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USING THE SEQUENTIAL BOX MODEL TO PREDICT TRANSIENT SOLVENT CONCENTRATIONS ARISING FROM APPLYING A SURFACE COATING INSIDE A CONFINED SPACE

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ABSTRACT

The sequential box model is a versatile and easy-to-use method to estimate both instantaneous and steady-state concentrations at arbitrary points inside a complex enclosure. This model is used to predict vapor concentrations experienced by workers spraying a coating inside a storage vessel. Also, it accommodates the generation of vapor and local air circulation that vary with time and location as the worker moves about inside the confined space.

INTRODUCTION

A confined space is a working environment possessing some or all of the following characteristics:

- limited openings for entry and exit—few or narrow openings that restrict workers wearing protective equipment or engaged in rescue;
- inadequate natural convection—insufficient oxygen, flammable atmospheres, accumulation of toxic vapors, excessive temperature, etc.;
- not designed for continuous occupancy—occasional entry for inspection, maintenance, repair, cleanup, application of surface coatings, etc.; inability to move about normally;
- unusual physical conditions—granular material that can engulf and suffocate workers, wet and slick surfaces, excessive noise reverberation, topside openings, and overhead work from which objects can fall on workers.

Examples of confined spaces include furnaces and boilers, cupolas, degreasers, pipelines, septic tanks, sewage digesters, collection pits, pumping stations, utility vaults, reaction or process vessels, silos, storage tanks, hoppers, and ship's holds. In rare instances when workers need to enter confined spaces, industry is expected to follow a strictly enforced confined-space entry program involving written guidelines, training of "qualified" personnel, entry permits, checklists, lock-out and disconnect procedures, gas sampling, forced ventilation, supplied air or self-contained breathing apparatus, lifelines, standby persons, and rehearsed rescue procedures.

Currently it is difficult to predict either the time-varying or steady-state concentration of contaminants at arbitrary points in a confined space, $c(x,y,z,t)$. Without actually measuring the concentration, it is impossible to determine whether hazardous conditions are due to inadequate oxygen, toxic vapors exceeding TLVs, or hydrocarbon concentrations approaching the limits of flammability. Such knowledge is useful to determine whether air-purifying respirators or air-supplying respirators are necessary. If the latter are necessary, it is also useful to know whether special clothing will be needed to prevent contamination through the skin. Considering the uncomfortably hot conditions of confined spaces, the latter concern should not be underestimated.

Computing contaminant concentrations is easy if there is a great deal of mixing within the confined space such that the concentration is spatially uniform and varies only with time, i.e., $c(x,y,z,t) = c(t)$. This condition is called "well mixed." If conditions are not well mixed, techniques in computational fluid dynamics (CFD) are available to predict steady-state conditions in enclosures of complex geometry where the concentration varies spatially but not temporally, i.e., $c(x,y,z,t) = c(x,y,z)$. Steady-state conditions occur if the ventilation flow rate and contaminant source strength are constant and sufficient time has elapsed that the concentration at a point in space no longer varies with time. Presently it is difficult to predict time-varying concentrations when the ventilation flow rate varies with time or when the contaminant generation rate varies with time or location within the confined space. As a general proposition, engineers need the capability to predict $c(x,y,z,t)$ since they need to anticipate hazardous conditions. Also, if a control system is needed, engineers need to predict $c(x,y,z,t)$ to determine the effectiveness of the control system and to make design changes prior to

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constructing the system or modifying it in the field. The purpose of this paper is to describe how one can use the sequential box model (Heinsohn 1989, 1991) or, as it is sometimes called, the well-mixed, multicell model (Skaret and Mathisen 1983; Skaret 1986) to estimate concentrations $c(x,y,z,t)$.

The sequential box model has been used in industrial ventilation for quite some time. It has been used both to predict the concentration of environmental tobacco smoke in commercial aircraft (CACAC 1986; Ryan et al. 1986, 1988), and it has been used to analyze the transport of contaminants between rooms of a building in which the time scale is large or well-mixed conditions exist in each room or in a portion of a room. The appealing feature of the sequential box model is the opportunity to discern both temporal and spatial variations simultaneously, with a minimum of computational difficulty.

SEQUENTIAL BOX MODEL

Figure 1 shows the elements of a one-dimensional sequential box model. The overall volume of the confined space is called the control volume (CV) and it contains a finite number of sequential boxes (V_i). The surface of the control volume is called the control surface. The phrase "one-dimensional" refers to the fact that a box exchanges air and contaminant only with boxes on either side. The control volume is defined by the boundaries of an enclosed space within which users are interested in knowing the concentration. The dimensions of the control volume must be known. Users must also know the location, mass flow rate of air, and the contaminant concentration in air crossing the control surface. These values may be constant, zero, or vary with time. The control volume may contain several inlets and outlets. It is assumed that the total mass flow rate of air entering the control volume is equal to the total mass flow rate leaving the control volume. Since the density is assumed to be constant, the total volumetric flow rate of air into and out of the control volume (Q_A) is constant.

The dimensions, location, and number of the boxes (V_i) are selected by the user. The principal assumption in the sequential box model is that within each box the concentration is spatially uniform, i.e., well mixed. Users must define boxes within which it is either known or believed that conditions are well mixed. Configurations similar to Figure 1 can be drawn for two- and three-dimensional flow.

Air and contaminants cross the boundaries of a box P because they may pass through the control surface. Air and contaminants are also transported between adjacent boxes (E and W). Air exchange between boxes is defined in terms of exchange coefficients (F, F'), which express the air volumetric flow rate out of and into a box as multiples of the total volumetric flow rate (Q_A). Across the east face of box P (Figure 1) the volumetric flow rate leaving box P is given by

$$Q_E = \int\int_{A_E} \vec{v}\cdot\hat{n}\, dA \qquad (1)$$

where $\vec{v}$ is the velocity vector and $\hat{n}$ is the outward normal unit vector. For purposes of analysis using the sequential box model, it is convenient to express Equation 1 in terms of exchange coefficients:

$$Q_E = F_E Q_A - F_E' Q_A. \qquad (2)$$

The exchange coefficients (F_E, F_E') have to be determined by independent means and are the principal unknowns in the analysis. Users either must measure these values or perform the analysis for a range of values of F_E and F_E' greater or less than what they believe the correct values to be. Small values of F_E or F_E' signify little exchange of air from one box to the other, whereas values in excess of unity signify a robust exchange of air.

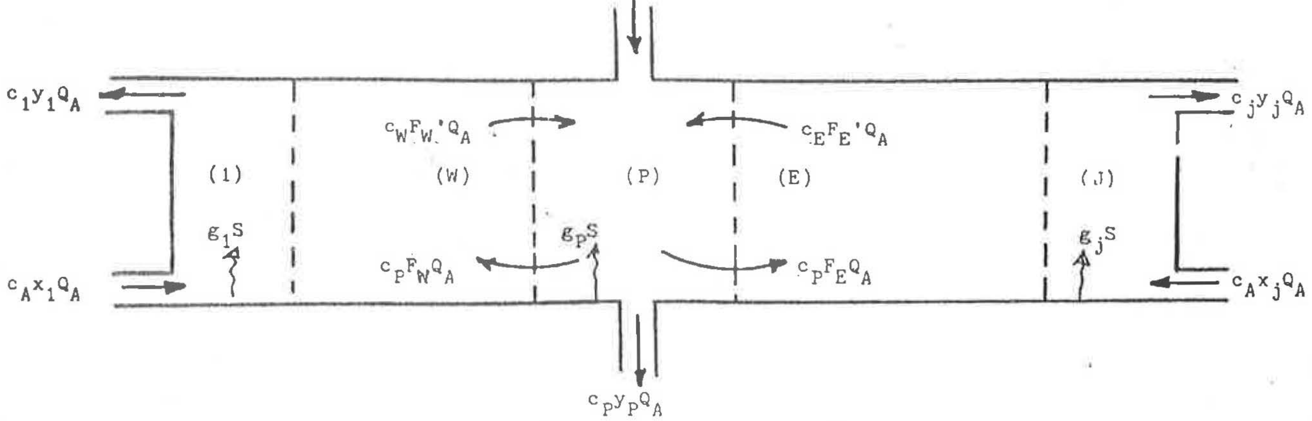

Figure 1 One-dimensional sequential box model.

Let the subscript P designate the box for which the conservation equations will be written and subscripts W and E designate boxes to the west and east of box P. Within each box, contaminant may or may not be generated, adsorbed, or react chemically. In the system modeled in this paper, it will be assumed that adsorption and chemical reactions do not occur. The fraction g_P is the known fraction of the total generation occurring in box P. Air from boxes adjacent to P is transported *into* box P at volumetric flow rates $F_W{}'Q_A$ and $F_E{}'Q_A$. Air *from* box P is transported to adjacent boxes at rates F_WQ_A and F_EQ_A. It is assumed that the mass of air inside each box is constant but that the mass of contaminant inside each box changes with time. Mass balances for air and contaminant for box P are as follows:

Contaminant:

$$\begin{aligned} k_P V dc_P/dt &= g_P S_t + c_A x_P Q_A + c_E F_E{}' Q_A \\ &+ c_W F_W{}' Q_A - y_P c_P Q_A - c_P F_E Q_A - c_P F_W Q_A. \end{aligned} \tag{3}$$

Air:

$$\begin{aligned} x_P Q_A &+ F_W{}' Q_A + F_E{}' Q_A \\ &= y_P Q_A + F_E Q_A + F_W Q_A. \end{aligned} \tag{4}$$

Equations similar to Equations 3 and 4 are written for each of the boxes inside the control volume. Users then solve a set of simultaneous ordinary differential equations equal to the number of boxes, using Runge-Kutta techniques. The following are the known, selected, and unknown quantities:

Known: k_P, y_P, x_P, g_P, Q_A, c_A, S, V, t
Selected: F_W, $F_W{}'$, F_E, $F_E{}'$ for each box P
Unknown: c_P, c_E, c_W.

Equations comparable to Equations 3 and 4 can also be written for two- and three-dimensional flow. The equations are of similar form, except that not all the boxes will share a boundary with the control volume. Obviously, the number of equations is large, i.e., two-dimensional flow consisting of an array of I by J number of boxes results in I times J equations similar to Equation 3 and another I times J equations similar to Equation 4. For a three-dimensional flow configuration consisting of an I by J by K array of boxes, the number of equations for air and contaminants is the product of I times J times K.

ILLUSTRATED EXAMPLE—RECOATING INSIDE THE SURFACE OF A RAILROAD TANK CAR

Consider reconditioning the inside surface of a railroad tank car (Figure 2). Tank cars are nominally 16,000-gallon (60.65 m^3) cylindrical vessels, 8.53 ft (2.6 m) in diameter, 37.49 ft (11.43 m) long. Reconditioning begins by removing the inside surface coating by abrasive blasting. Once a clean metal surface is obtained, selective materials are sprayed on the surface. Polyurethane or epoxy that contains toxic components is typically used.

The tank car has a single narrow circular opening (man-way) in the top center that barely accommodates the passage of a worker equipped with an air-supplying respirator. Fresh air enters the man-way, and contaminated air is withdrawn through a drain opening (approximately 6 inches in diameter) in the floor of the vessel by an exhaust fan. Air entering the topside man-way circulates poorly throughout the vessel since the vessel ends are cul-de-sacs. In addition to cramped quarters, poor air circulation, high temperatures and humidity, bulky protective clothing, a face mask, poor visibility, tethering lines, lighting cords, air hoses, and sprayer hoses create insufferable working conditions.

Predicting contaminant concentrations from spraying is unlike the usual analysis of confined spaces since the source of emissions varies with both time and location as the worker moves about inside the vessel and wet coating dries. Second, the movement of the worker and the sprayer produces unique exchange coefficients (F_i, $F_i{}'$) at each location that change as the worker moves from box to box.

The vessel will be divided into nine sections of circular cross section, each approximately 4 ft (1.22 m) long. Four feet is as much as a typical worker can spray while standing at one location. The subscript P assumes integer values 1 through 9. Figure 3 shows boxes 1, 2, and 3. The subscripts E and W will be replaced by R and L, which refer to the right and left side of a box designated by the integers 1 through 9. For example, Q_{3L} and Q_{3R} refer to volumetric flow rates *leaving* the left and right faces of box number 3. Similarly, Q_{2R} and Q_{4L} represent volumetric flow rates *entering* box 3 from boxes 2 and 4, respectively. Users should draw each box and label the volumetric flow rate across each face as shown in Figure 3.

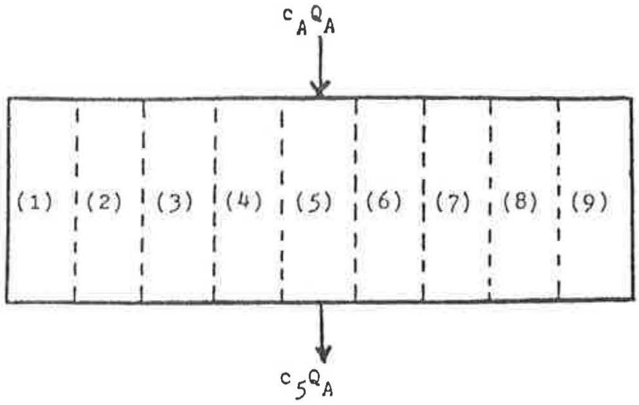

Figure 2 *Nine-cell sequential box model of a 16,000-gallon cylindrical storage vessel.*

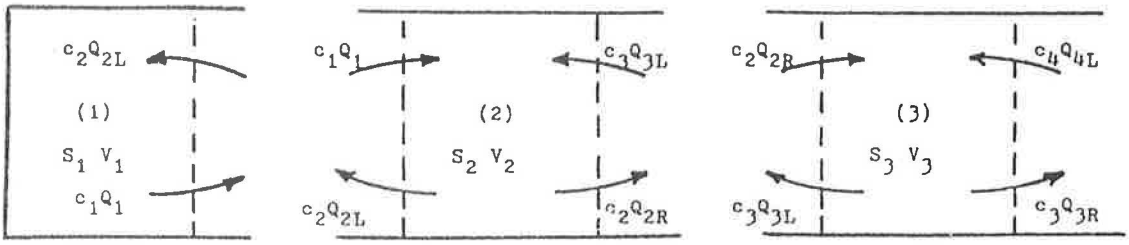

Figure 3 *Exchange coefficients for boxes 1, 2, and 3.*

Because boxes 1 and 9 are dead ends, the volumetric flow rate Q_1 must always equal Q_{2L}. As a result, the volumetric flow rate on the right face of box 2 always equals the volumetric flow rate on the left face of box 3. Thus ($Q_{2R} = Q_{3L}$), which implies $F_2 = F_3'$. For simplicity, the symbols F_2 and F_3' will be replaced by the symbol F_2. This pattern can then be repeated for the remaining boxes. For box 5, the volumetric flow rate of ambient air into the man-way is equal to the volumetric flow rate of air from box 5 through the drain hole. Thus,

$$\begin{aligned} Q_1 = Q_{2L} = F_1 Q_A:\ \ Q_{2R} = Q_{3L} = F_2 Q_A: \\ Q_{3R} = Q_{4L} = F_3 Q_A: \\ Q_{4R} = Q_{5L} = F_4 Q_A: \\ \ldots Q_9 = Q_{8R} = F_8 Q_A. \end{aligned} \tag{5}$$

Work Cycle

Coatings are typically applied in the two-step process described in Table 1. The first pass consists of the worker applying a light coating to an entire box for three minutes. The worker begins at one end of the vessel (box 1) and moves systematically to the other end of the vessel (box 9). Following the light coat, the worker returns to box 1 and applies a second and final coat that requires nine minutes per box. The final coat is applied box by box, as was the light coat except for a small area on the floor where the worker stands. After box 9 receives a final coat, the worker returns to box 1 and applies a final coat to the small floor area in which he stood to apply the final coat. These floor coats require only one minute per box. The floor coats are applied beginning at each end of the vessel so that the worker can finish in box 5 and exit the tank car through the man-way in box 5.

Solvent Vapor Generation Rate

In this example, the sequential box model will be used to estimate solvent vapor concentrations encountered by a worker spraying a novel surface coating containing very little solvent. It is assumed that solvent vapors are emitted at a constant rate during spraying and at a linearly decreasing rate as the coating dries. The best data can be obtained by experiment. In the absence of experimental data, knowledge of the percent solvent in the coating and the drying time will enable the engineer to estimate emission rates. Lacking this, the engineer should use emission factors or data obtained from the coating supplier or data from the literature for comparable coatings. For this analysis, it is assumed that only the solvent percent in the coating (as applied) and the drying time are known. It must be emphasized that the sequential box model can accommodate any analytical or tabulated function describing the solvent generation rate.

Within each box (i) solvent vapor is generated (S_i) while the coating is being sprayed and by evaporation as it dries. During spraying, it is assumed that S_i is constant, and while the coating dries, S_i is assumed to decrease linearly with time:

$$\begin{aligned} &\text{During spraying: } S_i \text{ (mg/min)} = S = \text{constant} \\ &\text{Drying: } Si \text{ (mg/min)} = S' - mt \end{aligned} \tag{6}$$

TABLE 1
Work Cycle

Time (min)	Worker Activity
1-3	First pass (light coat), Box 1
4-6	First pass (light coat), Box 2
7-9	First pass (light coat), Box 3
10-12	First pass (light coat), Box 4
13-15	First pass (light coat), Box 5
16-18	First pass (light coat), Box 6
19-21	First pass (light coat), Box 7
22-24	First pass (light coat), Box 8
25-27	First pass (light coat), Box 9
28-30	Worker returns to Box 1
31-39	Second pass (final coat), Box 1
40-48	Second pass (final coat), Box 2
49-57	Second pass (final coat), Box 3
58-66	Second pass (final coat), Box 4
67-75	Second pass (final coat), Box 5
76-84	Second pass (final coat), Box 6
85-93	Second pass (final coat), Box 7
94-102	Second pass (final coat), Box 8
103-111	Second pass (final coat), Box 9
112-114	Worker returns to Box 1
115	Third pass (floor coat), Box 1
116	Third pass (floor coat), Box 2
117	Third pass (floor coat), Box 3
118	Third pass (floor coat), Box 4
119	Third pass (floor coat), Box 9
120	Third pass (floor coat), Box 8
121	Third pass (floor coat), Box 7
122	Third pass (floor coat), Box 6
123	Third pass (floor coat), Box 5
124	Worker leaves vessel

where $t < t_d$ is the elapsed time after spraying in box i. The values of S, S', and m depend on the sprayer, coating composition, and thickness. The following data typify coatings applied inside storage vessels:

$$t_d = 30 \text{ minutes and constant for all coats} \tag{7}$$

final coverage = 4.0545 gal/1000 ft^2 (0.04362 gal/m^2)
number of coats = 2 (light coat, finish + floor coats)
coating density (kg/gal) = 9.373 lbm/gal (4.255 kg/gal).

In this example, it will be assumed that a novel low-solvent coating will be used in which the percent solvent (by mass) is 0.078%. For the railroad tank car, the inside surface area is 1117.5 ft^2 (103.87 m^2) and a total of 9.07 gallons (34.33 L) will be used for the two coats. Such a coverage generates 7.313×10^{-3} lbm (3.32 g) of solvent vapor within each box. Since the total time for spraying each box is 13 minutes, the mass of solvent vapor generated in each box is

$$\begin{aligned}
&\text{light coat:}\\
&\quad (3/13)(3320) = 766.15 \text{ mg } (1.688 \times 10^{-3} \text{ lbm})\\
&\text{finish coat:}\\
&\quad (9/13)(3320) = 2298.15 \text{ mg } (5.062 \times 10^{-3} \text{ lbm})\\
&\text{floor coat:}\\
&\quad (1/13)(3320) = 255.38 \text{ mg } (5.625 \times 10^{-4} \text{ lbm})
\end{aligned} \tag{8}$$

The variation of S_i with time is shown in Figure 4. Each graph is associated with a certain coat in the work cycle. The parameters S, S', and m are computed from a mass balance for each coat. It is assumed that the mass of solvent vapor generated during spraying (S) is a constant since no adjustments are made to the sprayer throughout the work cycle. For each coat, the area under the curve in Figure 4 (the integral of $S_i\,dt$) is equal to the mass of solvent vapor calculated above. Thus,

$$\begin{aligned}
&\text{light coat: } 766.15 \text{ mg} = S(3 \text{ min}) + S_{LC}'(30 \text{ min})/2\\
&\text{finish coat: } 2298.38 \text{ mg} = S(9 \text{ min}) + S_{FC}'(30 \text{ min})/2\\
&\text{floor coat: } 255.38 \text{ mg} = S(1 \text{ min}) + S_{RC}'(30 \text{ min})/2
\end{aligned} \tag{9}$$

Logic argues that the maximum evaporation rate occurs during spraying when the total surface area over which evaporation occurs is equal to the total surface area of all the droplets. Logic also argues that once the particles reside on the surface, i.e., during drying, that neither S_{RC}', S_{LC}', nor S_{FC}' will exceed S. In the absence of experimental data, it will be assumed that $S = S_{FC}' > S_{LC}' > S_{RC}'$ since the finish coat is the thickest. The above equations are satisfied when

$$\begin{aligned}
&\text{all coats:} && S && = 95.77 \text{ mg/min}\\
&\text{light coat:} && S_{LC}' && = 31.92 \text{ mg/min}\\
&\text{finish coat:} && S_{FC}' && = 95.77 \text{ mg/min}\\
&\text{floor coat:} && S_{RC}' && = 10.64 \text{ mg/min.}
\end{aligned} \tag{10}$$

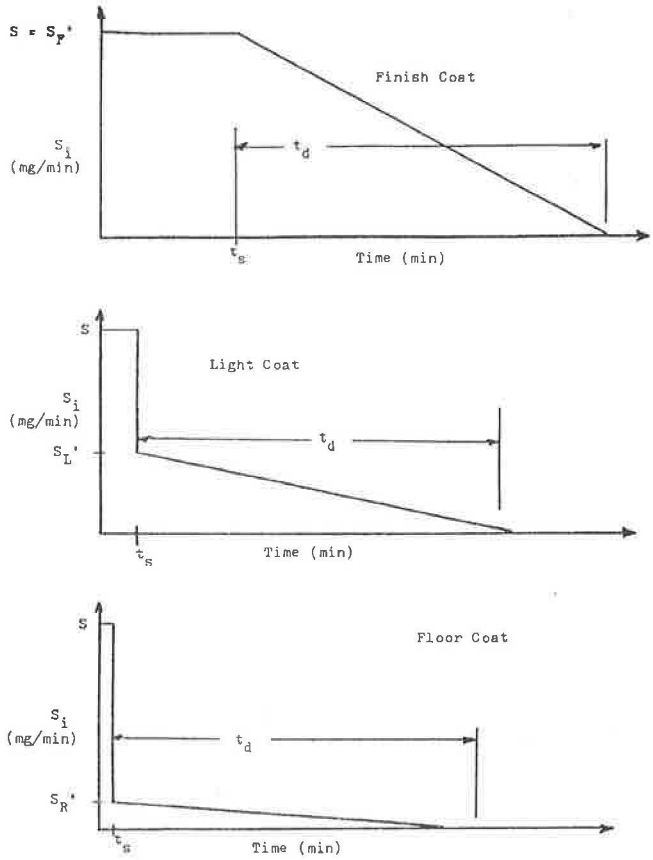

Figure 4 *Solvent vapor generation rate vs. time,* t_d = *drying time,* t_s = *spraying time.*

The slope (m_{FC}) of the curve representing the drying portion of the finish coat in Figure 4 can be found by setting $[S_{FC}' - m_{FC}(30 \text{ min})]$ equal to zero. Consequently,

$$\begin{aligned}
&\text{light coat:} && m_{LC} = 1.064 \text{ mg/min}^2\\
&\text{finish coat:} && m_{FC} = 3.192 \text{ mg/min}^2\\
&\text{floor coat:} && m_{RC} = 0.335 \text{ mg/min}^2
\end{aligned} \tag{11}$$

While the above assumptions are unsophisticated, the sequential box model will accommodate more sophisticated expressions for the time-varying evaporation rate within each box.

Numerical Computations

Once the ordinary differential equations, i.e., Equation 3, are written for all the boxes, Runge-Kutta formulae can be used to solve the equations. The following crude but nonetheless useful method can be used. For box 3, Equation 3 becomes

$$dc_3/dt = [S_3 + c_4 Q_{4L} + c_2 Q_{2R} - c_3(Q_{3L} + Q_{3R})]/Vk_3. \tag{12}$$

Expand the concentration c_3 as a Taylor series in time (t) and retain only the first two terms. Replace the first derivative in the series by Equation 12 and simplify:

$$c_3(t+\delta t) = c_3(t) + [S_3(t) + c_4(t)Q_{4L} + c_2(t)Q_{2R} - c_3(t)(Q_{3L} + Q_{3R})]\delta t/Vk_3 \tag{13}$$

where δt is an increment of time. Replace $c_3(t)$ in the last term above by its average,

$$[c_3(t) + c_3(t+\delta t)]/2. \tag{14}$$

Rearrange terms and simplify:

$$c_3(t+\delta t) = [L_3/M_3]c_3(t) + [N_3/M_3] \tag{15}$$

where

$$M_3 = 1 + [(Q_{3L} + Q_{3R})\delta t/2Vk_3] \tag{16}$$

$$L_3 = 1 - [(Q_{3R} + Q_{3L})\delta t/2Vk_3] \tag{17}$$

$$N_3 = [S_3(t) + c_4(t)Q_{4L} + c_2(t)Q_{2R}]\delta t/Vk_3. \tag{18}$$

Similar equations are written for boxes 1 through 9. Boxes 1 and 9 have simpler equations since they have a solid boundary at one end. Box 5 is slightly different since the access ports provide exhaust and makeup air. In the final analysis, nine algebraic equations are written in the form of Equation 15.

The solution begins by computing the concentration at the end of each time step (δt) in each box until the worker leaves the vessel. The worker's movement is defined by the spraying activities described in Table 1. At the end of each three-minute (or nine-minute) interval, the worker moves to the next box, whereupon new values of F_i and S_i are used in each of the nine boxes. Thus the values of the coefficients L_i, M_i, and N_i in Equation 15 change each time the worker moves. The concentrations in each box at the end of a time step become the initial values for the next time step.

In the absence of experimental data, values of F_i will be assigned to each box at each interval in the work cycle. The values cannot be assigned arbitrarily since the conservation of mass for air in each box must be preserved. One set of exchange coefficients representing modest internal circulation is the following:

F_i = 1.0 during spraying in box i
F_i = 0.3 when spraying occurs in boxes $i+1$ and $i-1$ (19)
F_i = 0.1 when spraying occurs in boxes $i+2$ and $i-2$.

The sequential box model does not restrict the exchange coefficients to the values in Equation 19 and will accommodate any values provided Equation 4 is satisfied.

The small diameter of the drain opening restricts the ventilation flow rate. For this analysis, it will be assumed that workers only have access to two exhaust fans that produce the following volumetric flow rates of fresh air into the vessel.

$$Q_A = 3176 \text{ cfm } (90.0 \text{ m}^3/\text{min}) \qquad Q_A = 665 \text{ cfm } (18.85 \text{ m}^3/\text{min}) \tag{20}$$

The above correspond to 18.65 and 89.04 room air changes per hour, which satisfy U.S. Navy requirements (Navy 1987) of 10 changes per hour prescribed for coating the interior of fuel storage tanks. The rates in Equation 20 are considerably less than the values recommended by the American Conference of Governmental Industrial Hygienists (CIV 1987) for spraying the inside of trailers when workers are equipped with air-supplied breathing apparatus. At each value of Q_A, three sets of exchange coefficients will be used:

Low Circulation: F_i = 50% the values in Equation 19
Moderate Circulation: F_i = Equation 19 (21)
Robust Circulation: F_i = twice the values in Equation 19.

RESULTS

The sequential box model computes the concentration in each box as a function of time. From these values, the user tracks the boxes the worker is in to determine the concentration to which the worker is exposed. Figures 5 and 6 show the solvent concentration to which the worker is exposed throughout the spraying process for three sets of exchange coefficients and two fresh air ventilation flow rates.

While applying the light coat ($0 < t$(min) < 30), the solvent concentration increases gradually as the worker approaches box 9. After returning to box 1 and beginning the finish coat ($30 < t$(min) < 66), the worker encounters high solvent concentrations that were not removed from boxes 1, 2, 3, and 4. The solvent concentration in box 5 ($67 < t$(min) < 75) is low because fresh air enters the man-way in the top and contaminated air is exhausted from the drain port in the floor. As the worker moves to boxes 6, 7, 8, and 9 ($76 < t$(min) < 111), the solvent concentrations rise. Serious conditions occur when applying the floor coat ($115 < t$(min) < 123) since the solvent concentrations are at their maximum values.

DISCUSSION

Figures 5 and 6 show that the concentration experienced by workers increases steadily with time. The 10 minutes consumed for the floor coat present the highest risk. It is instructive to note that if nothing was done to provide fresh air ($Q_a = 0$) the steady-state concentration throughout the entire vessel would be 493 mg/m^3, a value just somewhat higher than that encountered during the floor coat. Consequently 665 cfm and even 3,176 cfm do not provide much dilution.

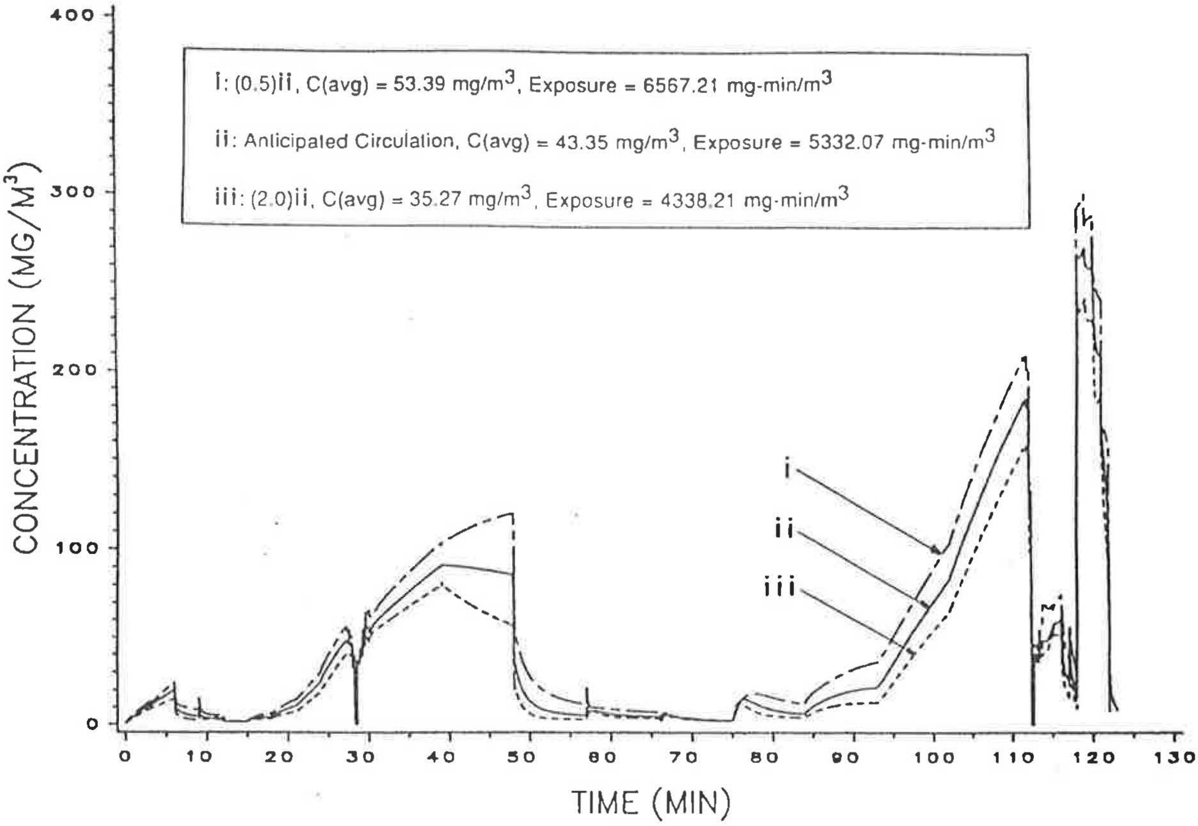

Figure 5 *Worker concentration vs. time, Q = 3,176 cfm (90 m^3/min).*

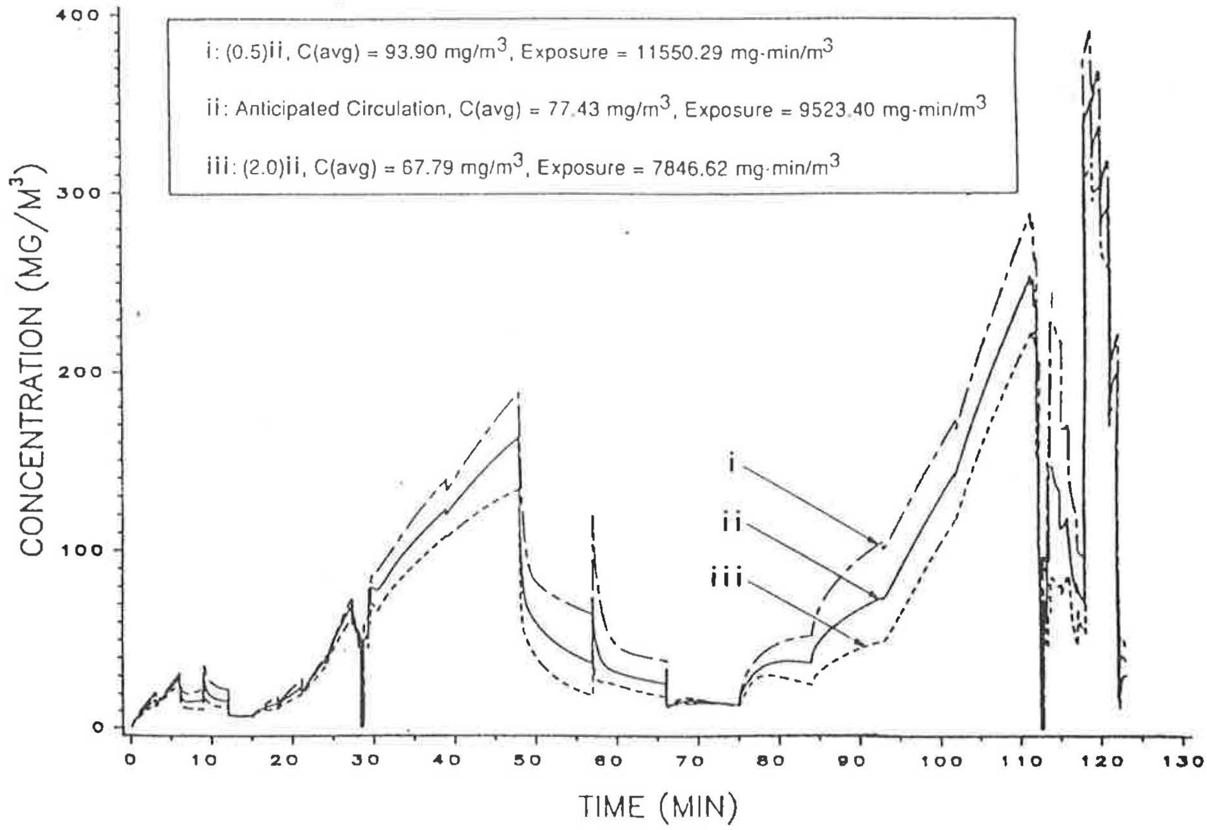

Figure 6 *Worker concentration vs. time, Q = 665 cfm (18.85 m^3/min).*

The hazard posed by solvent vapor can be assessed in terms of the arithmetic average concentration and the total exposure. Define the worker's total exposure (E):

$$E = \int_0^{123\ \text{min}} c\ dt = \text{SUM}_i\ c_i\ \delta t_i. \qquad (22)$$

The average concentration and exposure for two fresh air ventilation flow rates and three sets of exchange coefficients, i.e., levels of air circulation, are shown in the tables in Figures 5 and 6. The tables show that the ventilation flow rate (Q_A) is the dominant factor affecting exposure. Reducing the fresh air ventilation flow rate from 3,176 cfm (90 m^3/min) to 665 cfm (18.85 m^3/min) nearly doubles the average concentration and exposure for any value of the internal circulation. At any fresh air ventilation flow rate (Q_a), increasing the circulation by a factor of 4 reduces the average concentration and exposure by approximately 1.5.

It is instructive to normalize the arithmetic average concentration with a "steady-state concentration," $c(ss)$, defined as follows:

$$c(ss) = \int_0^{123} s_i(t)\ dt / \int_0^{123} Q\ dt. \qquad (23)$$

The steady-state concentration is the value one expects if the entire vessel is well mixed and the source strength and ventilation volumetric flow rates are constant. Table 2 shows the ratio of the actual arithmetic average concentration to $c(ss)$ for two ventilation flow rates and three levels of circulation. It is clear that the arithmetic average concentration actually experienced by the worker is considerably larger than the steady-state concentration in all cases.

Table 2 illustrates the serious error associated with assuming well-mixed conditions and using the "number of room air changes (Q_A/V)" to assess hazardous conditions in poorly ventilated spaces. First, if an enclosure is well mixed, the concentration will increase to 99% of its steady-state value after the passage of seven times the value (V/Q_A). In this problem, this would be 5 minutes at Q_A = 90 m^3/min and 23 minutes at Q_A = 18.85 m^3/min. Because the confined space is poorly ventilated and since the source strength is not constant, Figures 5 and 6 show that (a) steady-state conditions never occur during the 123-minute spraying period, (b) the average concentrations are 5 to 20 times the steady-state values, and (c) the concentration is never spatially uniform inside the vessel. Whether the solvent concentration experienced by the worker represents hazardous conditions depends on the TLV values of the components in the coating mixture.

If a specific coating is analyzed, the procedure enables engineers to predict the OSHA cumulative exposure or equivalent exposure index and ascertain whether workers are within OSHA permissible exposure limits (PEL). If engineers are interested in monitoring the concentration everywhere in the vessel to determine if lower explosion limits (LEL) are approached, they would need to examine the concentration in each box for the entire period of 123 minutes.

TABLE 2
Ratio of Average Concentration to Steady-State Concentration

c(ss) = 12.88 mg/m^3 at Q_A = 665 cfm (18.85 m^3/min)
c(ss) = 2.7 mg/m^3 at Q_A = 3,176 cfm (90 m^3/min)

Ventilation Q_A (cfm)	Low Circulation	Moderate Circulation	Robust Circulation
665	7.29	6.01	5.26
3,176	19.77	16.06	13.06

CONCLUSION

More accurate predictions of $c(x,y,z,t)$ can be computed by solving the conservation equations of mass, energy, and momentum by numerical (computer) techniques. Techniques for solving these equations are found in the field of computational fluid dynamics (CFD), but the effort represents a sizable investment in time, money, and talent. The sequential box model requires far less of these. It is a versatile, easy-to-use method that can estimate both the instantaneous and steady-state concentrations at arbitrary points inside a complex enclosure.

The major limitation to the method is that it replaces knowledge of the velocity field by vague exchange coefficients whose values cannot be predicted accurately. Experienced engineers can select a range of values that bracket the correct values and estimate a range of concentrations for design purposes and for anticipating hazardous conditions.

NOMENCLATURE

A	=	area
c_A	=	contaminant concentration in the ambient air
c_P, c_E, c_W	=	contaminant concentration in boxes P, E, and W
$c(ss)$	=	steady-state concentration, defined by equation
E	=	worker exposure, defined by equation
F_E, F_W	=	exchange coefficients, multiples of total volumetric flow rate transported from box P into boxes E and W
F_E', F_W'	=	exchange coefficients, multiples of the total volumetric flow rate transported from boxes E and W into box P
F_i	=	exchange coefficients for box i in the illustrated example
g_P	=	fraction of the total contaminant generation rate occurring in box P

I, J, K = number of boxes in the x, y, and z directions
k_P = fraction of the control volume represented by box P
L_i, M_i, N_i = constants defined by equation related to box i in the illustrated example
m_{FC}, m_{LC}, m_{RC} = slope of the drying portion of the solvent generation rate in the illustrated example
$\hat{n}$ = unit outward normal vector
Q_{2R}, Q_{2L} = volumetric flow rates leaving the right and left face of box 2 in the illustrated example
Q_A = total volumetric flow rate of air into the confined space
Q_E = volumetric flow rate leaving box P through its east face
S, S' = solvent vapor generation rate during spraying, initial solvent vapor generation rate during drying in the illustrated example
S_t = total generation rate within the control volume
$S_{FC}', S_{LC}', S_{RC}'$ = initial solvent generation rates during drying for the finish coat, light coat, and floor coat in the illustrated example
S_i = solvent vapor generation rate in box i
$t, \delta t$ = elapsed time, time step
t_s, t_d = duration of spraying, drying time
x_P = fraction of total volumetric flow rate transported into box P through the control surface
y_P = fraction of the total flow rate transported out of box P through the control surface
$\vec{v}$ = velocity
V = total volume of the control volume
V_i = volume of box i

REFERENCES

CACAQ (Committee on Airliner Cabin Air Quality), National Research Council. 1986. *The airliner cabin environment.* Washington DC: National Academy Press.

CIV (Committee on Industrial Ventilation), American Conference of Governmental Industrial Hygienists. 1988. *Industrial ventilation, A manual of recommended practice,* 20th ed. Committee on Industrial Ventilation, P.O. Box 16153, Lansing, MI 48901.

Heinsohn, R.J. 1989. Macro-modeling using sequential box models. *Building Systems: Room Air and Air Contaminant Distribution,* ed. L.L. Christainson, pp. 200-205. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

Heinsohn, R.J. 1991. *Industrial ventilation: Engineering principles.* New York: Wiley-Interscience.

Navy (Department of the Navy). 1987. Interior coating systems used on welded steel tanks (for fuel storage). NFGS-09872. Naval Facilities Engineering Command, October.

Ryan, P.B., J.D. Spengler, and P.F. Halfpenny. 1986a. Sequential box models for indoor air quality: Application to airliner clean cabin air quality. Paper 86-7.4, 79th Annual Meeting of the Air Pollution Control Association, 22-27 June.

Ryan, P.B., J.D. Spengler, and P.F. Halfpenny. 1986b. Sequential box models for indoor air quality: Application to airliner cabin air quality. *Atmospheric Environment* 22 (6): 1031-1038.

Skaret, E. 1986. Ventilation by displacement—Characterization and design implications. *Ventilation '85,* ed. H.D. Goodfellow, pp. 827-842. Amsterdam: Elsevier Science Publishers.

Skaret, E., and H.H. Mathisen. 1983. Ventilation efficiency—A guide to efficient ventilation. *ASHRAE Transactions* 89(2B): 480-495.