources were not available to carry out this analysis on the air samples. (It is perhaps of interest to note that the material safety data sheets on these solvents were very unspecific as to the hydrocarbon composition.) Gasoline was used to clean the spirit duplicators.

The continuous measure of concentration was the Miran reading calibrated for toluene. However, since it was likely that other aromatic hydrocarbons would contribute to the infrared signal, the monitoring results, averaged by hour, were compared with charcoal tube samples collected at the same time and location. Figure 3 shows a reasonable relationship between the Miran response and VOC determined from the charcoal tubes ($r^2 = 0.79$; slope = 1.2).

Ventilation Measurements

Measured ventilation rates are shown in Table III. The measured rates indicate that about two-thirds of the air was recirculated with a make-up air rate of 4942 ft^3/min (8391 m^3/hr). The mixed air flow rate of 12,358 ft^3/min (20,984 m^3/hr) was consistent with the total of the return and make-up air flow rates. There was no measurable flow through the doors connecting the print room to the six-color press area.

It is also possible to estimate the make-up rate from the ratio of air return and air supply concentrations. The material balance for an organic component at the make-up air addition point becomes

$$Q_{\text{return}} \cdot C_{\text{return}} + Q_{\text{make-up}} \cdot C_{\text{make-up}} = Q_{\text{supply}} \cdot C_{\text{supply}}$$

$$\text{and for } C_{\text{make-up}} \approx 0 \quad \text{and} \quad Q_{\text{supply}} = Q_{\text{return}} + Q_{\text{make-up}}$$

$$Q_{\text{make-up}} = Q_{\text{return}} \left(\frac{C_{\text{return}}}{C_{\text{supply}}} - 1 \right) . \qquad \textbf{(2)}$$

Over the 1.5 hours during which the ventilation measurements were made, the concentration ratio for VOC varied between 1.59 and 1.29. Using the measured air return rate of 8629 ft^3/min in Equation 2 gave a range of make-up rates between 5091 and 2502 ft^3/min, respectively, which was consistent with the measured value of 4942 ft^3/min. The concentration ratios for

TABLE II. Printing Solvent Compositions

	Weight %					
Component	*Step 1*	*Step 2*	*Blanket Wash*	*Clean Quik*	*Plate Wash*	*Gasoline*
n-Hexane	0	0	0	0	0	22.95
Benzene[A]	0.0004	$<2\cdot10^{-4}$	$<2\cdot10^{-4}$	0.0025	$<2\cdot10^{-3}$	2.41
i-Propyl-Alcohol	5.59	5.56	13.60	6.68	0	0.00
Toluene	3.56	2.67	11.61	28.22	0	6.53
Ethylbenzene	9.67	0.79	1.27	0.05	26.65	1.59
p-Xylene	0.00	0.47	0.00	0.17	0.00	1.69
m-Xylene	3.76	0.94	0.63	0.41	0.00	3.90
o-Xylene	5.23	1.53	0.00	1.64	0.00	2.33
n-Propyl-Benzene	2.17	4.25	0.00	4.14	0.69	0.60
p-Ethyl-Toluene	2.29	18.61	0.00	17.82	0.00	2.92
1,3,5-Trimethyl-Benzene	0.86	6.40	0.00	15.18	0.00	1.17
o-Ethyl-Toluene	0.61	4.51	0.00	3.99	0.00	0.68
1,2,4-Trimethyl-Benzene	1.73	11.79	0.00	9.74	0.00	3.33
m-Diethyl-Benzene	0.53	1.87	0.00	2.58	0.00	0.95
1,2,3-Trimethyl-Benzene	0.65	1.46	0.00	0.93	0.00	0.92
Total VOC, mg/mL	440.70	791.20	676.40	671.40	88.40	682.40
Aromatic C-9s[B]	8.31	47.02	0.00	51.80	0.69	9.62
Identified compounds[C]	36.65	60.85	27.11	91.55	27.34	51.97
Number of samples	3	2	1	1	1	1

[A] Benzene determined specifically only for solvents by commercial laboratory using a different column

[B] Total of n-propyl benzene, o- and p-ethyl toluene, and 1,3,5-, 1,2,4-, and 1,2,3-trimethyl benzene

[C] n-hexane, i-propyl alcohol, benzene, toluene, ethyl benzene, p-, o-, and m-xylene, m-diethyl toluene, n-propyl benzene, o- and p-ethyl toluene, and 1,3,5-, 1,2,4-, and 1,2,3-trimethyl benzene

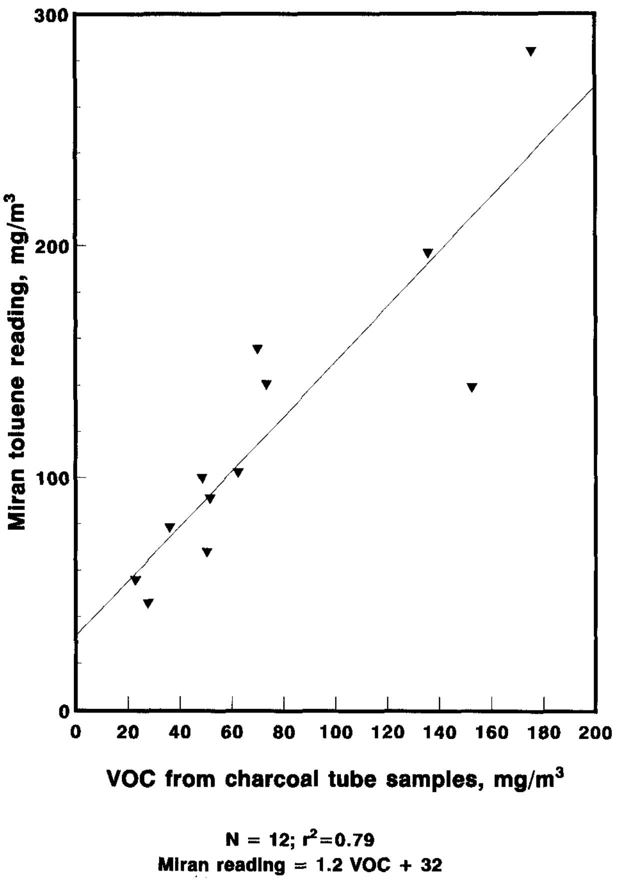


FIGURE 3. Miran "toluene" reading compared with VOC from charcoal tubes (1-hr averages)

some of the other measurement periods suggested occasional lower make-up rates with consequent recycle rates up to 90%. The emission calculations are based on the measured make-up rate, recognizing that this value may change depending on the season and outdoor temperature. (The make-up air damper control is basically a function of the indoor/outdoor temperature difference with a decrease in flow with increasing temperature difference).

The values of k from the SF_6 tests are shown in Figure 1. Measurements at different locations are quite consistent. Concentration decay also was determined in the six-color press area. This area is served by a separate ventilation system, but of similar design to that for the press/plate-making area. The presence and decay of SF_6 in this area was probably due to leakage from the section of the press/plate-making mixed air ventilation duct that was located in this space and was under positive pressure with respect to the six-color press work area.

Emission Rates

Emission rates were calculated in two ways. The Experimental Mass Balance Approach was to use the measured concentrations C (mass/volume), and flow rates Q (volume/time), at entry and exit points. The emission rate S (mass/time) is then

$$S_{\text{mass balance}} = \sum_{1}^{\text{total exit points}} Q_{\text{exit}} \cdot C_{\text{exit}} - \sum_{1}^{\text{total entry points}} Q_{\text{entry}} \cdot C_{\text{entry}}. \quad \textbf{(3)}$$

The Analytical Approach was to use a completely mixed space mass balance model. The form of this model for an integrated concentration over a specified averaging time is[(9,10)]

$$S = \frac{C_{av}kq - \left[C_s \dfrac{V}{t_{av}}\right]\left[1 - \exp\left(-\dfrac{kq}{V}t_{av}\right)\right]}{1 + \left[\dfrac{V}{kqt_{av}}\right]\left[\exp\left(-\dfrac{kq}{V}t_{av}\right) - 1\right]} \quad \textbf{(4)}$$

where

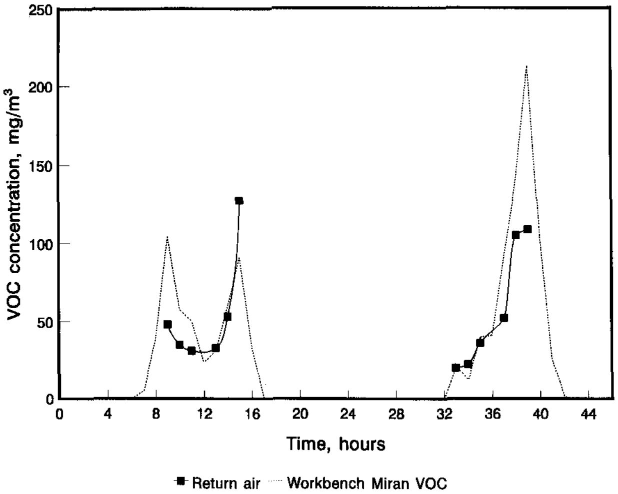
S	is the emission rate, mass of pollutant/time;
C_{av}	is the average concentration in the space;
t_{av}	is the sampling time;
C_s	is the instantaneous concentration at start of the sampling period;
V	is the volume of the space;
q/V	is the air change rate/time; and
k	is the mixing factor, which varies between 0 and 1.

The make-up air rate shown in Table III was used in both Equations 3 and 4. The air return and outdoor air concentrations (VOC < 0.6 mg/m^3) were used in applying Equation 3. In using the air return concentration it was tacitly assumed that leakage from the space, wherever it occurred, had this composition.

A different set of concentration measurements was used in applying Equation 4. In this case the concentration of the space was characterized with the hourly average values from the Miran adjusted to VOC equivalent with the relationship shown in Figure 3. The advantage of this approach is that Miran readings and activity observations were available for a total of 18 one-hour periods (but charcoal tube values for only 12). In addition, as is shown in Figure 4, the response of the Miran, even though it was on the opposite side of the room, was consistent with charcoal tube concentrations taken at the air return location. The mixing factor, k, was determined by dividing the average SF_6 decay rate of 2.19 hr^{-1} by the air exchange rate (based on the make-up air rate) of 5.1 hr^{-1} (Table III). A mean value of

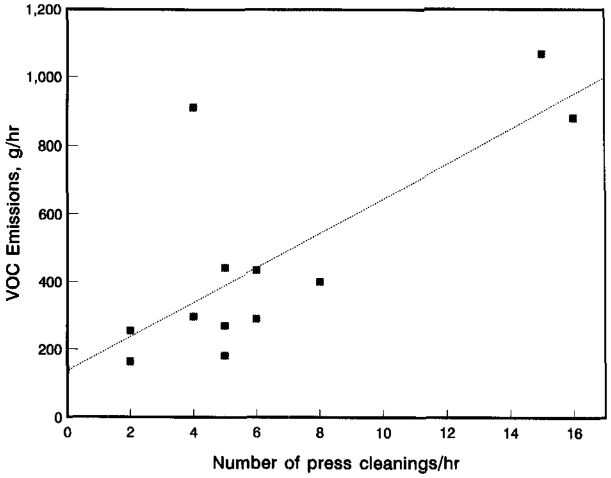
TABLE III. Ventilation Characteristics of the Print Shop Space

Make-up Air	4942 ft^3/min	(8391 m^3/hr)
Return Air (Recycle)	8629 ft^3/min	(14 652 m^3/hr)
Total to Print Shop	13 571 ft^3/min	(23 043 m^3/hr)
Mixed Air Flow (after Make-up Air Intake)	12 358 ft^3/min (20 984 m^3)	
Room Volume (Print/Plate-making, Storeroom)	1646.7 m^3	
Air Exchange Rate	5.1 hr^{-1}	
Mixing Characteristics	$kq/V = 2.19$ hr^{-1}	
(SF_6 concentration decay test)	$0.41 < k < 0.47$	



Miran concentration adjusted to VOC basis with the regression equation
Miran conc., mg/m³ = 1.2 (VOC, mg/m³) + 32

FIGURE 4. VOC concentration from two locations (return air charcoal tubes and continuous concentration from Miran record adjusted to charcoal tube equivalent)



Emission factor = 50.7 g VOC/press cleaning from least square fit
$r^2 = 0.55$

FIGURE 5. Emission rate based on air return concentration and Experimental Mass Balance (Equation 3) vs. solvent cleaning frequency

the mixing factor, k = 0.43, was used for the estimation, and the value of C_s was the instantaneous VOC concentration taken from the Miran record at the end of the previous hour.

As an example of the emission rate calculation, if we substitute the average VOC concentration for the air return (from Table I) in the Experimental Mass Balance (Equation 3), then:

$$C_{\text{air return}} = 55.62 \text{ mg/m}^3$$

$$C_{\text{make-up}} = <0.6 \text{ mg/m}^3$$

$$Q_{\text{make-up}} = 8391 \text{ m}^3\text{/hr.}$$

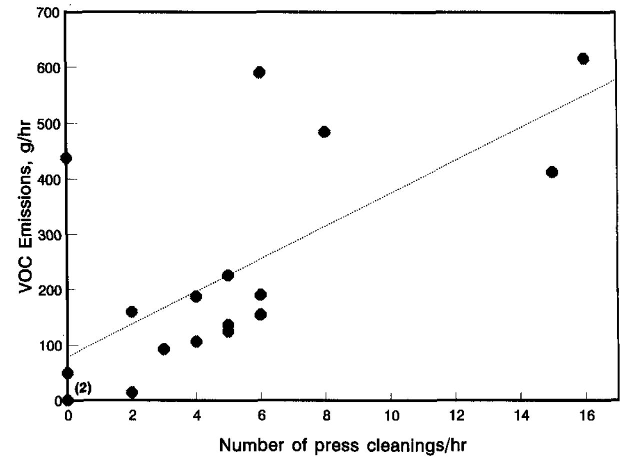
$$\frac{g_{\text{voc}}}{\text{hr}} = Q_{\text{make-up}}(C_{\text{air return}} - C_{\text{make-up}})$$

$$\frac{g_{\text{voc}}}{\text{hr}} = \frac{8391 \text{ m}^3}{\text{hr}} \times 55.62 \frac{\text{mg}}{\text{m}^3} \times \frac{\text{g}}{10^3 \text{ mg}} = 467 \frac{g_{\text{voc}}}{\text{hr}}. \qquad \textbf{(5)}$$

Emission rates were similarly calculated for each hour of measurement. The individual values are plotted in Figure 5.

The average emission rate for the 18 one-hour periods using Equation 4 was 221 g VOC/hr. Individual values are shown in Figure 6. The two emission rate estimates are consistent with each other as the additional hours included in determining the lower value were characterized by less source activity. Based on the same 12 hours, the average value was 267 g/hr. The difference is reasonable given that the concentration in the space is being described with only one measurement point (at the workbench).

If it is assumed all solvents used in the process are completely evaporated to workroom air, it is also possible to estimate an emission rate from measurements of solvent usage. Solvent use could not be measured directly during the period of the test. However, since each line usually was operated by the same person, the individual printers were asked to estimate weekly solvent usage. These estimations are given in Table IV. Solvent compositions given in Table II were then applied to the estimates of each solvent to determine VOC and component usage rates. The authors used typical work periods of 10 hrs/day (which were observed) and 5 days/week to put the usage data on the same basis as the emission rates determined using Equation 1 and the air return concentration. Comparisons for VOC and five of the speciated groups are shown in Table V. The



Emission rate based on completely mixed space model with
k = 0.43, q = 8391 m³/hr, V = 1646.7 m³, t_{av} = 1 hr; (r^2 = 0.46)
Emission factor = 29.5 g VOC/press cleaning (from least squares fit)

FIGURE 6. Completely mixed space emission rate (Equation 4) vs. frequency of cleaning

TABLE IV. Approximate Solvent Usage (Operator Estimate)

Line	*Solvent*	*Usage Gallons/Week*
Line #1	Clean Quik	2.0
	V-120 (plate wash)	2.0
	step #1	2.0
	step #2	0.5
Line #3	step #1	1.0
	step #2	1.0
Line #4	blanket wash	2.0
	Clean Quik	2.0
	V-120 (plate wash)	2.0
	step #1	2.0
	step #2	2.0
Letterhead	Clean Quik	0.5
	gasoline	0.5
Total Use		19.5

agreement is good considering the uncertainty in approximating the usage value.

Emission Factors

Hourly emission rates were compared with various source activities including total sheets printed, types and number of inks used, number of ink additions, duration of production, setup, and idle periods, and frequency of press cleaning with solvents. Frequency of cleaning and total pieces printed are shown in Table VI. During the test a total of 13 jobs was carried out on the three presses, and 36,704 sheets printed. The duplicator totals for the same period were 47,242 envelopes and letterheads.

Figures 5 and 6 show the VOC emission rates calculated from Equations 3 and 4, respectively, plotted versus frequency of solvent cleaning. In both cases there is an association. The resulting emission factors, which are the slopes of the least squares fits of the data, are 51 g VOC/press cleaning for the air return concentrations and Equation 3, and 30 g VOC/press cleaning for the Miran data and Equation 4 (see Table VII).

When estimated hourly emissions based on the average of all six monitoring locations and Equation 4 were compared with cleaning frequency, the same pattern was compared as indicated in Figures 5 and 6, and an emission factor of about 30. In order to define the range of emission rates and factors, the authors developed a number of cases with different assumptions (also shown in Table VII). The maximum value of 70 g VOC/press cleaning was derived by using the average of all six hourly concentrations as the exit concentration in Equation 3. This case emphasized the higher concentrations, i.e., the three sites immediately adjacent to the presses. However, the authors believe the most representative results are those using the air return concentration in Equation 3 (the first case in Table VII), and the Miran measurements in Equation 4 (the third and fourth cases in Table VII), because these cases have the most internal consistency. This agreement between emission factors derived from different data sets and models gives considerable confidence in the validity of the emission rates and emission factors.

With reference to Figure 5, it is also of interest that the high emission point at 4 press cleanings/hr occurred while an activity additional to press cleaning was taking place, i.e., small bottles were being filled with solvent from gallon jugs. From the association between emissions and cleaning of Figure 5, the authors estimated that this transfer activity caused an additional emission of about 700 g/hr of VOC.

The VOC emissions were not strongly associated with number of sheets printed, although this was an anticipated relationship. This is likely due to the typical cylinder roll cleaning pattern for sheetfed offset printing, the length of the print jobs, and whether work extended over more than one day. Typically there were 1–3 jobs/press each day, although some of these were continuations of jobs from the day before, or were continued to a subsequent day. However, regardless of whether a job was to be continued on a subsequent day, the presses typically were cleaned with solvents at the end of the day, and usually the ink fountain was cleaned and new ink added the next morning. This cleaning pattern, characterized by a rise in solvent release at the end of the day, is shown quite clearly in Figure 4. These same activities also took place between jobs, and additional roll cleaning occurred during the jobs but was not related specifically to amount of production. On a monthly or annual basis, it is suspected that solvent use and VOC emissions are likely to be

TABLE V. Comparison of Emission Rate with Estimated Solvent Usage

	Estimated Release Rate, kg/Day					
	VOC	*Hexane*	*Toluene*	*Ethylbenzene*	*Xylenes*	*Aromatic C9s*[A]
Emissions based on average air return concentration, make-up air rate, and Equation 3	4.7	0.11	1.5	0.02	0.07	1.0
Emissions based on operator estimates of weekly usage and measured solvent composition for each line[B]	7.4	0.06	0.90	0.27	0.26	2.3

[A] Total of n-propyl benzene, o- and p-ethyl toluene, and 1,3,5-, 1,2,4-, and 1,2,3-trimethyl benzene

[B] Usage data from Table IV; compositions are from Table II except for Step 1 and Step 2 solvents. Individual analyses were available for these solvents for each line and were used, rather than the average value shown in Table II, to calculate inventory emissions.

TABLE VI. Source Activities

		Line 1		Line 3		Line 4		Duplicator 1		Duplicator 2	
Time of Observation	Cumulative Time, hr	Sheet Count	Number of Solvent Cleanings	Sheet Count	Number of Solvent Cleanings	Sheet Count	Number of Solvent Cleanings	Sheet Count	Number of Solvent Cleanings	Sheet Count	Number of Solvent Cleanings
12/17/91											
8–9	8	1135	2		2	320	1	5081		730	1
9–10	9	1100		1489	2	576	4	540	1	7200	1
10–11	10	3400		1954		282	3	378	2	3135	1
11–12	11		1	3252		252				3243	1
12–13	12			643		252				3243	
13–14	13			643		252	1	3000	1	2754	3
14–15	14			643	1	252	2		1	2723	1
15–16	15		2		4	42	4		3		2
16–17	16										
17–18	17										
12/18/91											
8–9	32		2	2259	1			1000		252	
9–10	33	3373		672	1	2289		1000	1	805	
10–11	34	1572		672	2	2676	1			1972	2
11–12	35			897	1				3	6970	
12–13	36			2542		2500				1663	
13–14	37		1	763							5
14–15	38				7		5			1550	4
15–16	39				2				1		1

related to total number of sheetfed offset jobs, but it was not possible to test this hypothesis because of the limited duration of the test. As a reference, the ratios of overall emissions to source activities for the 12 hours monitored were 431 g VOC/press job and 153 g VOC/10^3 sheets printed.

The relationship between emissions and press cleaning is also of interest because another study of an offset printing shop reported an association between plate changes and personal exposure of printers to VOC.(2) Solvent cleaning always takes place during plate changing, although, as noted above, other periods of intensive press cleaning also will occur. The exposure relationship determined in Reference 2 does include considerable variability that might have been due to exposures during cleaning intervals other than plate changing.

CONCLUSIONS

An advantage of using emission factors is that they provide a common basis on which to rate control priorities. They can be used in predictive model analysis for estimating workroom concentrations and are potentially useful in estimating personal exposures. Although the installation tested did not have local exhaust control systems, emission factors also provide a method to quantitatively evaluate control efficiency of such systems, and a basis for planning and implementing maintenance procedures.

The emissions factor approach removes the effect of the particular interior space in which the data are collected. In this case the authors determined the emission rates from general ventilation measurements and the measured area concentration pattern

TABLE VII. VOC Emission Rates and Emission Factors

Model	Average Emission Rate g/hr	Emission Factor g/Press Cleaning
Experimental Mass Balance (charcoal tube concentration at air return; Equation 3; N = 12)	467	50.7
Experimental Mass Balance (average hourly charcoal tube concentration based on all six measurement sites; Equation 3; N = 12)	608	69.7
Completely Mixed Space (Miran VOC equivalent concentration at workbench and experimental value for k; Equation 4; N = 18)	221	29.5
Same hours as for charcoal tube samples, N = 12	267	33.2
Completely Mixed Space (average hourly charcoal tube concentration based on all six measurement sites; C_s from Miran VOC equivalent concentration at workbench; and experimental value for k; Equation 4; N = 12)	235	29.2

in the space transformed with a mass balance model. The measurements were taken while production was taking place, which allowed systematic description of variability in the emission rate. And by relating emissions to source activity the authors developed an emission factor for VOC release of 30–51 g VOC/press cleaning.

The application of this method also may have more general implications for the printing industry and for other surface coating operations. Presently these types of processes, characterized by significant uncontrolled and frequently unquantitated fugitive emissions, are required to be surrounded by a temporary total enclosure (TTE) for the purpose of determining VOC emissions.(11,12) In this study the emission rate was determined without recourse to a TTE and without interfering with worker activities, increasing worker exposure, or increasing safety and explosion hazards.(13,14)

If we use the emission rate of 467 g VOC/hr calculated previously and assume 10 hours/work day (as indicated in Figure 4), and 250 days/year, the annual emissions become

$$\frac{\mathrm{kg_{voc}}}{\mathrm{year}} = 467\,\frac{\mathrm{g_{voc}}}{\mathrm{hr}} \times \frac{10\ \mathrm{hr}}{\mathrm{day}} \times \frac{250\ \mathrm{days}}{\mathrm{year}} = 1167\,\frac{\mathrm{kg}}{\mathrm{year}}\left(\sim 1\,\frac{\mathrm{T_{voc}}}{\mathrm{year}}\right).$$

In addition, for this particular print shop, the six-color press was operated in an adjacent room. While not part of this test, some preliminary measurements were made of exhaust air concentrations and flow rates and of solvent usage. The total emissions from this single large press appeared to be at least as great as the total from the space tested.

Although the printing shop described here was small, a majority of printing installations are of this size. About half of all printing in the United States is carried out on offset presses. Eighty-five percent of offset shops employ fewer than 20 persons, and almost 50% have fewer than 5 employees.(15) Based on the authors' experience, small plants are much less likely to have local exhaust capability, which exacerbates workplace exposures to benzene and other toxic materials. In addition, the estimated emissions of 1 T/year or more of VOC from each such shop constitute a significant contribution as ozone precursors, and also of hazardous air pollutants such as toluene and xylene.

ACKNOWLEDGMENTS

The authors appreciate the contributions of the other students who participated in this test, Ruth Kerzee and Paul Sullivan, as well as the support of the print shop at which this study was carried out. And they would like to thank the anonymous reviewers for their insightful comments on the first draft of this paper.

REFERENCES

1. **Bender, J., N. Ho, D. Johnson, F. Little, and W. Schaeffer:** Sheet-fed offset printing. In *Air Pollution Engineering Manual,* A.J. Buonicore and W.T. Davis, eds. New York: Van Nostrand Reinholt, 1992. pp. 389–392.
2. **Hansen, D.J. and L.W. Whitehead:** The influence of task and location on solvent exposures in a printing plant. *Am. Ind. Hyg. Assoc. J. 49*:259–265 (1988).
3. **Ovrum, P., M. Hultengren, and T. Lindquist:** Exposure to toluene in a photogravure printing plant. *Scand. J. Work. Environ. Health 4*:237–245 (1978).
4. **Kalliokoski, P.:** Estimating long-term exposure levels in process-type industries using production rates. *Am. Ind. Hyg. Assoc. J. 51*:310–312 (1990).
5. **Franke, J.E. and R.A. Wadden:** Indoor contaminant emission rates characterized by source activity factors. *Environ. Sci. Technol. 21*:45–51 (1987).
6. **Gressel, M.G., W.A. Heitbrink, J.D. McGlothlin, and T.J. Fischbach:** Advantages of real-time data acquisition for exposure assessment. *Appl. Ind. Hyg. 3*:316–320 (1988).
7. **Wadden, R.A. and P.A. Scheff:** *Indoor Air Pollution: Characterization, Prediction, and Control.* New York: Wiley, 1983. p. 205.
8. **American Society for Testing and Materials (ASTM):** *Designation E1186–87: Practice for Air Leakage Site Detection,* vol. 4.07. Philadelphia: ASTM, 1987.
9. **Wadden, R.A., D.I. Baird, J.E. Franke, P.A. Scheff, and L.M. Conroy:** Ethanol emission factors for glazing during candy production. *Am. Ind. Hyg. Assoc. J. 55*: 343–351 (1994).
10. **Wadden, R.A., P.A. Scheff, J.E. Franke, L.M. Conroy, and Xiao-Min Yu:** "Measurements of solvent and lead release in a microcircuit and production facility." Paper presented at the American Industrial Hygiene Conference and Exposition, Boston, MA, June 1992.
11. **Edgerton, S.W.:** "Emphasis on containment: EPA's permanent total enclosure criteria and temporary total enclosure test procedures." Paper presented at the 85th Annual Meeting of the Air and Waste Management Association, Kansas City, June 1992.
12. **Edgerton, S.W., J. Kempen, and T.W. Lapp:** *The Measurement Solution: Using a Temporary Enclosure for Capture Efficiency Testing.* [EPA-450/4–91–020] Research Triangle Park, NC: U.S. Environmental Protection Agency, August 1991.
13. **Warlick, T.D.:** "Permanent total enclosures within the printing industry: a company's review of employee comfort factors." Paper presented at the 86th Annual Meeting of the Air and Waste Management Association, Denver, CO, June 1993.
14. **Lukey, M.E.:** "Total permanent enclosures for the surface coating industry." Paper presented at the 85th Annual Meeting of the Air and Waste Management Association, Kansas City, June 1992.
15. **Ramus, C.A.:** *Use Cluster Analysis of the Printing Industry.* Washington, D.C.: Office of Pollution Prevention and Toxics, U.S. Environmental Protection Agency, May 26, 1992.