Title
THE CONTROL OF FORMALDEHYDE IN INDOOR AIR BY AIR WASHING

Authors
Pedersen, B.S.
Fisk, W.J.

Publication Date
1984-03-01

LBL-17381
UC-41 c.2

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

APPLIED SCIENCE DIVISION

THE CONTROL OF FORMALDEHYDE IN INDOOR AIR
BY AIR WASHING

B.S. Pedersen and W.J. Fisk

March 1984

APPLIED SCIENCE DIVISION

Prepared for the U.S. Department of Energy under Contract DE-AC03-76SF00098

DISCLAIMER

LBL-17381
EEB-Vent 84-17

THE CONTROL OF FORMALDEHYDE IN INDOOR AIR BY AIR WASHING

Brian S. Pedersen and William J. Fisk

Building Ventilation and Indoor Air Quality Program
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

March, 1984

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Buildings and Community Services, Buildings Division and the Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness, Office of Environmental Safety and Health, Office of Environmental Analysis of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the U.S. Environmental Protection Agency, Office of Research and Development.

Although the research described in this article has been funded in part by the U.S. Environmental Protection Agency (EPA) through Interagency Agreement Number AD-89-F-2A-062 to the Department of Energy, it has not been subjected to EPA review and therefore does not necessarily reflect the view of EPA and no official endorsement should be inferred.

ABSTRACT

Formaldehyde is an indoor air pollutant that is present in significant concentrations in many indoor environments, particularly residences. One potential energy efficient control technique for indoor formaldehyde which has not been previously evaluated is removal of airborne formaldehyde by absorption in water, also referred to as air washing. This technique may be suitable for use in residential, commercial, and industrial indoor environments.

A mathematical model of an air washer for formaldehyde control is presented and a laboratory investigation of this technique is described. Two full-scale experimental air washers were designed, fabricated, and tested under a variety of controlled conditions, including constant inlet formaldehyde concentration. The air washers consisted of air-solution contact arrangements through which air was forced by a fan. A small amount of the washing water was continuously replaced to prevent its saturation with formaldehyde. The air washer designs incorporated a refrigeration cycle to control the humidity of the outlet airstream.

Airflow rates for the tests were 100-160 ℓ/s and inlet formaldehyde concentrations were 80-480 ng/ℓ. With water replacement rates 1.7-7.9 ℓ/hr., the formaldehyde removal efficiency of the first air washer was 0.36-0.47. The second air washer had formaldehyde removal efficiencies of 0.30-0.63 with water replacement rates of 0.5-2.3 ℓ/hr. The formaldehyde removal efficiencies were affected by the water replacement rates, air flow rates, inlet airstream formaldehyde concentration, and the design of the air-solution contact arrangements. Based on experimental results and the mathematical model, we discuss the impact of these various parameters on air washer efficiency. The power consumption for an air washer with a 140 ℓ/s flow rate is predicted to be 1500-1800 W. The energy consumed by the refrigeration cycle can be delivered either to the indoor space, thus reducing the heating load of the building, or rejected to outdoors, thus providing cooling indoors. Results show that an air washer which has an acceptable water requirement can effectively remove formaldehyde from indoor air. The energy requirements could be acceptable in situations where most of the energy consumed provides usable heat or cooling.

INTRODUCTION

Particleboard, plywood, and urea-formaldehyde foam insulation are common building materials that are manufactured from resins of which formaldehyde is a major component. These materials typically emit formaldehyde, often for extended periods of time, into the surrounding air. Since they are frequently found in the built environment in substantial quantities, their emissions can cause significant formaldehyde concentrations indoors. These elevated formaldehyde levels may be aggravated by low building ventilation rates (a desirable building energy conservation feature); however, it is most often the presence of significant formaldehyde sources indoors which is principally responsible for high indoor formaldehyde concentrations.

Because there is concern about the adverse health effects of exposure to formaldehyde and since human exposure occurs primarily indoors (National Research Council, 1981a) there has been a move to establish indoor formaldehyde standards. The American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) has recommended a 120 ng/ℓ (25^{o}C, 1 atm) maximum indoor concentration (ASHRAE, 1981). (This concentration is equivalent to 97.8 parts per billion by volume). Recent studies have, however, found that residential indoor formaldehyde levels frequently exceed this guideline (Hawthorne et al, 1983; Colombe et al, 1983). Formaldehyde concentrations above 1200 ng/ℓ have even been measured in some mobile homes (National Research Council, 1981b).

One method of insuring low indoor formaldehyde concentrations is to control the sources of formaldehyde. Source control techniques reduce or eliminate formaldehyde emissions and are probably the preferred formaldehyde control technique in the long term. Research has been directed to the development of formaldehyde-containing resin products which have low emission rates and to the development of coatings and other treatments to reduce formaldehyde release. Ammonia fumigation and indoor dehumidification have been suggested for reducing the source strength of materials in situ. In one study, a decrease in relative humidity from 70% to 30% in an environmental chamber resulted in a 50% reduction in the formaldehyde concentration of the chamber air (Andersen et al, 1975). These techniques have not been extensively evaluated, however.

A second technique for controlling indoor formaldehyde levels is ventilation. By replacing indoor air with outdoor air, which normally has a low formaldehyde concentration, formaldehyde is removed from the occupied space. However, because formaldehyde emission rates have been shown to increase as the indoor formaldehyde concentration is decreased, the ventilation rates required to adequately reduce formaldehyde levels in homes with strong formaldehyde sources may be very high (Berge et al, 1980). High ventilation rates are not usually desirable due to energy considerations, even when heat-recovery ventilation systems are utilized.

A third possible method of formaldehyde control is air cleaning, i.e., the removal of formaldehyde from the air. There are two major air cleaning processes suitable for indoor formaldehyde control: adsorption (including chemical adsorption) and absorption. In an adsorption air

cleaning process, formaldehyde attaches to the surface of a solid material that has a very large surface area due to the presence of microscopic pores. In a chemical adsorption process, the formaldehyde reacts chemically with the adsorbent. The results of limited studies with commercially available adsorbent materials have indicated that adsorbent air cleaning systems were capable of reducing indoor formaldehyde concentrations but that the materials quickly became saturated and required replacement (A.D. Little, 1981; Eriksson, Johansson, and Svedung, 1981). Further studies are needed to determine the costs of such systems.

Absorption air cleaning, also referred to as air washing, removes gaseous pollutants by dissolution in a washing solution. An air washer is a device which consists of an air-solution contact arrangement through which air is forced by a fan. As formaldehyde-contaminated air and the washing solution come into contact, formaldehyde may be dissolved into the solution. The potential of air washing as an indoor formaldehyde control technique has not, to our knowledge, been previously investigated but it is potentially suitable for use in residential, commercial, and industrial indoor environments.

To investigate the feasibility of air washing for indoor formaldehyde control we have designed and fabricated two air washers and evaluated their performance with the aid of an air cleaner test system. In this report we present a discussion of air washer design considerations, a description of the experimental air washers and the method of evaluating their performance, the results of tests of each air washer in which the effects of various factors on performance were examined, and a comparison of ventilation and air washing as formaldehyde control techniques.

AIR WASHER DESIGN CONSIDERATIONS

The choice of washing solution to be employed in an air washer is a primary design consideration. Water has been chosen as our washing solvent for two major reasons. First, water has a very high capacity for dissolved formaldehyde. Second, to prevent the water from becoming saturated with dissolved formaldehyde, the washing solution (aqueous formaldehyde) may be simply replaced with fresh, formaldehyde-free water.

One potential problem associated with operating an air washer which employs water as the washing solvent is that contact between air and water at room temperatures may result in humidification of the indoor air. Humidification is not appropriate since, besides being generally undesirable in energy-efficient buildings, increasing indoor humidity may increase formaldehyde emission rates. By incorporating a refrigeration cycle in the air washer design, the humidity of the outlet airstream may be controlled and the device may actually operate as a dehumidifier. In the remainder of this section we discuss air washer design with respect to formaldehyde removal and humidity control.

Formaldehyde Removal

The formaldehyde removal efficiency of an air washer, ε_1, is defined to be

$$\varepsilon_1 = \frac{C_{in} - C_{out}}{C_{in}} \qquad (1)$$

where: C_{in} = concentration of formaldehyde in air at the air washer inlet (this is also normally the concentration of formaldehyde in the indoor space) and
C_{out} = concentration of formaldehyde at the air washer outlet.

There are several factors which affect this efficiency:

1) The resistance to the transfer of formaldehyde from the air into solution. This includes the resistance to transfer through the air to the surface of the washing solution and through the solution itself.

2) The interface area between the air and the solution.

3) The driving potential for mass transfer. This potential is a function of the concentration of formaldehyde in the air, the concentration of formaldehyde in the solution, and the solution and air temperature.

4) The flow rate of air through the air washer.

5) The operating configuration of the air washer.

The relationship between these parameters and the formaldehyde removal efficiency can be represented by a simple theoretical model. Figure 1 is a schematic of the control volume employed for derivation of the one-dimensional model. The formaldehyde mass balance equation for the element shown is

$$QC(x) - Q\left[C(x) + \left[\frac{dC}{dx}\right]dx\right] = [C(x) - C_e]h_d\left[\frac{A}{L}\right]dx \qquad (2)$$

where: Q = volumetric air flow rate,
$C(x)$ = concentration (mass/volume) of formaldehyde in air in a plane located a distance x from the air washer inlet,
C_e = concentration of formaldehyde in air that would be in equilibrium with the washing solution (i.e., vapor pressure of formaldehyde above solution at equilibrium),
h_d = mass transfer coefficient,
A = total air-solution interface area, and
L = length of air washer in the x direction.

The term C_e accounts for the concentration of formaldehyde in the washing solution. In the experimental air washers the washing solution was recirculated through the air. Thus in deriving Equation 2, we have assumed that the solution is well-mixed so C_e is independent of x. We have also assumed that the increase in C_e during each pass through the airstream is negligible, i.e., the increase in the washing solution's formaldehyde vapor pressure during each pass through the airstream is small compared to the total formaldehyde vapor pressure of the solution.

Equation 2 may be solved for C(x) and, from the resulting expression, the outlet formaldehyde concentration determined:

$$C_{out} = C(x=L) = C_{in} \exp(-h_d A/Q) + C_e \left\{1 - \exp(-h_d A/Q)\right\} \tag{3}$$

Then, from Equation 1, the formaldehyde removal efficiency is

$$\varepsilon_1 = \left\{1-\exp\left[-h_d \left[\frac{A}{Q}\right]\right]\right\}\left[1- \frac{C_e}{C_{in}}\right] \tag{4}$$

This expression relates the formaldehyde removal efficiency to the factors discussed previously.

As may be seen from Equation 3, the minimum value of C_{out} is C_e (for $C_{in} > C_e$). Since C_e limits the formaldehyde removal efficiency, it is useful to define a second, "air washer device" efficiency which is independent of C_e,

$$\varepsilon_2 = \frac{C_{in} - C_{out}}{C_{in} - C_e} \tag{5}$$

Again, using the expression for C_{out}, we have

$$\varepsilon_2 = 1 - \exp[-h_d(\frac{A}{Q})] \tag{6}$$

This device efficiency is also the first term in the formaldehyde removal efficiency expression (Equation 4). The second term in Equation 4 incorporates the effect of the driving potential for mass transfer on formaldehyde removal efficiency.

Values of the mass transfer coefficient, h_d, were not calculated as part of the air washer design process. To insure a reasonable device efficiency, and, thus, formaldehyde removal efficiency, we designed air washers with a large air-solution interface area.

The equilibrium formaldehyde concentration of the solution, C_e, was considered prior to the design of the air washer. An ideal relationship, Henry's law, states that the concentration of a solute in the gas phase above a dilute solution at equilibrium is directly proportional to the concentration of the solute in solution. Even though formaldehyde undergoes hydration reactions on dissolution in water (to form methylene glycol ($CH_2(OH)_2$) and, as the dissolved formaldehyde concentration is increased, higher order polyoxymethylene glycol ($HO(CH_2O)_nH$) polymers) experimental evidence indicates that Henry's law holds for dilute aqueous solutions. (Our experience has indicated that these hydration and dehydration reactions are essentially instantaneous so the kinetics of the reactions can be neglected in the model.) Thus,

$$C_e = K(T)\ C_s \tag{7}$$

where: $K(T)$ = proportionality constant dependent on temperature and
C_s = total concentration of formaldehyde in the solution (both hydrated and unhydrated states).

Anthon, Fanning, and Pedersen (1984) have calculated an expression for K(T) from data for dilute solutions,

$$K(T) = 0.97\exp[24.33 - 6560/T], \left[\frac{ng/\ell}{mg/\ell}\right] \tag{8}$$

where T is the absolute temperature, (K). From Equation 8 it can be seen that K(T) decreases with decreasing temperature, thus, the capacity of water for formaldehyde is greater at low temperatures. For example, the values of K(T) (and the corresponding value of C_e) decrease by a factor of approximately three for a temperature decrease from 20°C to 5°C.

At steady-state operating conditions, the concentration of formaldehyde in the solution, C_s, will depend on the rate at which formaldehyde is removed from the air and the rate at which the solution is replaced with formaldehyde-free water, i.e.,

$$C_s = \frac{\varepsilon_1\ C_{in}\ Q}{R} \tag{9}$$

where R is the solution replacement rate. The solution replacement rate needed to maintain a particular value of C_e is directly proportional to the value of K(T). Because of the dependence of K(T) on temperature, there is considerable advantage to maintaining low solution temperatures in order to reduce water requirements. Reduced solution temperatures are also useful for humidity control of the air washer

outlet airstream as is discussed in the next section.

Humidity Control

It is desirable for an air washer to both maintain a low indoor humidity and remove formaldehyde because formaldehyde emission rates are generally lowered by indoor humidity reductions. The humidity of the air at the outlet of an air washer is a function of the temperature at which contact between the air and water occurs. Contact between the air and water at room temperatures would result in high outlet humidities. Low outlet humidities may be achieved by contact at below-room temperatures.

Contact between air and water at less than the ambient temperature may be accomplished either by cooling the washing solution, and consequently the air, using a liquid chiller, or by cooling the air with an air conditioner prior to solution contact so that the air will, in turn, cool the solution. The heat produced by the refrigeration cycle may be used indoors during the heating season and, thus, reduce the building heat load. Alternatively, the heat may be rejected outdoors so that the unit will act as an air conditioner.

Equipment availability and design simplicity led us to choose to cool the air for the experimental air washers. The air washers were configured so that the heat produced by the refrigeration cycle was returned to the air downstream of the air-solution contact arrangement.

EXPERIMENTAL

In this section we describe the two experimental air washers, the experimental apparatus, the testing procedure, and the tests performed.

Experimental Air Washer Design

Both air washers utilized the same case to hold the air-solution contact arrangements and additional components that were common to each air washer. The insulated, stainless steel case, as shown in Figure 2, included a chamber for air-solution contact (0.71 m x 0.56 m high x 0.56 m wide) and a sump (30 ℓ capacity). The evaporator coil of the 4.0 kW (output) refrigeration system was mounted upstream of the air-solution contact chamber and the condenser coil was mounted downstream. The refrigeration cycle was fitted with a hot gas bypass system to control evaporator refrigerant pressure and thus, the temperature of the air entering the contact chamber. This control was adjusted to minimize the air temperature without causing ice build-up on the evaporator. Washing solution was removed from the sump by a constant-flow, adjustable-rate piston pump. Fresh make-up water was provided by a city water connection to the case through a float valve which maintained a constant solution level in the sump.

The two air washers were distinguished by their air-solution contact arrangements. The contact arrangement for Air Washer No.1 consisted of either three or four rotating mats such as the one shown in Figure 3a. The airstream passed through both thicknesses (0.5 cm each) of each

porous foam mat. The mats were maintained wet by rotation through the solution in the sump. Baffles at the top and side of the mats minimized the amount of air that bypassed the wetted surfaces. Air Washer No. 2 was based on a commercially available mass transfer media (Munters, Model GS XF 6560/15) comprised of stacked corrugated sheets of nonporous glass fiber material that were arranged vertically in packs (Figure 3b). A pump continuously circulated solution from the sump through holes in the top of solution distribution pipes located above the media. The resulting jets impinged on a plate and the solution dripped down onto the media, spread over the surfaces, and drained back to the sump. In the unit tested, the air flowed through two 30 cm deep packs of the mass transfer media. Four water distribution pipes and a 60 W (output) water circulation pump were used. Again, baffles were employed to prevent significant amounts of air from bypassing the wetted surfaces.

Experimental Apparatus

The formaldehyde removal performance of the experimental air washers was evaluated by supplying an airstream with a controlled formaldehyde concentration to the air washer and measuring the inlet and outlet formaldehyde concentrations. The test system (including the formaldehyde measurement apparatus) is only briefly described here but is discussed in detail by Pedersen and Fisk (1984). The gaseous formaldehyde was introduced to the airstream by continuous evaporation of a methanol-free aqueous formaldehyde solution that was delivered by a syringe pump. A blower supplied the temperature- and humidity-controlled airstream (70-160 ℓ/s) to the air washer through a duct (15 cm diameter). The formaldehyde concentration of the air was measured by drawing a sample airstream through chilled, water-filled impingers and subsequently analyzing the water by the modified pararosaniline method (Miksch et al, 1981). This integrating formaldehyde measurement system was calibrated before and after the air washer tests with a formaldehyde calibration system (Geisling, Miksch, and Rappaport, 1982). The air flow rate through the air washer was measured with a calibrated orifice plate mounted in the duct upstream of the air washer (American Society of Mechanical Engineers, 1971).

Air temperature was measured at the air washer inlet and outlet with calibrated thermistor-based temperature sensors (Yellow Springs, Model 705). The output signal of the sensors was recorded by chart recorders and their output was regularly compared with precision thermometers. The air humidity was similarly measured and recorded. The humidity sensors were either a calibrated hygroscopic-type (Yellow Spring, Model 9102) or calibrated capacitance-type (Humicap, Model HMP 23U). Humidity sensor outputs were compared with wet and dry thermometer bulb measurements on a regular basis.

Test Procedure

The test procedure was designed to evaluate the air washers under steady-state operating conditions. Since the air washers contained a large volume of water they had a considerable capacity for storing formaldehyde. When the air washers were started with formaldehyde-free water in the sump, the formaldehyde removed from the air will cause the

concentration of dissolved formaldehyde in the washing solution to increase. At steady-state the formaldehyde concentration in the solution will be high enough so that the rate of formaldehyde removal from the air (by dissolution in the solution) equals the rate at which dissolved formaldehyde is removed from the sump by the continuous solution replacement process. To allow the concentration of formaldehyde in the washing solution to increase to its steady-state value, the air washer was first operated for a period of time, ranging from 4 to 12 hours, with a constant inlet formaldehyde concentration but without any replacement of washing solution. The actual test was then initiated by starting the measurements of formaldehyde concentration in air and the solution replacement process. Typical test lengths were 8 to 16 hours; this length was generally required to assure accurate measurements of formaldehyde concentration.

A sample of washing solution was drawn from the sump at the beginning and end of each test and its formaldehyde concentration determined, also by the pararosaniline method mentioned earlier. These measurements permitted us to determine if the air washer was operating at steady-state and also made possible corrections of the measured formaldehyde removal efficiencies for tests performed when steady-state had not been attained.

Tests Performed

For tests of both air washers, relevant parameters were varied from test to test so that their impact on air washer performance could be assessed. The parameters varied included inlet formaldehyde concentration, air flow rate through the air washer, solution replacement rate, and air-solution interface area. The controlled inlet air humidity was also varied for tests of Air Washer No.1; a low inlet air humidity was maintained for all tests of Air Washer No. 2. The inlet air temperature was controlled at 20.0 ± 0.5 ^{o}C (maximum deviation) for all tests.

To demonstrate that the materials from which the air washers were fabricated did not, at steady-state, remove formalehyde from the air, background tests were run with each air washer. To conduct these tests, the washing solution was drained from the air washers and the refrigeration cycle was not operated.

Two additional tests were performed to determine the formaldehyde removal capability of air dehumidifiers which condense water vapor on the cold evaporator coil of a refrigeration system. For the first of these tests the air washer evaporator coil served as the dehumidifier. For the second test a commercially-available room dehumidifier (White-Westinghouse, Model ED358D) was mounted in the air cleaner test system.

DATA ANALYSIS

The formaldehyde removal efficiencies of the two experimental air washers and of the two simple dehumidifiers were calculated for each test from Equation 1. These efficiencies, however, do not necessarily represent the formaldehyde removal efficiencies of the air washers when

operating at steady-state . Despite our efforts to achieve a steady-state formaldehyde concentration in the washing solution (steady-state operation) prior to initiating formaldehyde concentration measurements, the formaldehyde concentration of the solution increased during most of the tests. The concentration increases indicate that the average C_e, the equilibrium formaldehyde concentration above the solution, was lower than would be expected during steady-state operation. Consequently, the measured values of ε_1 were higher than would be expected during steady-state operation. (For two tests C_e was slightly higher than expected at steady-state causing ε_1 to be low.) To compensate for this inaccuracy, we corrected the experimental results by applying the theoretical model. We also employed the model to calculate values of several theoretical parameters from the experimental results.

The corrected formaldehyde removal efficiencies, denoted ε_1^*, were calculated from the theoretical expression for ε_1, Equation 4. To solve this expression, the value of the mass transfer coefficient-interface area product, h_dA, was determined from Equation 3 using the average calculated value of C_e. The steady-state value of C_e, denoted C_e^*, also had to be determined. This was calculated from Equations 7, 8, and 9 using ε_1^* in place of ε_1. (This calculation required further mathematical manipulations).

Other parameters that were calculated include the device efficiency, ε_2 (from Equation 6), the corrected (steady-state adjusted) outlet formaldehyde concentration, C_{out}^* (based on C_{in} and E_1^*), the ratio $\varepsilon_1^*/\varepsilon_2$, and the effective clean air flow rate, Q_c. The ratio $\varepsilon_1^*/\varepsilon_2$ is an indicator of the impact of C_e on the formaldehyde removal efficiency. The effective clean-air flow rate is defined as the product of ε_1^* and the air flow rate, Q. This parameter represents the equivalent flow of formaldehyde-free air that is provided by an air washer. It is a particularly useful quantity for comparing the rate of formaldehyde removal by an air washer to the rate of formaldehyde removal by a given amount of ventilation.

RESULTS AND DISCUSSION

Formaldehyde Removal

The formaldehyde removal results and significant test condition data are listed in Tables 1 and 2. The formaldehyde concentrations are ng/ℓ at 25°C and 1 atm. Since the test procedure assured that the dehumidifiers were tested at steady-state conditions and, because the theoretical model does not apply, only test conditions, the measured formaldehyde removal efficiency, ε_1, and the effective clean-air flow rate, Q_c, are presented for the tests of the dehumidifiers. These same data are also presented for the two air washer background tests.

Our use of the theoretical model to correct the results of nonsteady-state tests and to calculate the various theoretical parameters can be justified. The assumptions made to derive the model clearly hold for most experiments. The design of the air washers assured that the solution in the sump was well mixed and, therefore, C_e did not change in the direction of the air flow (x direction), as was assumed.

Calculations indicate that the second assumption was also valid in most cases: the concentration of formaldehyde in the washing solution did not increase significantly as the solution passed through the air flow and so C_e may be considered to have been essentially constant as the solution passed through the air flow. Based on the results, the increases in C_e were calculated to have been less than 8% for tests of Air Washer No. 1, except tests 1-1 (18%) and 1-3 (13%). The increases in C_e were less than 2% for all tests of Air Washer No. 2.

The limitations of the model must also be realized. In particular, the model is not capable of accurately representing all relationships between variables. For example, in an actual air washer h_dA may be a function of air flow rate or washing solution circulation rate although the model does not account for these dependencies. Despite the limitations, the model can provide valuable information on the relationships between many variables and air washer performance as is demonstrated later.

Uncertainty Analysis. The measured formaldehyde removal efficiencies are based on the inlet and outlet formaldehyde concentrations. Because this efficiency is determined from a ratio of concentrations, many potential sources of error cancel out and the most significant remaining error is the imprecision in the measurements. The uncertainty in the measured formaldehyde removal efficiencies due to this imprecision (based on duplicated formaldehyde concentration measurements during each test and during calibrations) has been determined to a 5% level of significance. When combined with our estimate of the very small systematic error due to adsorption of formaldehyde in the sampling lines, the resulting uncertainty in the measured formaldehyde removal efficiencies is ±0.04 or less for Air Washer No. 1 and ±0.03 or less for Air Washer No. 2. From these uncertainties and conservative estimates of the error in other measurements, the uncertainty in the corrected formaldehyde removal efficiencies and the theoretical parameters has been determined by error propagation calculations. To make these calculations we assumed that the model was completely accurate. For tests of both air washers, the uncertainties are ±0.05 for the corrected formaldehyde removal and device efficiencies and ±8 ℓ/s for the effective clean-air flow rates. The background and dehumidifier tests had somewhat higher uncertainties in the measured formaldehyde removal efficiencies and effective clean-air flow rates. The uncertainties in the mass transfer coefficient-interface area products, h_dA, the corrected equilibrium formaldehyde concentration above the washing solution, C_e^*, and the corrected outlet formaldehyde concentration, C_{out}^*, are ±21%, ±27%, ±14% of the measured value, respectively. All these reported uncertainties are maximum values; for some tests the uncertainties were less than half of these maxima. Based on calibration data, the maximum uncertainty in the inlet formaldehyde concentrations was estimated to be ±15%.

Air Washer Test Results. The corrected formaldehyde removal efficiencies for Air Washer No. 1 ranged from 0.36 to 0.47 and the effective clean-air flow rates were from 41 to 57 ℓ/s. The solution temperature during these tests was 7.5°C to 16°C. The background formaldehyde removal test showed there was no measurable formaldehyde removal without the presence of water in the air washer, thus, all formaldehyde removal

capability may be attributed to the air washing process.

Figure 4 shows the relationship between ε_1* and Q for the 9 tests of Air Washer No. 1. The curve shown is the theoretical relationship based on the average test values of h_dA and ε_1*/ ε_2 and is not intended to accurately represent the data points. This figure shows the strong effect of the air flow rate on the formaldehyde removal efficiency.

The formaldehyde removal in tests 1-1, 1-3, and 1-7 was due in part to measured removal at the cold, wetted surface of the evaporator coil. The accuracy of the corrected efficiency and the calculated parameters for these tests is reduced because this removal process is not accounted for in the model.

For all tests of Air Washer No. 1, the values of ε_1*/ε_2 were high (0.64 to 0.95 with a mean of 0.86) because the washing solution replacement rates were high. Thus, the efficiency of this air washer was not reduced substantially by the content of formaldehyde in the washing solution. Instead, the efficiency was limited by the physical design of the air washer, i.e., limited interface area per unit air flow rate.

The calculated values of h_dA for Air Washer No. 1 varied from 62.0 to 103 ℓ/s . As the model suggests, we would expect the value of h_dA to be proportional to the number of rotating mats employed (3 or 4). While this factor most likely had some effect on h_dA, the data were insufficient to show the proportionality relationship. Several factors not accounted for by the model probably also contributed to the variations in h_dA. As mentioned above, there was formaldehyde removal by the evaporator coil during three tests. The condensate on the coil had the effect of increasing the interface area but in a manner which could not be accounted for by the model. Additionally, the tests were conducted with different air flow rates which may have affected the mass transfer coefficient and the amount of air which bypassed the mats. The available data are inadequate to allow determination of the effect of air flow rate on h_dA.

Figure 5 shows the measured and corrected formaldehyde removal efficiencies for tests of Air Washer No. 2. The corrected formaldehyde removal efficiencies for tests 2-1 through 2-7 were 0.30 to 0.63. The effective clean-air flow rates for these tests were 35 to 74 ℓ/s. These quantities were lower for test 2-8 because one-half of the mass transfer media was removed from the air washer. The measured background formaldehyde removal efficiency was an insignificant 0.02 which again indicates that virtually all formaldehyde removal is attributable to the air washing process. The solution temperature during these tests was 8 to 9^{o}C.

The performance of Air Washer No. 2 was superior to that of Air Washer No. 1. It should be noted that the similar or higher formaldehyde removal efficiencies were achieved with generally lower solution replacement rates. This was possible because the device efficiencies, ε_2, were much greater than for the first air washer.

As with Air Washer No. 1, there were variations in the calculated values of h_dA. While tests were performed at different solution circulation and air flow rates, the number of tests was inadequate to show the relationship between these factors and h_dA. For Air Washer No. 2, it was possible, however, to observe the effect of reducing the available surface area of the mass transfer media. For test 2-8, one-half of the media was removed from the air washer. As would be expected the value of h_dA calculated for this test is roughly one-half of the values calculated for tests with the same air flow rate, and the same solution circulation rate per unit of media.

In general it is not known how well the solution was distributed over the media, i.e., whether all media surfaces or only some fraction were wetted. During the tests it could be seen that the solution was more thoroughly distributed over the top of the media (by the spray from the distribution pipes) when the solution circulation rate was higher, but, according to the manufacturer of the media, an air flow adequately distributes water over the surfaces. An investigation of media characteristics and of the performance of solution distribution systems would be a valuable component of any future efforts to improve air washer design.

We did not attempt to determine the values of h_d or A separately for either air washer and so cannot compare the mass transfer coefficients or the interface areas of the two air washers.

Results of Analysis Using the Theoretical Model. While, as mentioned above, the theoretical model is relatively simple and cannot account for many complexities, further analysis using the theoretical model provides results that are useful for air washer design optimization. Figure 6, for example, shows the relationship between formaldehyde removal efficiency and solution replacement rate for various solution temperatures. The curves are for an air washer with an air flow rate of 140 ℓ/s and a device efficiency of 0.90. As the solution replacement rate, R, is increased, there is an improvement in the formaldehyde removal efficiency, ε_1. However, ε_1 is limited to 0.90 since the device efficiency is 0.90. The solution replacement rate required for ε_1 to be 0.80 is 6 ℓ/hr when the solution temperature is 2.0°C, a reasonable rate. Also shown by Figure 6 is the effect of solution temperature on solution replacement rates. The figure clearly illustrates that if water consumption is to be minimized without comprimising efficiency, air-solution contact at reduced temperatures is superior to the alternative air washing-dehumidification technique: air-washing solution contact at room temperature followed by dehumidification.

The relationship between effective clean-air flow rate and the air flow rate through the air washer for various values of h_dA is shown in Figure 7. As air flow rate increases (for an air washer with a constant h_dA), the effective clean-air flow rate asymptotically approaches the value of h_dA. However, the disadvantages of operating an air washer near its maximum possible effective clean-air flow rate are the power required to cool the air (or washing solution) and the fan power required to overcome the pressure drop through the air washer.

Dehumidifier Test Results. The results of the two dehumidifier formaldehyde removal tests are presented in Table 2. The dehumidifier for Test D-1 was the cold evaporator coil of the air washer. A commercial refrigeration cycle dehumidifier was employed for test D-2. The formaldehyde removal efficiency measured in Test D-1 was 0.33 with an inlet air relative humidity of 45% (RH). In Test D-2 the measured efficiency was 0.02 with an inlet air relative humidity of 48%. The large difference in the measured efficiencies was most likely due primarily to the large difference in wetted surface area. Since the inlet air humidities were high for these tests both coils were coated with condensate; however, the air washer evaporator coil was finned so it had a much larger wetted surface area than did the smaller, unfinned coil of the commercial dehumidifier.

The removal efficiency of a dehumidifier will be strongly affected by the inlet humidity. At low indoor humidities (30% RH at 20°C), the amount of water condensed on the coil will be small so the wetted surface area will be limited. This was observed during tests of the air washers with a 30% relative humidity at the inlet. For these tests the air washer evaporator coil was free of condensate and no formaldehyde removal by the coil was measured. These results suggest that a dehumidifier successfully maintaining a low humidity in a house will probably remove very little formaldehyde, however, as mentioned earlier, low indoor humidity limits formaldehyde source strengths. Significant formaldehyde removal by the wetted evaporator surfaces of an air conditioner appears likely when the indoor humidity is high.

Humidity Control

The measured moisture content of the air washer outlet airstreams during the air washer tests was generally higher than the desired outlet moisture content corresponding to a 25% to 30% RH at 20°C. The outlet humidity for tests of Air Washer No. 1 ranged from 25 to 45% RH (20°C) and those for Air Washer No. 2 ranged from 45 to 55% RH (20°C). The poor dehumidification performance of the experimental air washers was probably due primarily to the bypassing of air around the evaporator coil. We were unaware that air could bypass this coil until the tests were completed; correction of this problem would have been relatively simple. An additional factor that increased the outlet humidity was heat gain through the uninsulated or inadequately insulated portions of the air washer.

Power and Water Consumption

The power requirement for an air washer with an air flow rate of 140 ℓ/s and dehumidification capability has been calculated. The principle power demand is the refrigeration cycle which must meet both the sensible (temperature) and latent (dehumidification) heat loads. The sensible load was determined by assuming that the air would be cooled from indoor temperature, 20°C, to 0.5°C. The latent heat load was based on a typical generation rate of moisture indoors. This combined heat load is approximately 3300 W. Coefficients of performance for efficient refrigeration cycles of this capacity range from 2.3 to 2.9, so the heat load can be met with a 1150 to 1450 W power input. A media-type air washer

(such as No. 2) would require a solution circulation pump with, approximately, a 250 W power requirement (this pump can also serve to remove solution for solution replacement). A fan to provide 140 ℓ/s air flow through the air washer would consume approximately 75 W. This estimate is based upon the measured pressure drop of 1000 Pa at 140 ℓ/s through Air Washer No. 2 and fan product literature. The total power consumption would then be in the range 1500-1800 W. Based on the experiments performed, such an air washer could potentially have a formaldehyde removal efficiency of at least 0.80.

A removal efficiency of 0.80 would require a washing solution replacement rate of approximately 6 ℓ/h. An air washer operated year-round with a 6 ℓ/h washing solution replacement rate would require 5.2 x 10^4 ℓ/yr of water. This rate would increase the water consumption of a typical residential consumer by 14% and cost an average of $14/yr (American Waterworks Association, 1983).

Comparison of Ventilation and Air Washing

At present, ventilation is the most readily available formaldehyde control technique available for existing residences with unacceptable formaldehyde concentrations. Ventilation of indoor spaces may be provided naturally, through cracks, open windows, or other openings in a building envelope, or in a more energy-efficient manner with a mechanical ventilation system which incorporates an air-to-air heat exchanger (MVHX system). MVHX systems employ two fans, one to exhaust air from indoors and the other to supply outdoor air to the indoor space. The two airstreams pass through a heat exchanger core where heat is transferred between them (without mixing of the air); thus, during the heating season the supply air is warmed before entering the residence. Ventilation of indoor spaces can reduce the levels of other indoor-generated pollutants, as well as formaldehyde, but it may also increase the indoor levels of pollutants that are primarily generated outdoors. By comparison, an air washer, as described in this report, would probably remove only formaldehyde at a significant rate but it would not increase the rate at which outdoor pollutants penetrate to indoors.

During the heating season, natural ventilation will increase the heating load of a building by exchanging air at less than indoor temperatures with indoor air. Even when the ventilation is provided by an MVHX system, an additional heat load will be imposed on the building since these heat recovery systems are not perfectly efficient. In addition, operation of the fans will require energy. An air washer will not impose an additional heat load and, as described earlier, the energy consumed by the air washer may offset the heat load of the house.

To compare the energy requirements of natural ventilation, MVHX systems, and air washers, we performed a simple energy analysis. From data in Fisk and Turiel (1983), the operating energy requirements during a heating season for the two alternative ventilation strategies (with and without heat recovery) have been calculated for typical energy-efficient, electrically-heated single-family residences in Minneapolis, Minnesota and Chicago, Illinois. The energy required to operate an air washer for the heating season has also been calculated assuming an

1800 W power consumption. It has been assumed that the three formaldehyde control techniques would operate continuously during a seven month heating season. The ventilation and air washer effective clean-air flow rates were chosen to be 90 ℓ/s. (For an air washer with a 140 ℓ/s air flow, a 90 ℓ/s effective clean-air flow rate would be expected if the formaldehyde removal efficiency is 0.8 and the "ventilation efficiency" is 0.8. This so-called ventilation efficiency accounts for the imperfect mixing of air indoors. This factor has also been accounted for in the energy requirement calculations for the two ventilation alternatives.) The calculated operating energy requirements are listed in Table 3. The energy requirement of the MVHX system is the least of the 3 alternatives in both cities, however, this does not account for the heating load offset resulting from heat produced by the air washer.

The magnitude of the heating load offset has been determined by the following procedure. The change in the balance point temperature of a typical energy-efficient residence that is caused by operation of an air washer has been calculated from energy performance data for energy-efficient residences provided by Offermann, et al (1982). (The balance point temperature is the minimum outdoor temperature at which no heat is required from a residence's heating system.) An 1800 W air washer would reduce the balance point temperature from a typical 12.8^{o}C to 3.7^{o}C. Using weather data (Nicholson, 1978), we calculated the fraction of operating time during which the heat released by the air washer could substitute for heat normally provided by the heating system. In Minneapolis and Chicago, these fractions are 0.82 and 0.76, respectively. The net increase in the residence's energy requirement caused by operation of an air washer is, thus, significantly less than the air washer energy requirement.

From Table 3, it can be seen that of the three control strategies, air washer operation results in a significantly smaller increase in energy requirements during the Minneapolis heating season than either ventilation alternative. In Chicago the air washer also causes the smallest increase in the energy requirement, but the advantage is smaller. This energy comparison is limited to electrically-heated residences. In buildings which use forms of heating energy that are less expensive than electricity, the reduction in heating load offset caused by air washer operation is less advantageous so the other strategies may be preferred.

As during the heating season, ventilation will increase space conditioning requirements during the cooling season. An air washer, if configured appropriately, can offset air conditioning requirements. We have not calculated the energy requirements of the three control strategies during a cooling season, however, it is clear that air washing should also have an energy advantage over ventilation.

The economic feasibility of air washing has not been assessed. Fisk and Turiel (1983) have shown residential MVHX systems to be economically attractive compared to ventilation without heat recovery (from a homeowner's perspective) primarily in colder climates and in buildings heated by expensive forms of energy. While the energy requirements of an air washer may be less than MVHX systems, an air washer would probably

have higher initial and maintenance costs than an MVHX system. Further research is necessary before an accurate economic comparison can be made.

CONCLUSIONS

The results of this study show that an air washer can effectively remove formaldehyde from indoor air -- formaldehyde removal efficiencies as high as 0.63 were obtained with one of the experimental air washers tested and, based on the theoretical model, it is likely that higher efficiencies can be achieved with practical designs. Formaldehyde was removed effectively by the air washers even when the inlet concentrations were comparable to or lower than current guideline values for indoor formaldehyde concentration. Thus, an air washer with sufficient capacity could reduce indoor formaldehyde concentrations to below these guideline levels. The water requirements of an efficient air washer can be reasonable. The energy load imposed on a residence by operation of an air washer will, in some cases, be less than the energy load imposed by a mechanical ventilation system with heat recovery which has an equivalent formaldehyde removal capability. Air washing will be most attractive compared to ventilation with heat recovery when most of the energy required by the air washer provides usable heat or cooling and when the structure is heated or cooled with electricity or some other expensive form of energy. There will also be instances where an air washing process can be easily incorporated into the existing air conditioning system of a commercial or industrial building without causing a significant increase in energy demands. In such situations, air washing may be an attractive formaldehyde control measure. An air washer, as described in this report, will also reduce indoor humidities in residences that would otherwise be humid, and this reduction in humidity will in turn, lower the rate of formaldehyde emanation from building materials. While an air washer is a complicated device, it is not prohibitively complex for use in a residence.

We have not attempted to predict the impact of air washer operation on indoor formaldehyde concentrations. Further study is needed to quantify the relationships between formaldehyde source rates, removal rates, and indoor concentrations. It is likely that, in many cases, the formaldehyde source strength will increase significantly as the indoor concentration is reduced, therefore, large amounts of ventilation or air cleaning will be required to substantially reduce indoor formaldehyde concentrations. Future investigations of air washing or other air cleaning techniques for formaldehyde control should be directed toward developing air cleaners with even larger air flow rates than the units described here. Another major objective of future investigations should be to identify methods to reduce the energy required by the air washing system. Finally, study is needed to assess potential adverse effects of air washer operation.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the assistance received on this project from our LBL colleagues, principally, Lloyd Davis, who fabricated the experimental air washers; Richard Allen, Yoshiko Otonari, and Stephen Uno, for analyzing the many formaldehyde samples; and Keith Archer, who assisted with performing the tests. We thank Ray Chant, John Girman, and Bill Nazaroff for reviewing this report. And we greatly appreciate the efforts of Gayle Milligan, Edythe Dobbins, and others, who prepared the various drafts, and Moya Melody, for supervising the preparation of the technical illustrations.

This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Building Energy Research and Development, Buildings Systems Division and the Assistant Secretary for Environmental Protection, Safety, and Emergency Preparedness, Office of Environmental Analysis of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098 and by the U.S. Environmental Protection Agency, Office of Research and Development.

Although the research described in this article has been funded in part by the U.S. Environmental Protection Agency (EPA) through Interagency Agreement Number AD-89-F-2A-062 to the Department of Energy, it has not been subjected to EPA review and therefore does not necessarily reflect the view of EPA and no official endorsement should be inferred.

REFERENCES

A.D. Little, Inc. 1981. "Formaldehyde Concentration Level Control in the Air of Mobile Homes." Cambridge, Massachusetts.

American Society of Heating, Refrigeration, and Air-Conditioning Engineers. 1981. "Ventilation for Acceptable Indoor Air Quality." ASHRAE Standard 62-1981. Atlanta, Georgia.

American Society of Mechanical Engineers. 1971. Fluid Meters: Their Theory and Application. ASME. New York, New York.

American Waterworks Association. 1983. Private Communication. Denver, Colorado.

Andersen, I., Lundquist, G.R., and Molhave, L. 1975. "Indoor Air Pollution Due to Chipboard Used as a Construction Material." Atmospheric Environment 9: 1121-1127.

Anthon, D.W., Fanning, L.Z., and Pedersen, B.S. 1984. "Efficiency of Absorption of Formaldehyde by Dilute Aqueous Solutions." University of California, Lawrence Berkeley Laboratory Report, in draft. Berkeley, California.

Berge, A. et al. 1980. "Formaldehyde Release from Particleboard - Evaluation of a Mathematical Model." Holz als Roh- und Werkstoff 38: 251-255.

Colombe, S.D., et al. 1983. "Investigation of Indoor Residential Air Quality in Southern California Mobile Homes." Presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 19-24.

Eriksson, B., Johansson, L., and Svedung, I., 1980. "Filtration of Formaldehyde Contaminated Indoor Air." Presented at the Nordtest Symposium on Air Pollution Abatement by Filtration and Respiratory Protection, Copenhagen, Denmark.

Fisk, W.J. and Turiel, I. 1983. "Residential Air-to-Air Heat Exchangers: Performance, Energy Savings, and Economics." Energy and Buildings 5: 197-211.

Geisling, K.L., Miksch, R.R., and Rappaport, S.R. 1982. "The Generation of Dry Formaldehyde at PPB to PPM Levels by the Vapor-Phase Depolymerization of Trioxane." Analytical Chemistry 54: 140.

Hawthorne, A.R., et al. 1983. "Results of a Forty-Home Indoor Air Pollutant Monitoring Study." Presented at the 76th Annual Meeting of the Air Pollution Control Association, Atlanta, Georgia, June 19-24.

Miksch, R.R., et al. 1981. "A Modified Pararosaniline Method for Determination of Formaldehyde in Air." Analytical Chemistry 53: 2118-2123.

National Research Council. 1981a. "Indoor Pollutants." National Academy Press (National Academy of Sciences), Washington, D.C.

National Research Council. 1981b. "Formaldehyde and Other Aldehydes." National Academy Press (National Academy of Sciences). Washington, D.C.

Nicholson, B.J., ed. 1978. "Facility Design and Planning Engineering Weather Data." U.S. Departments of the Air Force, the Army, and the Navy, Air Force Manual 88-29. Washington, D.C.

Offermann, F.J., et al 1982. "Residential Air-Leakage and Indoor Air Quality in Rochester, New York." University of California, Lawrence Berkeley Laboratory Report LBL-13100. Berkeley, California.

Pedersen, B.S. and Fisk, W.J. 1984. "A System for Producing Large Air-streams with PPB-Level Formaldehyde Concentrations." University of California, Lawrence Berkeley Laboratory Report, in draft. Berkeley, California.

Table 1. Results of Air Washer No.1 Tests.

Test No.[1]	Air Flow Rate (ℓ/s)	Inlet [HCHO][2] (ng/ℓ)	Solution Replacement Rate (ℓ/hr)	No. of Mats	Efficiencies[3] ε_1	ε_1^*	ε_2	$\varepsilon_1^*/\varepsilon_2$	$h_d A$[4](ℓ/s)	Equilibrium [HCHO] above solution[5] Calculated (ng/ ℓ)	Corrected (ng/ℓ)	Corrected Outlet [HCHO][2] (ng/ℓ)	Effective Clean Air Flow Rate(ℓ /s)
1-1[a,b,c]	98.3	467	3.0	3	0.57	0.44	0.60	0.73	90.6	25.3	122	262	43.3
1-2[c]	101	148	1.7	3	0.55	0.41	0.64	0.64	103	19.6	51.9	87.3	41.4
1-3[b,c,d]	145	94.2	7.9	3	0.36	0.36	0.38	0.95	69.4	4.28	5.83	60.3	52.2
1-4	119	116	7.6	4	0.42	0.41	0.44	0.93	69.0	6.87	8.15	68.4	48.8
1-5	119	106	4.5	4	0.40	0.40	0.44	0.91	69.4	8.72	10.6	63.6	47.6
1-6	118	218	7.4	4	0.42	0.42	0.45	0.93	70.6	15.8	16.0	126	49.6
1-7[d]	119	222	5.7	4	0.49	0.47	0.53	0.89	90.6	17.4	25.0	118	55.9
1-8	120	250	4.1	4	0.38	0.36	0.40	0.90	62.0	17.0	25.2	160	43.2
1-9	157	360	4.1	4	0.38	0.36	0.41	0.88	83.6	33.0	47.5	230	56.5
1-B	120	294	---	4	0.00	----	----	----	----	----	----	---	0.0

NOTE: Numbered, column heading footnotes are shown on Table 2.

[a] No environmental control: inlet air temperature ≅ 23°C and solution temperature ≅ 16°C.

[b] Significant increase in C_e (equilibrium formaldehyde concentration in air above solution) as solution passed through air flow. Calculated parameter values will not be accurate.

[c] Rotating mat arrangement used permitted less air bypassing.

[d] Considerable formaldehyde removal at evaporator. Calculated parameter values will not be accurate.

Table 2. Results of Air Washer No.2 and Dehumidifier Tests.

Test No.[1]	Air flow Rate (ℓ/s)	Inlet [HCHO][2] (ng/ℓ)	Solution Replacement Rate (ℓ /hr)	Solution Circulation Rate (ℓ/min)	Efficiencies[3] ε_1	ε_1^*	ε_2	$\varepsilon_1^*/\varepsilon_2$	h_dA[4] (ℓ/s)	Equilibrium [HCHO] above solution[5] Calculated (ng/ℓ)	Corrected (ng/ℓ)	Corrected Outlet [HCHO][2] (ng/ ℓ)	Effective Clean Air flow Rate(ℓ /s)
2-1	117	269	2.3	57	0.77	0.63	0.93	0.68	304	45.4	85.4	99.5	74
2-2	117	252	2.3	23	0.68	0.56	0.81	0.69	197	40.6	76.5	111	66
2-3	160	84.6	1.7	38	0.65	0.46	0.78	0.59	242	14.6	35.3	45.7	74
2-4	116	79.7	1.4	38	0.70	0.51	0.86	0.59	226	14.7	32.5	39.1	59
2-5	116	161	2.3	38	0.72	0.60	0.84	0.71	211	22.5	47.0	64.4	70
2-6	116	102	0.66	38	0.74	0.35	0.89	0.39	257	17.8	60.5	66.3	41
2-7	116	136	0.54	38	0.63	0.30	0.77	0.39	172	24.7	84.6	95.2	35
2-8	116	159	0.72	19	0.50	0.30	0.60	0.50	105	26.5	77.5	111	35
2-B	116	143	---	--	0.02	----	----	----	----	---	--	---	2.3
D-1	122	398	---	--	0.33	----	----	----	----	---	--	---	40
D-2	63.3	241	---	--	0.03	----	----	----	----	---	--	---	1.9

1 "1-" denotes Air Washer No. 1 tests, "2-" denotes Air Washer No. 2 tests, "-B" denotes air washer background tests, and "D-" denotes dehumidifier tests.

2 [HCHO] is formaldehyde concentration in air (25°C, 1 atm.).

3 ε_1 is measured formaldehyde removal efficiency, ε_1^* is corrected formaldehyde removal efficiency, and ε_2 is device efficiency.

4 Mass transfer coefficient-interface area product.

5 Concentration of formaldehyde in air that would be in equilibrium with the solution. Calculated [HCHO] is C_e and corrected [HCHO] is C_e^* (25°C, 1 atm).

Table 3. Heating Season Energy Comparison of Ventilation and Air Washing.

		--- Energy, GJ---	
		Minneapolis, MN	Chicago, IL
Operating Energy Requirements	Natural Ventilation	47.7	34.9
	MVHX System[a]	14.9	11.6
	Air Washer	33.0	33.0
Heating load offset due to Air Washer operation		27.0 (0.82)[b]	25.0 (0.76)[b]
Net energy requirement for Air Washer operation		6.0	8.0

[a] Mechanical ventilation system with an air-to-air heat exchanger.

[b] Fraction of air washer energy consumption that will offset building heat load.

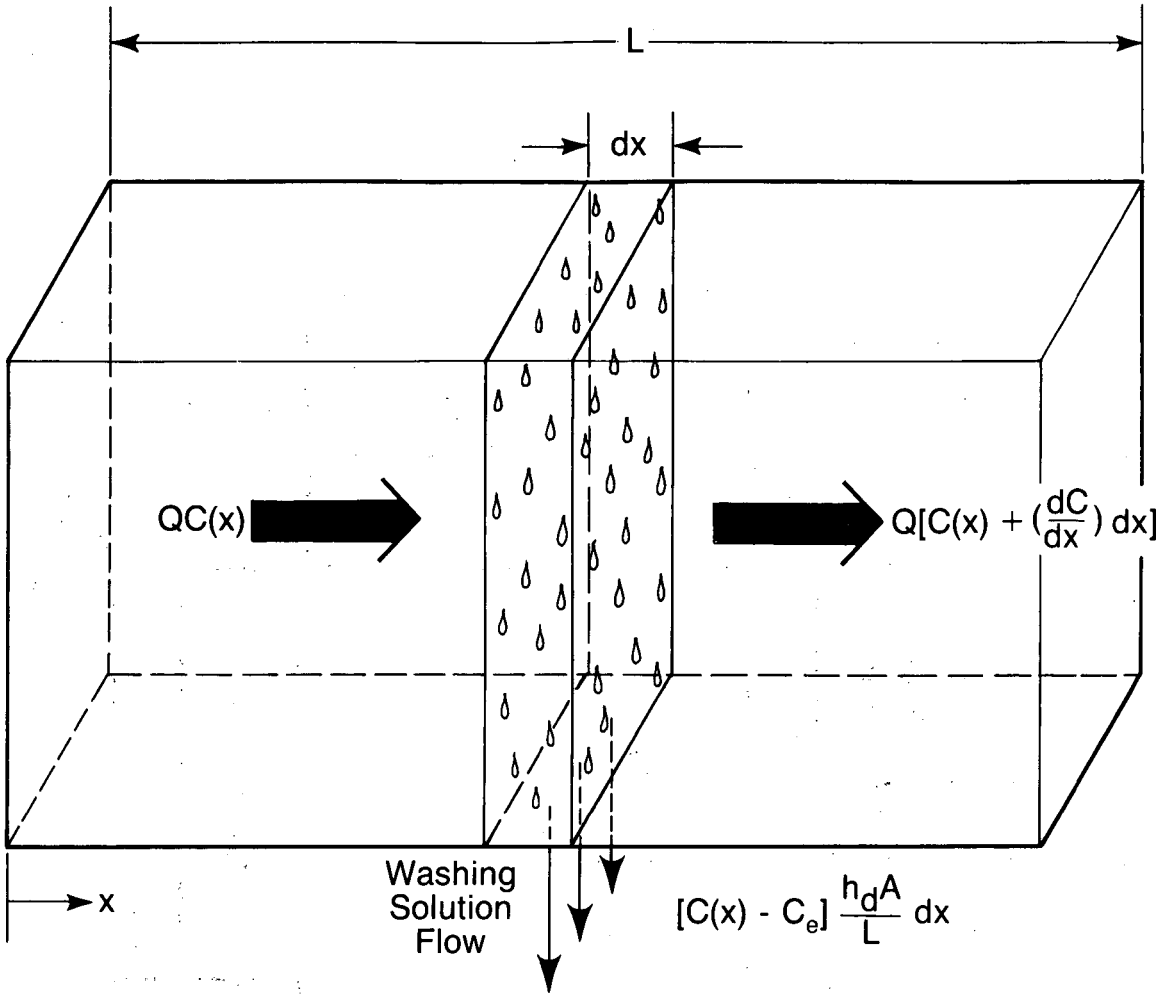


Figure 1. Control volume employed for derivation of air washer model. Symbols: Q is the air flow rate, C(x) is the formaldehyde concentration in air at position x, C_e is the concentration of formaldehyde that would be in equilibrium with the washing solution, h_d is the mass transfer coefficient, and A is the total air-solution interface area.

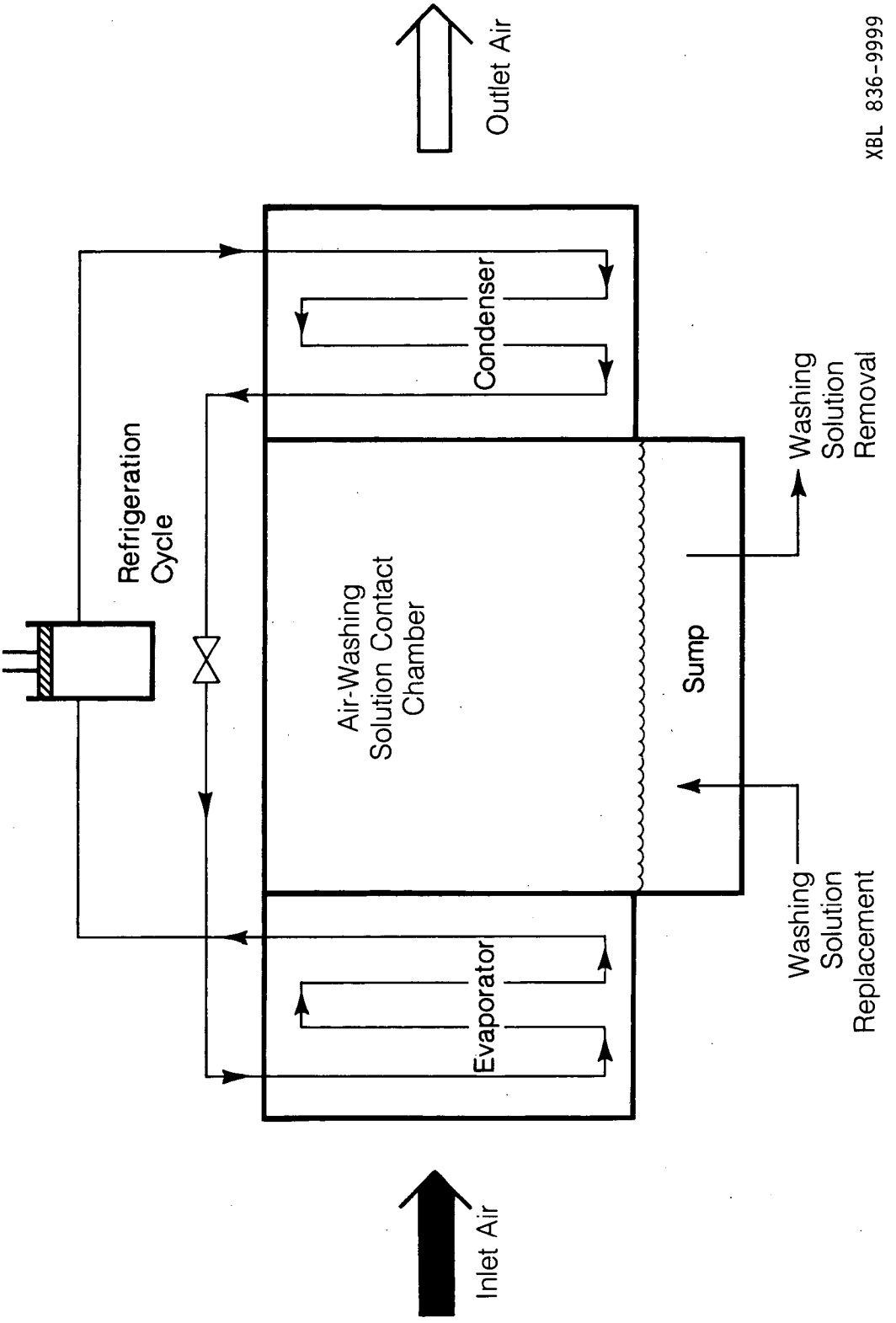


Figure 2. Schematic of air washer case. The air-solution contact arrangements are shown in Figures 3a and 3b.

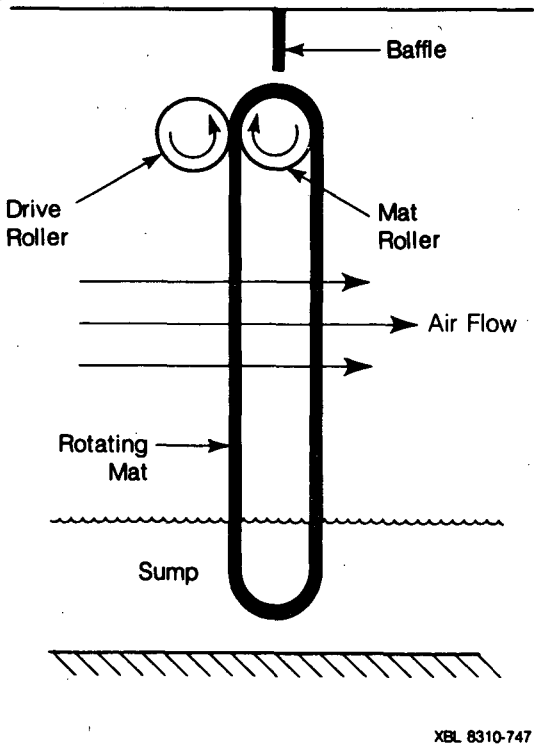


Figure 3a. Air-solution contact arrangement for Air Washer No. 1. Three or four rotating mats were employed simultaneously.

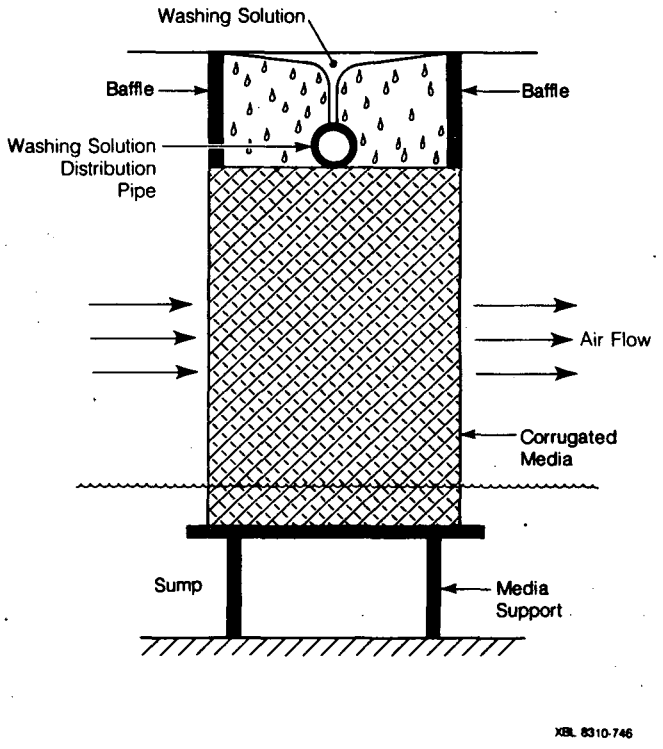
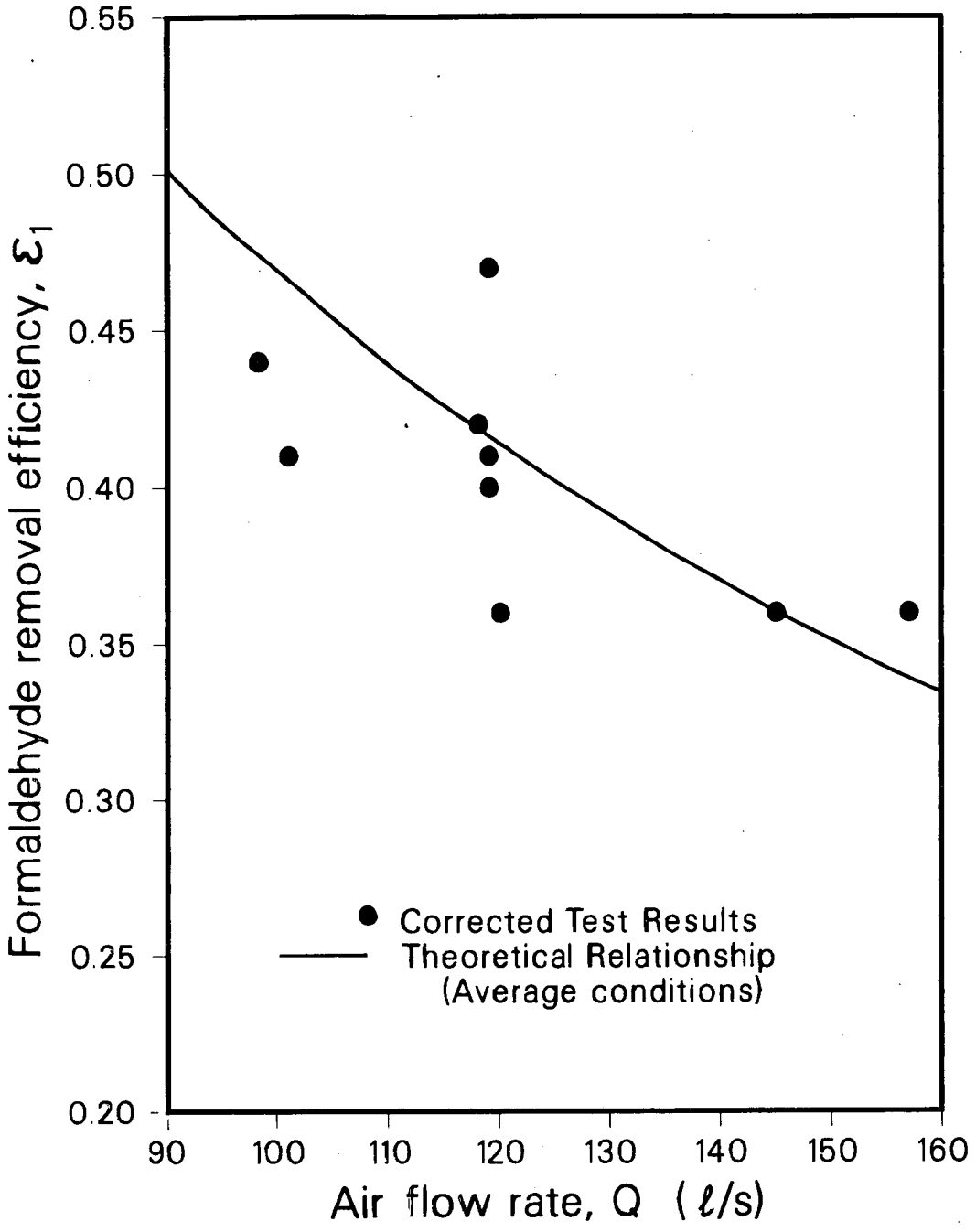


Figure 3b. Air-solution contact arrangement for Air Washer No. 2. During most tests, two packs of corrugated media were employed with four solution distribution pipes.



XCG 8310-7258

Figure 4. Corrected formaldehyde removal efficiency versus air flow rate for Air Washer No. 1. The theoretical relationship shown is for average test conditions and is not intended to accurately represent the data points.

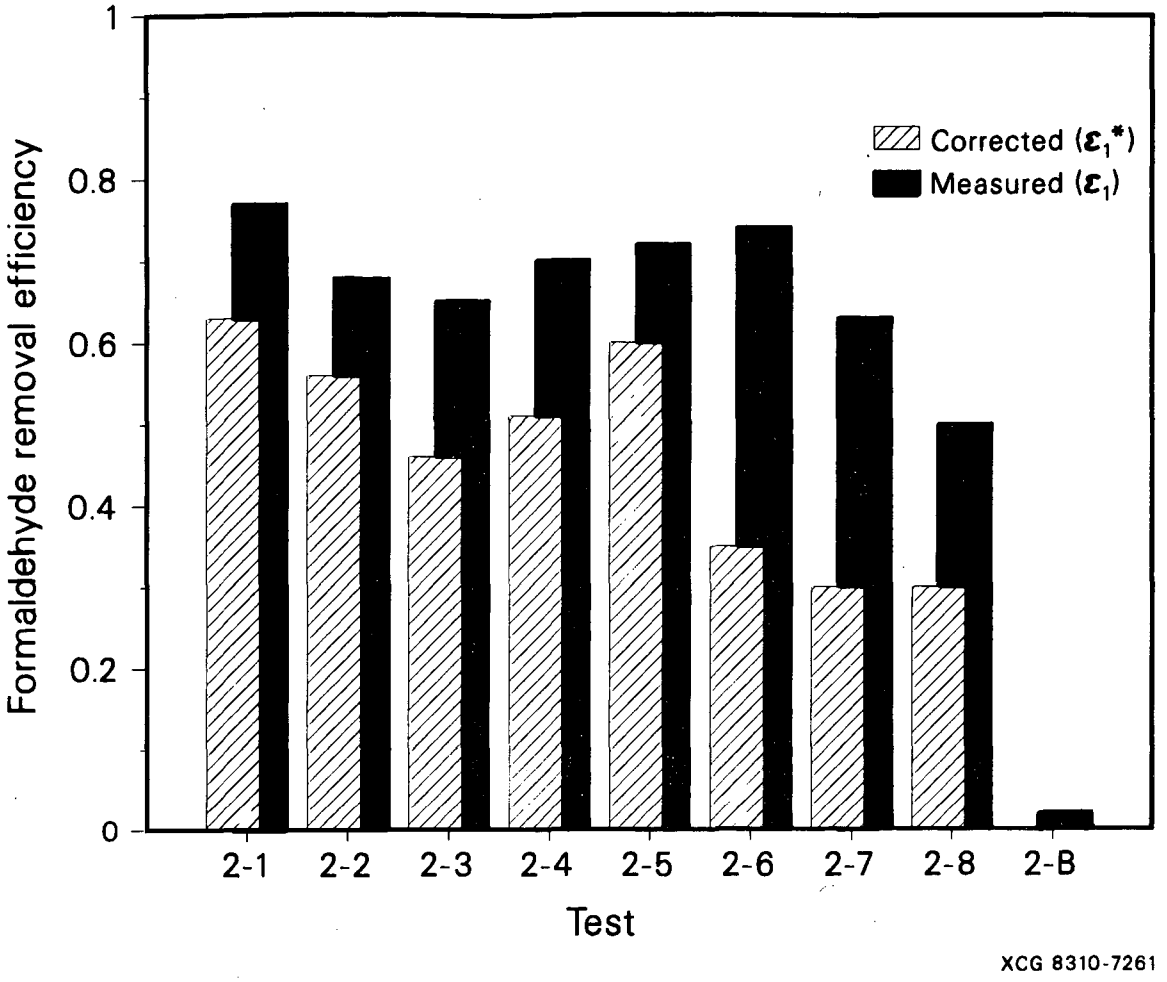
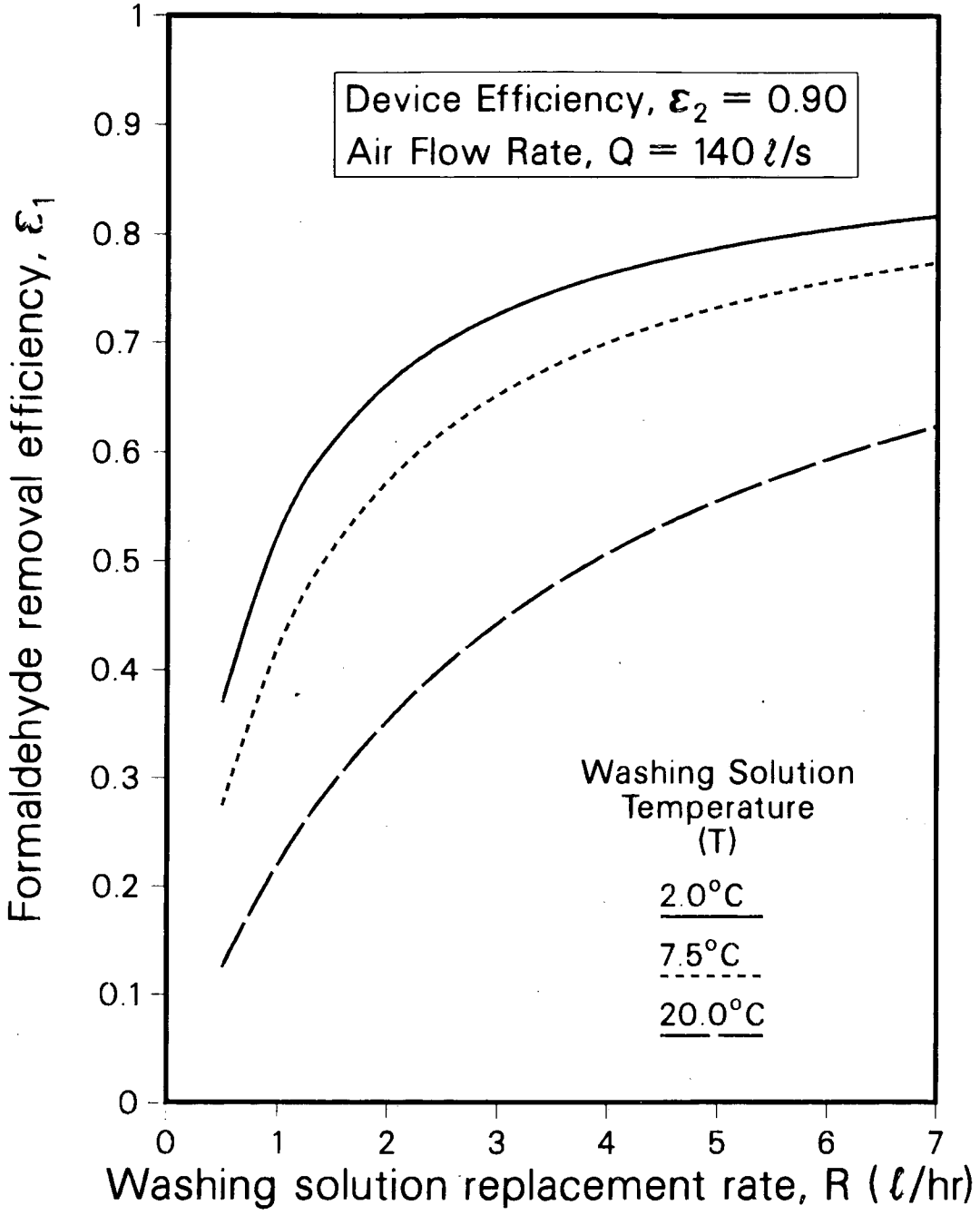


Figure 5. Measured and corrected formaldehyde removal efficiencies for tests of Air Washer No. 2.



XCG 8310-7260

Figure 6. Theoretical relationships between formaldehyde removal efficiency and washing solution replacement rate for various solution temperatures.

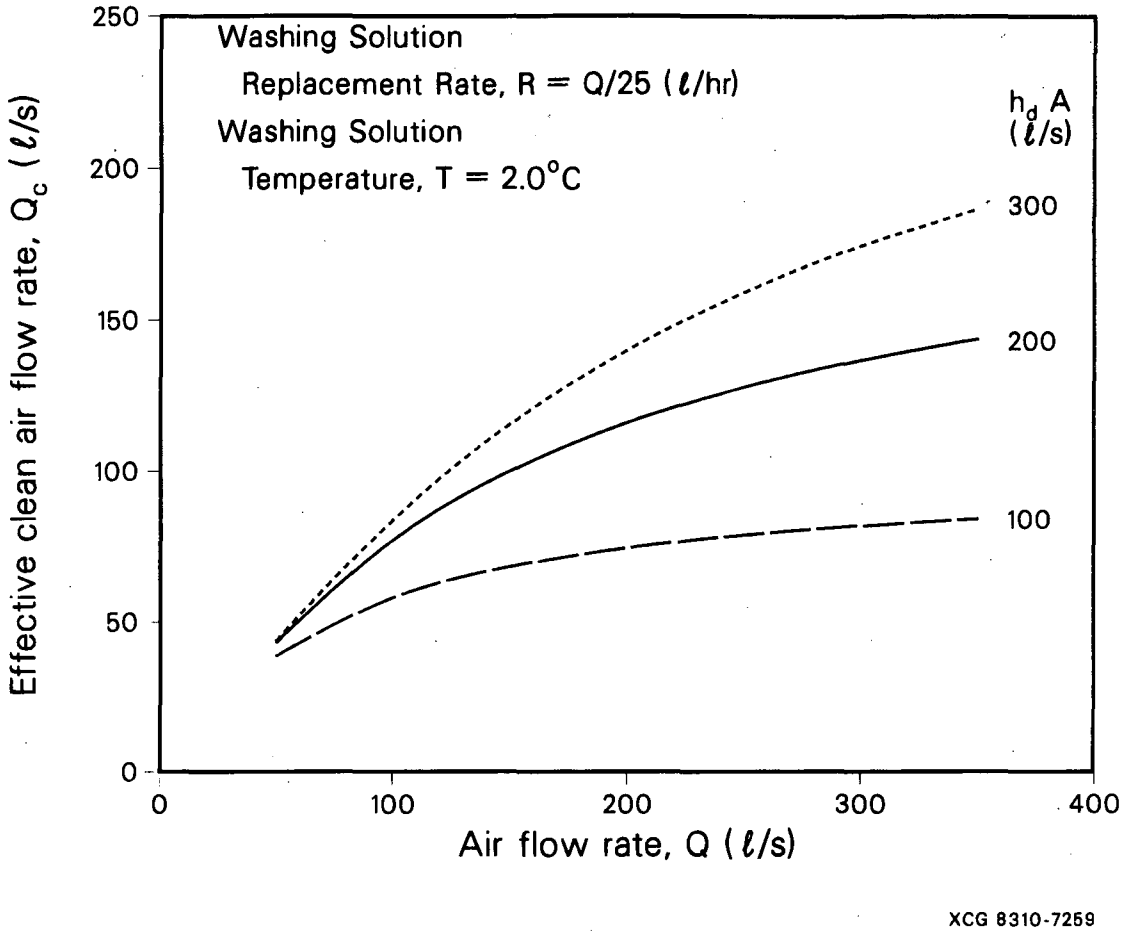


Figure 7. Theoretical relationship between effective clean air flow rate and air washer air flow rate for various values of the mass transfer coefficient - interface area product, $h_d A$.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720