SHELTERING EFFECTIVENESS AGAINST PLUTONIUM

PROVIDED BY STATIONARY AUTOMOBILES

by

Rudolf J. Engelmann

William R. Pendergrass

J. Randall White

and

Mark E. Hall

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FINAL REPORT

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Rudolf J. Engelmann
Global Atmospheric Response
11701 Karen Drive, Potomac, MD 20854

William R. Pendergrass
Atmospheric Turbulence and Diffusion Division
National Oceanic and Atmospheric Administration (NOAA)
456 S. Illinois Ave., Oak Ridge, TN 37831

J. Randall White
Mark E. Hall
Oak Ridge Associated Universities (ORAU)
P. O. Box 117, Oak Ridge, TN 37831

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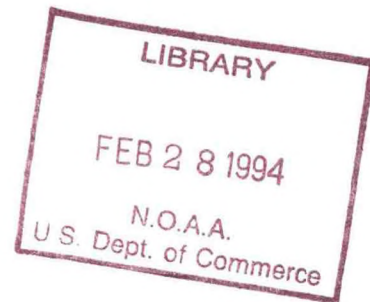
ABSTRACT. The protection offered occupants of stationary automobiles against airborne gases and respirable particles, such as might result from an accidental release, was measured and found to be substantial. Four of the five autos tested were equipped with air conditioning systems; when those were tested with the air conditioning (AC) system on and in recirculate position, the equilibrium ratios of inside to outside concentrations (I/O) for 2 μm particles were less than 0.2, and some ratios were as small as 0.014. With both the AC compressor and the system fan off, the I/O for the five autos ranged from 0.04 to 0.18. The highest I/O value was found to occur for the auto with no AC system. These low I/O ratios are primarily a result of deposition within the autos. However, three of the four autos with AC had substantially higher I/O ratios when the AC fan was on than when off, indicating significant added intake of outside air. Air exchange rates were on the order of 0.5 hr^{-1} with AC off, and 2.5 hr^{-1} with AC on.

Whether it is advisable to operate the vehicle's AC or not depends upon the time duration of the plume, whether the contaminant is gaseous or particulate, and the risk that operating the system fan may induce substantial intake of outside air. An insufficient number of autos have been tested to adequately evaluate the latter aspect.

This report presents the basic equations that determine the interior concentrations of contaminants when a vehicle is enveloped by a constant concentration. Parameters determined in the experiments can be used directly or adjusted as appropriate, and used in the equations to predict the interior concentrations versus time, and the I/O ratios, with and without AC systems operating.

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KEY WORDS -- Sheltering, inhalation, accident (nuclear), plutonium, emergency planning, Dose Reduction Factor

1. INTRODUCTION

This report describes research to determine the protection against plutonium particles offered by stationary automobiles, conducted in support of the NASA Galileo and Ulysses missions. However, the results have a broader application to a wide range of gases and particles.

The primary questions to be answered were whether stationary automobiles could serve as effective shelters against inhalation of respirable particles released in an accident, whether greater protection exists with or without operation of the automobiles' air conditioning systems, and whether automobiles should immediately be "aired out" following an apparent cloud departure.

A detailed study was first conducted for one automobile to verify the experimental design, formulas, and analysis techniques, and to obtain a good understanding of the processes that determine the inside concentrations. Then, abridged studies were conducted on four other automobiles to determine the protection offered for general application.

This report presents the equations describing inside concentrations, the experimental design, how parameters are determined from the data, discussion, and conclusions as to the protection offered against particles and gases.

2. CALCULATIONS OF DOSE UNDER SHELTERING CONDITIONS

The airborne concentration within a vehicle relative to that outside depends primarily upon the rate at which air is exchanged with the outdoors, removal of the contaminant as it passes into the vehicle from the outdoors, and deposition rate of the contaminant within the vehicle (Peterson and Sabersky 1975; Cristy and Chester 1981; Birenzvige 1983; Sherman 1987; Chester 1988; Engelmann 1990; and other references following this paper).

The "air change rate", "exchange rate", or "infiltration rate" is the volumetric flow rate of air into and out of the vehicle, Q, divided by the interior volume of the vehicle, V. The exchange rate primarily depends upon the automobile's volume, the tightness of fit of doors and windows, whether heating, cooling and ventilation systems are operating, and pressure differences produced by the speed of the air past the vehicle. The exchange rate for buildings and other shelters is consistently provided in the literature in units of hr^{-1}, and when units are not provided in this paper should be assumed to be hr^{-1}.

General equations that estimate an inside concentration from external and internal sources are found throughout the literature, e.g., Shair and Heitner (1974), Wadden and Sheff (1983) and Engelmann (1990). At the request of the sponsor, the following development is more detailed than found in the literature.

The equations relating the inside concentration C_i to the outside concentration C_o are derived from the mass balance of the air flow and contaminant, illustrated in Fig. 1. It is convenient theoretically to consider the removal and/or destruction of the contaminant, through interaction with the interior surfaces, as equal to the product of a dry deposition velocity, v_d, and the area of the interior, A.

For a single compartment vehicle with the interior concentration well mixed, the differential equation has the form

$$\frac{V\, d(C_i - C_0)}{dt} = \frac{a\, C_0 - bC_i - VdC_0}{dt} \tag{1a}$$

For the purpose of sheltering calculations, an outdoor plume may be regarded as a sudden change from a concentration of zero to the average concentration of the plume, followed by a sudden departure of the plume. Under this assumption, the change in external concentration with time equals zero ($d\, C_0/dt = 0$). After rearranging (1a), and setting the outside concentration constant,

$$\frac{V\, d(C_i - C_0)}{dt} = (a - b)\, C_0 - b(C_i - C_0) \tag{1b}$$

where:

$$a = \{fQ_1 + f_r Q_2\} \tag{2}$$

$$b = \{Q_1 + Q_2 + v_d A + (1 - f_r)\, Q_r\} \tag{3}$$

A is the surface area of the interior of the car

f is the fraction of contaminant that escapes capture during ingress

f_r is the fraction of contaminant that escapes capture during passage through the AC

Q_1 is the natural infiltration into a stationary car with the air conditioning (AC) and fans off

Q_2 is the air exchange when the AC is operating

Q_r is the recirculation air flow through the air conditioner

t is time

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V is the interior volume of the car

$v_d A$ is the removal of contaminant by interior surfaces

Up to this point, Q_1, Q_2, Q_r, and $v_d A$ have volumetric flow units (m^3/hr or ft^3/hr). For the remainder of this report, to simplify the presentation of formulas and data, the volume of the automobile will be understood to be an implicit divisor in the parameters a, b, Q_i, and $v_d A$. That is, Q_2/V will be simply denoted as Q_2, and will have units of hr^{-1}.

Equation (1b) is of the form $dX/(A + BX) = dt$, where $X = (C_i - C_o)$, $A = (a - b)C_o$, and $B = -b$. Recall that the integral of $dX/(A + BX)$ is $(1/B) \ln(A + BX)$. The integral of Equation (1b) is then $(1/B) \ln(A + BX) = T + $ (constant of integration). This can be rewritten in the exponential form

$$(A + BX) = \text{(constant)} \ e^{BT}, \text{ or}$$

$$X = -A/B + \text{(constant/B)} \ e^{BT}.$$

Substituting back for A, B, and X,

$$C_i = \frac{a}{b} C_o - \frac{Constant}{b} \exp(-bt).$$

To determine the constant of integration, note that at $t = 0$, $C_i = C_{ii}$, the initial value of C_i. This yields

$$Constant = -b \, C_{ii} + a \, C_o,$$

and the general solution is

$$C_i = \frac{a}{b} C_o + \left(C_{ii} - \frac{a}{b} C_o \right) \exp(-bt). \tag{4}$$

Particular solutions are obtained by substituting specific initial interior concentrations for C_{ii}.

For example, if the initial value of $C_{ii} = 0$, then

$$C_i = \frac{a}{b} C_o (1 - \exp(-bt)). \tag{5}$$

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If, however, the initial concentration inside is some fraction or multiple of that outside, i.e., if the initial value of $C_{ii} = N\,C_o$, then

$$C_i = \frac{a}{b}\,C_o + \left(N - \frac{a}{b}\right)C_o\,\exp(-bt).$$

In particular, if the initial value of C_{ii} is the same as the outside concentration, C_o, (i.e., N = 1), then

$$C_i - C_o = C_o\left(\frac{a}{b} - 1\right)(1 - \exp(-bt)). \tag{6}$$

From Equation 4, once the outside concentration has decreased to zero, then the inside concentration decays according to

$$C_i = C_{ii}\,\exp(-bt). \tag{7}$$

In Equation 7, t = 0 when the initial inside concentration is C_{ii}.

3. EXPERIMENTAL DETERMINATION OF THE PARAMETERS

The parameters in the equations for an automobile can be determined from measured concentrations inside and outside of the auto of depositing and nondepositing tracers. Because of the form of the solution, it is convenient to plot the concentrations as functions of time on semi-logarithmic coordinates.

The equations have the following characteristics that can be used to determine the parameters from measured concentrations:

- As time becomes very large, the inside/outside ratio, I/O or C_i/C_o, approaches a/b.

- If the initial interior concentration is zero, then up to a very small time later, $d(C_i - C_o)/dt = a\,C_o$.

- At all times, $dC_i/dt = -b\,C_i$ if the outside concentration is zero.

- From Eqn. (1b), if C_o is constant, if C_i initially equals C_o, and if t is very small, then dC_i/dt approximately equals $(a - b)\,C_i$.

- When $C_i = C_o$ and the AC is off, $dC_i/dt = -v_d A\,C_i$ at small times.

(The application of these characteristics for the automobiles investigated is described in Section 5, "Determination of the Parameters From the Data".)

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The parameters can be used to produce the time history of the inside concentration for comparison to the experimental data. Such comparison of theoretical and experimental curves will verify the parameters. The parameters and equations can then be used in practical application for other outside concentrations and time frames.

4. EXPERIMENTAL DESIGN

The experiments were conducted with automobiles in a large room that had walls and ceiling of corrugated metal, a large garage door, and two standard personnel doors (Fig. 2). The room had a smooth concrete floor of approximately 7.3 x 7.7 m, and had a sloped flat ceiling with a height of approximately 3.95 m sloping to 3.3 m. The air exchange rate between the closed room and its surroundings was measured as 0.64/hr when the indoor-outdoor temperature difference and wind speed were too small to influence the exchange rate.

Monosized polymer microspheres, or uniform latex microspheres, sold by Duke Scientific Corporation[1], were suspended in isopropyl alcohol and dispensed into the air of the room using a small Wagner paint sprayer. The sprayer was mounted on top of a stool placed in front of a large pedestal fan. A magnetic stirrer was used to maintain a uniform distribution of the particles in the alcohol. The particle analyzer used to measure concentrations was capable of distinguishing between airborne single and aggregated particles, and there was no evidence of aggregated particles.

Most tests were conducted with 2 µm aerodynamic diameter particles, since these best represent respirable plutonium particles. When preparing a safety analysis for an hypothetical accidental release of plutonium, Dewart et al. (1982) reasoned that a 2 µm aerodynamic equivalent diameter could be used to conservatively represent the respirable range of plutonium for organ dose calculations.

Although most tests used the isopropyl alcohol as a tracer to determine air exchange rates and to simulate a nondepositing gas, a few tests were conducted using ethane or ethylene released from cylinders. Three Beckman Model 400 Hydrocarbon Analyzers were used to monitor the concentration of isopropyl alcohol, ethane, or ethylene in the room and automobile. Standard gas mixtures of 5.0, 50.4, and 510 ppm ethane were used to calibrate the analyzers. The instruments were not corrected for the small difference from their response to alcohol, since only relative concentrations were used in the data analyses.

The data show that the measured exchange rates were essentially the same for the three gases. Although ethane appeared to be a superior tracer, in that the alcohol appears to have some deposition and subsequent offgassing, it was very convenient to use the alcohol since it was also used as the carrier liquid for the spray dispersion of particles.

Three or four large fans were used to mix the air in the room. These fans and the sprayer were not directed at the car. Measured alcohol concentrations in the room were used to regulate the rate at which the alcohol-particle mixture was sprayed into the room. The electric power to the sprayer

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[1]Mention of a commercial company or product does not constitute an endorsement. Use for publicity or advertising purposes of information from this report concerning proprietary products is not authorized.

was controlled (first manually, and later using feed-back control) to maintain the room alcohol concentration constant. This worked quite well, although the concentration of particles in the room tended to decrease slowly over time, presumedly toward a state of balance between the generation and decay rates. The experiments were analyzed so that the gradual decrease of particle concentration was not a major problem.

Two Climet CI-226 Particle Analyzers were used to determine particle concentrations in the room and automobile. The instruments are represented by the manufacturer as linear in response to the concentration, and as self-calibrating with respect to particle size. However, they did not read the same particle concentration in the same environment. This difference was accounted for in the experimental design and analysis, in that the coefficient b can be determined from the changing concentrations as measured with only one sampler. The I/O ratios were obtained from the inside particle analyzer readings obtained when the car doors were opened (O), and the readings shortly before opening (I).

4.1 Experiments on the K Car

An intensive series of tests was first conducted on a 1988 Plymouth Reliant 4-door automobile in good body condition, manufacturer's model identification KPH41 Chrysler IP3 BP46DOJC2 14735, hereafter referred to as the "K car". Changes in the conduct of the experiments were made as the work proceeded to overcome minor problems and to improve data quality. The experiment evolved into the more effective forms described here.

In the basic experiment, one particle analyzer was placed with its entrance port between the front seats at about waist height. The intake tubing to one hydrocarbon analyzer was taped to the steering wheel. A second hydrocarbon analyzer intake was placed in the trunk, or in the rear seat at about breathing height. Usually, two small fans were used in the auto to improve mixing and representativeness of the data. The second particle analyzer and third hydrocarbon analyzer intake were in the room, away from the tracer release point.

Computers were used to record particle concentrations every 2 minutes (the particles disappeared inside the car so fast that a 3-minute interval was often too long). A Campbell Scientific model 21X data logger, sampling at 1 Hz, was used to record average HC concentrations every minute.

Starting with insignificant concentrations in both the automobile and room, the sprayer would be operated to attain a relatively high and constant isopropyl alcohol concentration in the room, while the increasing hydrocarbon and particle concentrations in the autos were measured. The quickness at which a given room concentration was reached, and the constancy of the concentrations can be appraised from Fig. 3 (manual control) and Figs. 4 and 5 (automated control). The increasing alcohol concentrations inside the auto were used to determine air exchange rates, Q_1 or Q_2 (as from Figs. 3 and 6) for the AC off and on, as explained later.

After enough alcohol concentration data inside the auto were available to determine air exchange rates, the car doors were opened to obtain a high concentration of particles in the automobile (as done at about 62, 88, 108, 128, and 158 minutes in Fig. 7). The particle count data shown in Fig. 7 portray many features of a successful particle experiment, and can be used to assist in understanding the following description. While the car doors were open, the AC could also be turned on or off (the AC was turned off at about 128 minutes in Fig. 7), then the car doors were

closed, and the decays of alcohol and particles inside the car monitored while the outside concentration of alcohol was maintained constant.

Note that for the first 60 minutes of the test in Fig. 7, the inside particle concentration was only about 0.01 of that outside the car. This result was quite unexpected, and for several initial experiments we thought that something must be wrong with our equipment, calculations, or experiment design. After some analysis, the air conditioning system was credited with greatly enhanced particle deposition.

The concentrations inside the car and in the room were compared when car doors were opened. The hydrocarbon analyzers compared very well, and were adjusted to the calibration gas standards between experiments. The particle analyzers did not compare closely, as evident when the car doors were open in Fig. 7. The data from the particle analyzer in the room were therefore used primarily to assure that the room concentration of particles was sufficiently constant in each experiment, and as a qualitative check on the performance of the sampler inside the auto.

If the interior concentration was sufficiently high, the car doors could be kept closed, and the room quickly aired out to obtain the decay of alcohol and particles with an outside concentration of near zero. This method was successful when the AC fan was off. However, the exchange rate is higher when the AC fan is on. In this case the inside concentrations will merely track the rate of change of concentrations in the room, unless the room is cleared almost instantaneously. A strong indication of this tracking is evident if the exchange rate appears to have different values when the inside concentration is increasing versus decreasing.

Because the decay rate of particles inside the car is so rapid, one can expect that the particles inside the car will quickly reduce to the equilibrium I/O ratio, and thereafter faithfully track a slow or moderate rate at which the outside concentration decreases. In the test shown in Fig. 7, the outside concentration decreased very rapidly after the room was aired out at about 175 minutes, more rapidly than the inside particle concentration decreased. The inside decay of -9.72/hr was comparable to those measured on the same and other days with a nearly constant outside concentration. Since it was quite linear (on a semi-log plot) for 15 minutes, it was accepted as the best measurement of b with the AC off for the K car.

The inside concentration of gases also appeared to track changes in the outside concentration when the AC was on, because of an enhanced air flow into the car from outside. After this problem was discovered, in order to obtain some particle data with an outside concentration of zero, the room was kept open and ventilated, particles were briefly generated inside the car, and the subsequent decay monitored (an example is shown in Fig. 8). These decay rates were comparable to those observed when the car doors were opened and then closed (Fig. 9). Of course, with this procedure one could not obtain I/O ratios.

4.2 Application to Other Automobiles

Having established that the theory and experimental techniques were compatible for the K car, it was then possible to conduct definitive, quick, and less exhaustive experiments on other autos. The basic experiment for other autos followed the following protocol, which is an abbreviation of that used for the K car.

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As before, one particle analyzer was placed on the front seat and an intake for a hydrocarbon (HC) analyzer was attached to the steering wheel; a second particle analyzer and HC intake were placed in the room, well away from and upstream from the paint sprayer. The intake to the third HC sampler was usually placed in the back seat of the car or van, or sometimes at a different site in the vehicle trunk, or in the room to check on mixing.

While spraying at the rate needed to maintain a high concentration of alcohol in the room, the rates of increase of alcohol and 2 μm particle concentrations inside the car were used to determine infiltration. The car doors were then opened and closed several times to obtain the decay rate and I/O ratio of particles with AC on and off.

5. DETERMINATION OF THE PARAMETERS FROM THE DATA

The exchange rates (a) and decay rates (b) for the K car are given in Table 1. From these results, it was possible to determine the values of the parameters in Equations (2) and (3), in the following manner.

The value of f, the fraction of particles escaping capture during ingress into the car, was assumed to be nearly 1.0. Cristy and Chester (1981) reported that there was no evidence of such ingress capture of 2 μm diameter spores in their experiments with buildings. All of the data in these experiments with automobiles were compatible with this assumption. However, as particle size and deposition velocities are increased, at some point the fraction penetrating into the shelter should decrease.

Q_1 was obtained from the initial increasing or decreasing slope of the nondepositing gas with the AC off. This is the "exchange rate" referred to in the literature on natural infiltration of residences or other shelters (this exchange rate is often denoted as "R" in the literature). For this K car, Q_1 was variously measured[2] as 0.42, 0.46, 0.38 (this experiment is shown in Fig. 3), and 0.51/hr. A value of 0.5/hr seemed to represent all of the experimental data adequately, except for some values measured on July 26. The latter will be discussed separately.

Q_2 was obtained from the initial increasing slope of the nondepositing gas with the AC on (such as can be seen in Fig. 6). This is the flow of outside air forced or drawn into the car by the AC system and/or fan. It was assumed that the pressurization inside the auto by the AC fan effectively halts natural infiltration. Consequently, it was assumed that $Q_1 = 0$ when the AC is on. A value of 2.5 hr^{-1} for Q_2 seems to represent all of the experimental data adequately.

The decay slope of the particles with the AC off is $fQ_1 + v_d A$ (Equation 5). This value is in the column headed "b" in Table 1. This value is the "virtual exchange rate" (or R^*, referred to in Engelmann, 1990.) The best measurement of b with the AC off is believed to be 9.72. Q_1 is evaluated as 0.5 hr^{-1}, and f is believed to be near 1.0, so $v_d A$ is deduced to be 9.22 hr^{-1} with the AC off. This value is independently supported by the fact that the initial slope of the inside

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[2]The provision of several significant digits in the parameters in this report is not meant to imply that the numbers are that accurate. They are used to convey the degree of repeatability of the experiments, to help in distinguishing between experiments, and to avoid inadvertently losing information.

concentration on July 27 at 1713 was 9.17 hr^{-1}, just after the car doors were opened to the room particle concentration and then closed (recall that $dC_i/dt = - v_d A C_i$ when $C_i = C_o$, with the AC off.)

The ratio a/b is the expected equilibrium ratio of inside/outside concentrations of particles, I/O, when the outside concentration is constant. With the AC off, measurements of the I/O on three different days ranged from 0.039 to < 0.06 (Fig. 10 and Table 2). The ratio (0.5/9.72) has the value of 0.051, showing that f can be assumed to be near 1. In words, the experimentally derived $Q_1/(Q_1 + Q_2 + v_d A)$ has the same value as the I/O ratio, which by theory must equal $fQ_1/(Q_1 + Q_2 + v_d A)$. This good agreement supports the use of a value of near 1 for f.

The sum of $Q_1 + Q_2 + v_d A + (1-f_r)Q_r = b$ is the decay slope of the particles with the AC on. This slope had the value of 55.9 hr^{-1} in eight successive measurements on August 21 (some of these are shown in Fig. 8). Other less definitive experiments (where particle concentrations were much lower) support this value. Experiments on August 24 with the AC off, but with the AC fan on (Fig. 11), had slopes very similar to those with the AC on. Using the values of $Q_1 = 0$ and $Q_2 = 2.5$, one concludes that $v_d A + (1-f_r)Q_r = 53.4$ hr^{-1}.

At this point it would be agreeably convenient to assume that the deposition velocity was not enhanced by the AC fan, and substitute $Q_2 + v_d A = 11.72$ hr^{-1} to obtain a value of 44.18 hr^{-1} for $(1-f_r)Q_r$. The equilibrium value of I/O with the AC on is $f_r Q_2/(Q_2 + v_d A + (1-f_r)Q_r$. This was measured several times as near 0.013 for 2 μm diameter particles. These two equations in f_r and Q_r can be solved to deduce that $f_r = 0.29$, and that $Q_r = 62.2$ hr^{-1}. (These values are later used to create the curve in Fig. 12.)

However, it is clear from the data that the AC fan <u>is</u> enhancing deposition inside the car, and that $v_d A$ is different when the AC fan is on from when the AC fan is off. I/O ratios with the AC off but the AC fan on were 0.019, 0.041, 0.021, and < 0.04. Part of an experiment providing these ratios is shown in Fig. 11. These ratios are half of those with the AC fan off, and somewhat larger than those with the AC on, as listed in Table 2. With the limited time available, it was not appropriate to expend further effort to resolve the several parameters composing the slope b when the AC fan is on.

6.0 DISCUSSION

Calculations of concentration versus time were set up on a Lotus 1-2-3 spreadsheet, which made it easy to verify the effects of different values of the parameters. Such programs can also provide estimates of the parameters by trial fitting of the curves even when the slopes of the concentrations are changing. This was done, for instance, to estimate that the I/O ratio for 2 micrometer particles on August 16 at 1524 would have reached 0.046 if the experiment had not been terminated early. Curve fitting was also used to determine an exchange rate of 0.9 hr^{-1} with the AC off on July 26 at 1328, despite a non-constant, slow decrease in the outside concentration. These estimates are not as reliable, but can be used to extract useful information from experiments in which the desired endpoints are not attained.

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Table 1. Summary of data for K car and garage. Gas is isopropyl alcohol and particles are 2 μm unless noted. The coefficients a and b are those of Equation 2 and Equation 3 respectively. The values of coefficient a were obtained with increasing (i) and decreasing (d) inside concentration, as noted.

DATE/TIME	TRACER	a (/hr)	b (/hr)	REMARKS
AC OFF				
5/16/1435		0.42 (d)		
5/16/1920		0.46 (d)	4.83?	
7/23/1630		0.38 (i)		
7/24/1450		0.51 (i)		AC on but fan inoperative
7/25/1425		4.26		
7/26/1328	ethane	0.9 (i)		est. from curve fit
7/26/1430	ethane	0.43 (d)		
7/26/1712	ethylene	1.01 (d)		
7/26/1733	ethylene	1.15 (d)		AC off, but large fan in car
7/26/1904	ethylene	0.87 (d)		
7/26/2026		1.09 (d)		AC on but fan off
7/27/1627			10.65	
8/16/1524			11.8	
8/16/1548			9.72	
8/24/1305			8.67	
AC OFF, FAN ON				
7/26/1300		2.90 (d)		
7/26/1604	ethane	1.56 (d)		
AC ON				
7/24/1659		1.96 (i)		slope of 2.5 will fit
7/26/1512	ethane	3.41 (d)		
7/26/1929	ethylene	3.21 (d)		
7/26/2040		3.23 (d)		
7/27/1345		2.49 (i)		
7/27/1518		2.45 (i)		
8/15/1319		2.45 (i)		
8/16/1420			58.5	
8/16/1450			55.9	
8/21/			55.9	
GARAGE				
7/23/1710		0.64 (d)	1.063	mix of 2 & 7 μm
7/26/1330	ethane	0.64 (d)		

(Note: Garage A/V ratio without ceiling 0.814/m, with ceiling 1.12/m)

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Table 2. Inside/Outside (I/O) data for autos tested

Date/time	Operating Condition	I/O Ratio	Remarks
1988 Plymouth 4 door ("K car")			
8/16/1524	AC OFF	0.046	Est from curve fit
7/27/1710	AC OFF	0.042	3 μm particles
8/24/1216	AC OFF	0.039	
8/24/1257	AC OFF	0.045	
8/24/1340	AC OFF	< 0.06	
8/24/1505	AC OFF, FAN ON	0.019	
8/24/1524	"	0.041	
8/24/1541	"	0.021	
7/27/1624	AC ON	0.00353	3 μm particles
8/16/1414	"	0.013	
8/16/1430	"	0.008 - 0.015	
8/16/1450	"	0.014	
8/16/1515	"	0.015	
1990 Oldsmobile Cutlass Ciera S			
8/29			
	ENGINE & AC FAN OFF	0.05	
	AC & FAN OFF	0.041	
	AC ON HIGH	0.071	
	"	0.082	
	"	0.066	
	AC OFF, FAN ON HIGH & VENT	0.46	
1988 GMC Pickup, separate camper shell, 75,000 miles			
8/28/1200	AC OFF	0.16	
8/28/1251	AC ON	0.022	
8/28/1310	AC ON	0.020	
8/28/1408	AC OFF	0.137	
1978 GM Suburban 4WD, est. 100,000 miles			
Note: No AC available, only fan and vent			
8/27/1740	FAN ON	0.705	
8/27/1512	FAN OFF	0.178	
1982 Buick Regal, 4-Door, 158,605 miles			
(This auto burned oil and the exhaust particles may have overwhelmed the 2 μm tracer particles.)			
8/30/1228	AC ON	0.13	
8/30/1300	AC OFF/FAN ON	0.56	
8/30/1318	ALL OFF	0.07	

The values of $Q_1 = 0.4$ hr^{-1}, $Q_2 = 2.5$ hr^{-1}, $v_dA = 9.22$ hr^{-1} for particles, $v_dA = 1.25$ hr^{-1} for isopropyl alcohol, $Q_r = 62.2$ hr^{-1}, and $f_r = 0.29$, as derived above from the various tests, and the observed outside concentrations were used to "predict" inside concentrations for some of the tests with the K car. These predictions are provided for comparison to plots of the experimental data (Fig. 9 and Fig. 12; Fig. 10 and Fig. 13; Fig. 14 and Fig. 15). The agreement between the data and these solutions is quite good, indicating that the experimental techniques, theory, and extraction of independent parameters from parts of different experiments give consistent results when applied to a particular event.

Because a high and constant outside concentration could not be achieved instantaneously, zero time is not known exactly for these tests, and closer fits than these can be obtained by very small adjustments in zero time. Even closer fits could be obtained by fine-tuning the parameters to fit individual experiments, but this would not demonstrate that a set of parameter values derived from different experiments can reasonably describe a particular experiment.

The results show that a limited amount of data may be sufficient to adequately predict concentration of gases and particles in a stationary auto. However, there remain some uncertainties and unresolved problems for further research.

6.1 Uncertainties and Unresolved Problems

Usually, only one HC sampler and one particle analyzer were used to measure the concentrations in the room. It has been assumed that, when these values are constant, they represent the concentration surrounding the car, and that the room air is sufficiently well mixed for deducing exchange rates.

The exchange rates, or Q_1 and Q_2, for the tests on July 26 do not agree with those on other dates. On July 26 a high initial inside concentration of gas was attained by opening the car; then, with a closed car, the room was aired out, and the inside concentration was allowed to decay over more than 2 hours. Several times during this decay, after a new slope was determined with some confidence, the car doors would be opened and the AC settings changed. An experiment with increasing ethane and the experiments with decreasing ethane, ethylene, and alcohol yielded essentially the same decay rates. We are as yet unable to explain this difference of July 26 from other dates.

There was initially some concern that the introduction into the cars of the several sampling tubes, signal cables, and power cords needed for the instruments would affect the exchange rate. These were placed between the doors and the door frames, and not through the windows or special openings. The repeatability of the experiments suggested that this was no problem, and it is believed that the small leakage introduced by the insertion of the lines would be within the range of variability that would be found between cars of the same model with different fitting door gaskets. The protection offered by the car should be the same or slightly better in the absence of these minor leaks. The experiments were intended to determine the protection offered for particles, not gases in particular, and there is no indication that the conclusions as to particles have been compromised.

There is also the experimental challenge of suddenly going from an outside concentration of zero to a high, well-mixed, and constant value. For some experiments, a plastic tent was put over the

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car and taped to the floor while the concentration in the room was created. The intent was to remove the tent when a sufficiently high and constant concentration was reached in the room. The rate of diffusion of the gas into the car was decreased by the presence of the tent, but still occurred while the tent was in place (as can be seen in Fig. 3). Nor did the automobile engine stall for lack of air.

These leaks, and the fact that the tent could not be removed instantaneously, made it difficult to determine a zero time. Nevertheless, the data were quite adequate to provide Q_1 at small values of time after the tent was removed, and to quantify the curvature of the concentration-time of the gas. The most essential data are those of the particulate I/O particle concentrations, which do not require a zero time, and for which a tent is not needed. For these reasons, extraordinary efforts were not made to make the tent leakproof, and its use was abandoned as a "nice idea" that was not necessary.

Minor time discrepancies, usually about a minute or so, can be found in the data as to the precise times of observation, and as portrayed in the figures in this paper. These discrepancies are too small to affect the interpretation of the results. They arise from the mix of hand-written log books, automated data logging, and the use of sampling intervals that are not integer multiples of minutes.

When spraying was stopped, if the room doors were not opened, concentrations of gases and particles in the room decreased exponentially, as predicted from theory. From these decay slopes, exchange rates for the room were determined.

Ethane was found to have exactly the same decay rate in the room as isopropyl alcohol. However, there is good evidence that the alcohol vapor is diffusing into the myriad of small reservoirs inside the auto, such as the upholstery, glove box, under the dashboard, etc., and later outgassing. This is equivalent to a multi-compartment situation, where the second compartment is closed to the outside, and the flow into the main compartment is small. Absorption of the gas should not affect the initial slope of the increase or decrease of the gas, and therefore one can obtain Q_1 and Q_2, but it does change the curvature of the concentration versus time, laying the curve over so that the inside concentration takes a significantly longer time to reach the value of the outside concentration.

From the theory, for a non-depositing contaminant, the difference between inside and outside concentration, $C_o - C_i$, should be linear when plotted in semi-logarithmic coordinates. This did not strictly apply for alcohol. A small departure can even be seen when the AC is on, as can be seen in Fig. 14. The observed departure from theory can be approximated by introducing a false deposition rate for the alcohol, as was done to create Fig. 15. However, use of a deposition does not allow the inside and outside concentrations of alcohol to eventually become equal, whereas it was observed in multi-hour-long tests that the inside concentration does approach the outside concentration. When the automobile was left closed after a test was terminated, a strong odor of alcohol was still evident inside the auto the following morning. This occurrence suggests reversible deposition or storage in crevices and upholstery.

Measurements on May 16, July 23 (Fig. 3), and July 24 (Fig. 16) showed that alcohol increased and decreased in the passenger compartment at close to the same rates as in the trunk, with the trunk lagging somewhat. This indicates that Q_1 was somewhat less for the trunk. The inside concentration of the alcohol in Fig. 16 also shows a changing slope during decay, between 1723 and 1735, probably resulting from a combination of offgassing and some feedback from the trunk. The trunk would have to be treated as a second compartment if one wished to more precisely

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describe the passenger compartment concentration of a gas over a long period of time. It was not necessary to better define the behavior of the gases in order to predict the behavior of particles, so the complexities of using a multi-compartment model were not introduced.

Before the experiments were conducted, an air pump was first used to force air into the K car, and later to draw it from the car; the same absolute air flow was observed for the same absolute inside-outside pressure difference. This was interpreted to mean that preferential flow directions did not exist, that is, that "one-way valving" did not exist that would produce a difference in Q_1 according to whether the concentrations were increasing or decreasing. Still, despite theory, there was a concern that different exchange rates might be observed depending upon whether the inside concentration was decreasing or increasing. As can be seen from Table 1, the gaseous exchange rates were not substantially affected by the outside concentration.

Two small fans were used to mix the air inside the car, and the concentrations of hydrocarbons measured in the rear seat were similar to those in the front seat. There was a concern that these fans, used to improve the likelihood that measured concentrations would be representative, might affect the deposition of particles. However, the flow from these fans was much less than that of the AC fan when the AC was on. To verify whether there was an effect from the mixing fans, in one test on July 26, a large floor fan with a high flow rate was placed in the driver's seat when the AC was off. It had only a small effect, if any, on the slope of the concentration of the gas.

The high flow and associated turbulence with the AC operating clearly increase the deposition of particles inside the AC system and inside the passenger compartment of the car. Measurements did not permit the determination of what fraction of the particle decay with the AC on was due to enhanced deposition in the car, and what fraction of the particles was removed in the AC itself. A series of measurements on August 21 showed that the concentration of particles in air flow coming from the AC was less than that in the rear seat. However, these measurements were not consistent and are not easily interpreted in view of the uncertainty over representativeness of the concentrations. It did not appear that the particle concentration in the air coming from the AC was as low as 0.29 of the concentration in the rear seat. (Recall from Section 5, "Determination of the Parameters from the Data", above, that if the AC fan were not enhancing deposition, f_r would be estimated from these experiments as 0.29.)

With the very rapid decay of particles, it seems impractical to resolve the several factors affecting removal: mixing inside the car, enhanced deposition in the passenger compartment, and the separate "filtering" by the AC (the deposition within the AC and its ducts). Fortunately, application of the I/O ratio does not depend upon knowing the relative contributions of the separate removal mechanisms.

The parameter v_dA can be regarded as a single variable, but it would be pleasing to be able to quantify its two components. If the effective interior deposition area, A, were known, then in theory one could predict the influence of changes in particle size by introducing their respective deposition velocities. The deposition velocities under low turbulence for 2 and 3 μm particles are probably 0.014 and 0.03 cm/s respectively (Sehmel 1984). Values of A/V = 18.2/m (5.55/ft) and v_d = 0.013 cm/s yield a deposition of v_dA = 9.22 hr^{-1}. (As a matter of interest, Peterson and Sabersky (1975) estimated a value of A/V = 23/m for their "stock Chevrolet" using I/O measurements of ozone.)

The single measurement of I/O of 0.00353 for 3 μm particles on July 27 at 1624 is a factor of four lower than would be predicted by substituting 0.03 cm/s into v_dA and keeping other parameters the

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same as were used to fit the 2 μm decay rate and equilibrium I/O ratio. Perhaps the high air flow with the AC is significantly affecting the possibility of extrapolating to other particle sizes. In effect, the product $v_d A/V$ presently can be regarded as a single empirical parameter for which the data are very inadequate. This matter of deposition within shelters is clearly a high priority research area.

Sehmel (1973) predicted significant differences in deposition to floors, walls and ceilings, with the difference being very dependent upon particle size, and on turbulence and air velocity. Following Sehmel, for low turbulence, the deposition of 2 μm particles on the ceiling is predicted to be orders of magnitude smaller than that on walls and floor.

It must be noted that the experimental data and theory agree closely for the room. The value of A/V for the room is 0.81/m (0.248/ft) without the ceiling area and 1.12/m (0.34/ft) when the ceiling is included. A deposition velocity of 0.014 cm/s, A/V of 0.81/m, and Q_1 of 0.64/hr as measured, predicts $Q_1 + v_d A = 1.05$/hr, very close to the measured 1.063/hr. This gives us considerable confidence in the experimental measurements for the auto. It also gives support to the idea that the ceiling area should not be included in the interior area when buildings are considered as shelters. Although that is not relevant to this study on autos, it is relevant to other studies on buildings as shelters (Engelmann, 1990).

7.0 DOSE REDUCTION FACTORS (DRF)

For those many contaminants for which effects are linear with the airborne concentration, such as is presumed to be the case for plutonium, it is convenient to define a Dose Reduction Factor (DRF). For this report, which is concerned only with the inhalation pathway, the DRF is equivalent to the ratio of the time-integrated airborne concentrations inside the shelter and outdoors.

For the case where the initial concentration inside is zero, and the shelter is ventilated after cloud departure, the DRF is the integral of C_i (the integral of Equation 4) divided by $C_o T$, the integral of the outside concentration:

$$DRF = \frac{a}{b}\left(1 - \frac{1}{bT} + \frac{1}{bT}\exp(-bT)\right) \tag{7}$$

where a/b = I/O at equilibrium. Thus

$$DRF = \frac{I}{O}\left(1 - \frac{1}{bT} + \frac{1}{bT}\exp(-bT)\right) \tag{8}$$

The DRF for a contaminant that deposits will always be smaller than the equilibrium I/O ratio. The DRF will be even less (that is, better protection is offered) for plumes that surround the shelter for times less than needed to reach the equilibrium I/O.

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8.0 CONCLUSIONS

8.1 Particles

The experiments demonstrate a rapid decrease of inside concentration when the inside concentration is significantly greater than that corresponding to the equilibrium I/O ratio. This decrease is especially rapid with the AC system fan on. The concentration of particles in the closed vehicle will thus always be less than that outdoors, even as the cloud is departing, unless the departure is quite abrupt as was the case on August 16 (shown in Fig. 7). Very little additional dose saving can be achieved by ventilating the vehicle, whereas there is some associated risk. *Therefore, it is not necessary to "air out" the vehicle for 2 μm and larger airborne particles, and this should not be done unless one is certain that the cloud has departed.*

Because the particle concentration inside the car changes so quickly to its equilibrium value with the AC fan or other fan on, the Dose Reduction Factor will be less than, but quickly approach, the equilibrium I/O ratio (see the very start of the test of August 16, shown in Fig. 7). For this reason, observed I/O values for 2 μm particles are most important, and are presented for the various automobiles tested up to the time of this report (Table 2).

However, with the AC fan off, the particle concentration does not increase to its equilibrium I/O ratio nearly as rapidly. For instance, refer to the plot of particles for the GM Suburban 4WD without an AC or fans operating (Fig. 5). Although the I/O for this vehicle is 0.18 with the fan off, the inside concentration is considerably less than 0.18 of the outside concentration for the first ten minutes of the cloud. For this vehicle, the I/O was 0.70 with the fan on, and this concentration will be more quickly reached when the fan is operated, as we observed from Fig. 7 for the K car.

One should expect that all AC systems will introduce additional outside air. For some autos, such as the K car and 1988 GMC Pick-up, the high deposition by the AC fan more than offsets this leakage, and the I/O ratio is less with the AC on. For some, such as the 1982 Buick and the 1990 Oldsmobile, the I/O ratio is less with the AC off. The fifth car tested (GMC 4WD) did not have AC.

None of the designs of the AC or ventilation systems on these five vehicles were investigated. It was reported to us by the project technical monitor that Ford advised him that, for most Ford vehicles, when the AC is on "recirculate", there is no makeup air admitted into the system. Chrysler also advised that this was true for most of their vehicles and trucks. However, General Motors advised that when their systems are on "recirculate" or "maximum", the amount of makeup air may vary from 0 to 100%, depending on the make and model, and whether or not the system is an automatic computer-controlled air handling system. They advised that many of the GM air handling systems also depend on ambient air conditions as to whether or not they provided makeup air.

We have not determined the specifics of the particular 1990 Oldsmobile and 1982 Buick used in these tests, or the effect of the ambient (room) conditions. Therefore, for these cars, it may be that the amount of outside air may change dramatically with changing indoor/outdoor temperatures and with AC and heater settings. A sufficient range of vehicles has not been tested to date to provide an estimate of the risk of an operating AC bringing in substantial outside air.

For all of the five vehicles tested, the I/O ratio was less than 0.2 for particles with the fans off, and the DRF would be even less. However, for two of them, the I/O was ≤ 0.02 with the AC on. Although the I/O ratios are small, whether they are smaller with or without the AC fan operating

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depends upon the particular vehicle among those tested. *For these reasons, if the cloud is of short duration, the best overall public guidance to optimize protection may be to keep the AC fan or other fan system off, to minimize any substantial introduction of outside air that might exist for some autos.*

As evident from the GM 4WD and 1990 Oldsmobile results (Fig. 17), *it is imperative that systems not be operated in a vent setting with the fan operating.*

8.2 Gases

Note that it is quite likely that an operating AC will bring in some outside air and thereby reduce the protection against toxic gases during the presence of the cloud. Therefore, if the contaminant is a gas, it is probably advisable to not operate the AC and fan. However, as it is for particles, the sheltering ability of autos against inhalation of gases is affected by whether the gas has a significant removal on the interior surfaces. These experiments did not address a variety of depositing gases and the effects of fans and AC systems on them.

Only for nondepositing tracers, the exposures inside and outside will eventually integrate to the same values if the occupants do not exit and the air exchange rate remains constant (i.e., the shelter is not aired). For example, Fig. 16 shows substantial inside concentration of alcohol that is only slowly decreasing after cloud departure at 1723. For this reason, it has generally been recognized that a shelter should be aired after passage of the cloud (such was done for the K car at time 1735 in Fig. 16).

However, unless the cloud is of a long duration, it is almost certain that the inside concentration of a gas in a stationary automobile will be less than that outside for all the time that the cloud is present. This is illustrated for isopropyl alcohol in the various figures. *Therefore, when the plume is of short to moderate time duration, before airing the shelter there should be strong assurance that the gaseous cloud has substantially passed. Although this is also true for a gas that weakly deposits, such as alcohol, this is particularly true for gases that deposit or react strongly with the interior surfaces.*

8.3 Making Calculations for Application

For emergency planning for potential releases of contaminants to the atmosphere, the solutions of the applicable equations can be readily obtained for a range of parameters. Such calculations can be made for the range of cloud concentrations and durations postulated to occur in different accident scenarios. One could use the parameters measured in this research, or adjust them to account for different interior deposition rates, system leakage, interior area and volume, and infiltration.

Extrapolation from the I/O ratios measured in these experiments to the I/O ratios for other particle sizes is theoretically simple, when the AC fan is off, and is accomplished by changing the value of v_d for 2 μm (0.014 cm/s) in Equation 3 to the appropriate deposition velocity. When a strong AC fan is operating, it may be that the deposition rate of respirable particles is driven by the turbulence and is independent of particle size. If so, then no adjustment to these I/O ratios is needed for respirable particle sizes.

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9.0 FUTURE RESEARCH

There are several important questions to be answered before the sheltering offered by automobiles is adequately defined. These include the air exchange rate for moving automobiles, the deposition rate for various gases and for particle sizes other than 2 μm, the mechanisms of particle removal when the AC system fan is operating, and the protection offered against a variety of gases.

Similar questions exist with regard to a variety of buildings, contaminants, and interior surfaces. The results of continued research will have application not only to emergency planning and response, but also to building and ventilation design, indoor air pollution and pollen evaluations, and exposure minimization in the workplace.

10.0 ACKNOWLEDGEMENTS

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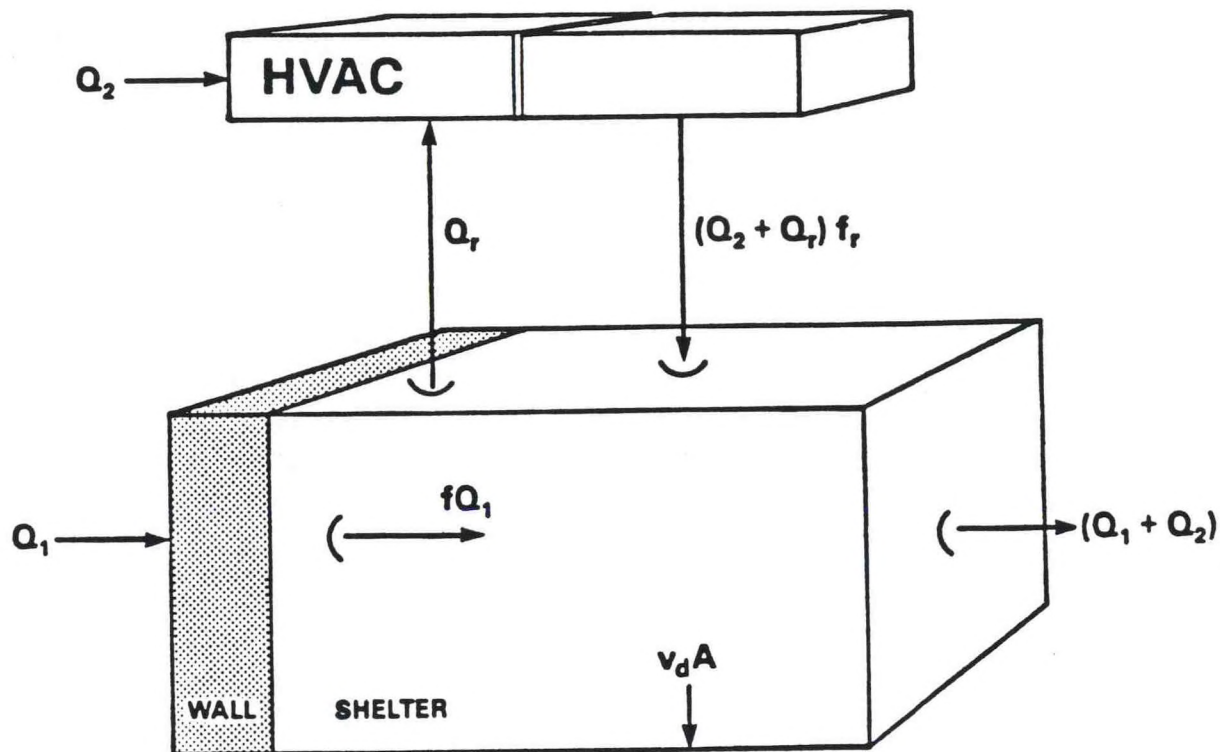
Fig. 1. Diagram illustrating air flows into a shelter and into a shelter's heating, ventilating and air conditioning unit (HVAC), air flow between the shelter and its HVAC, removal of a contaminant by filtration and capture in the shelter wall and HVAC, and removal by deposition within the shelter. The terms are defined in the text.
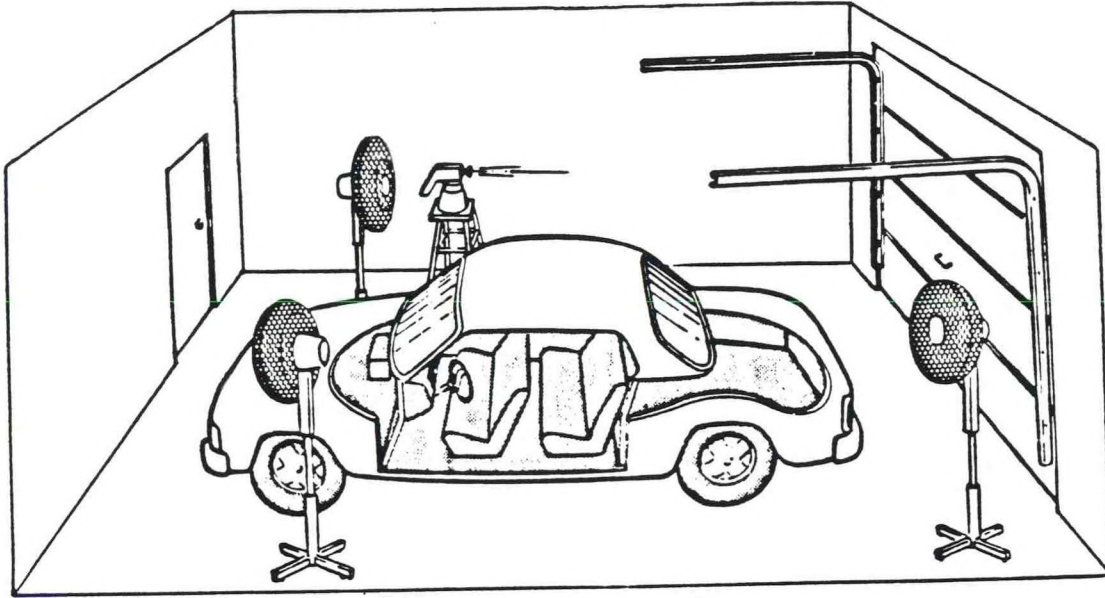
Fig. 2. Room setup, illustrating relative positions of automobile, sprayer and fans.
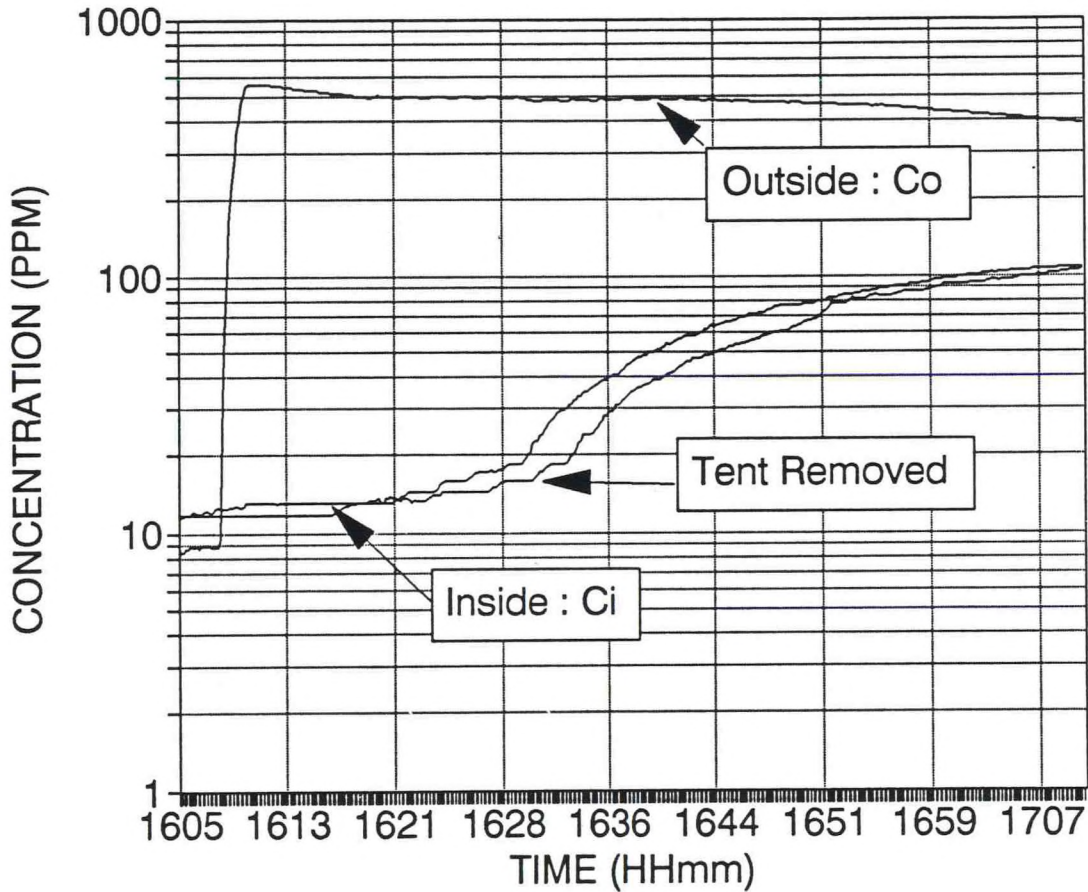
Fig. 3. 7/23/1605-1710 K car. AC off. Alcohol concentrations illustrating initial slopes inside K car passenger compartment and trunk, and the adequate if limited ability to hold outside alcohol concentrations constant by manual operation of sprayer. The exchange rate was 0.38/hr after the tent was removed at 1630. The data suggest that there was minor leakage of the external alcohol into the car prior to the removal of the tent.

8/27/90, GM 4WD, Fans off

Plot — CONCENTRATION (PPM) vs TIME (HHmm). Labels: "Outside : Co" and "Inside : Ci". Y-axis from 1 to 1000 (log scale), X-axis from 1400 to 1510.
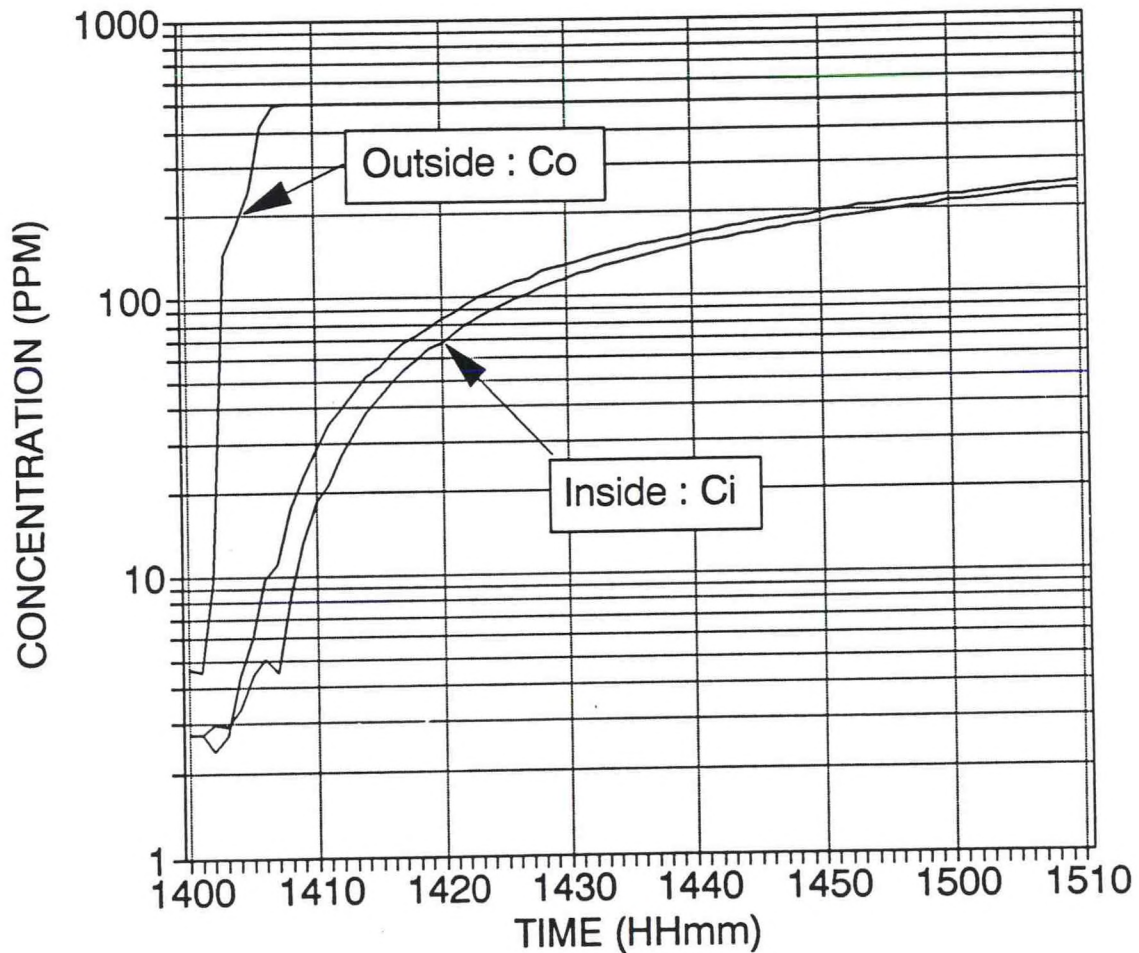
Fig. 4. 8/27/1400-1510. GM 4WD. Fan off. (This vehicle did not have AC.) Illustrating ability to achieve rapid and adequate constancy of outside alcohol concentrations through automated control of the sprayer. The inside concentrations of alcohol were measured in the front and the back of the van. The natural exchange rate was 0.54/hr, and after 30 minutes the inside airborne concentration of the gas has reached about 0.3 of that outside.

8/27/90, GM 4WD, Fans off
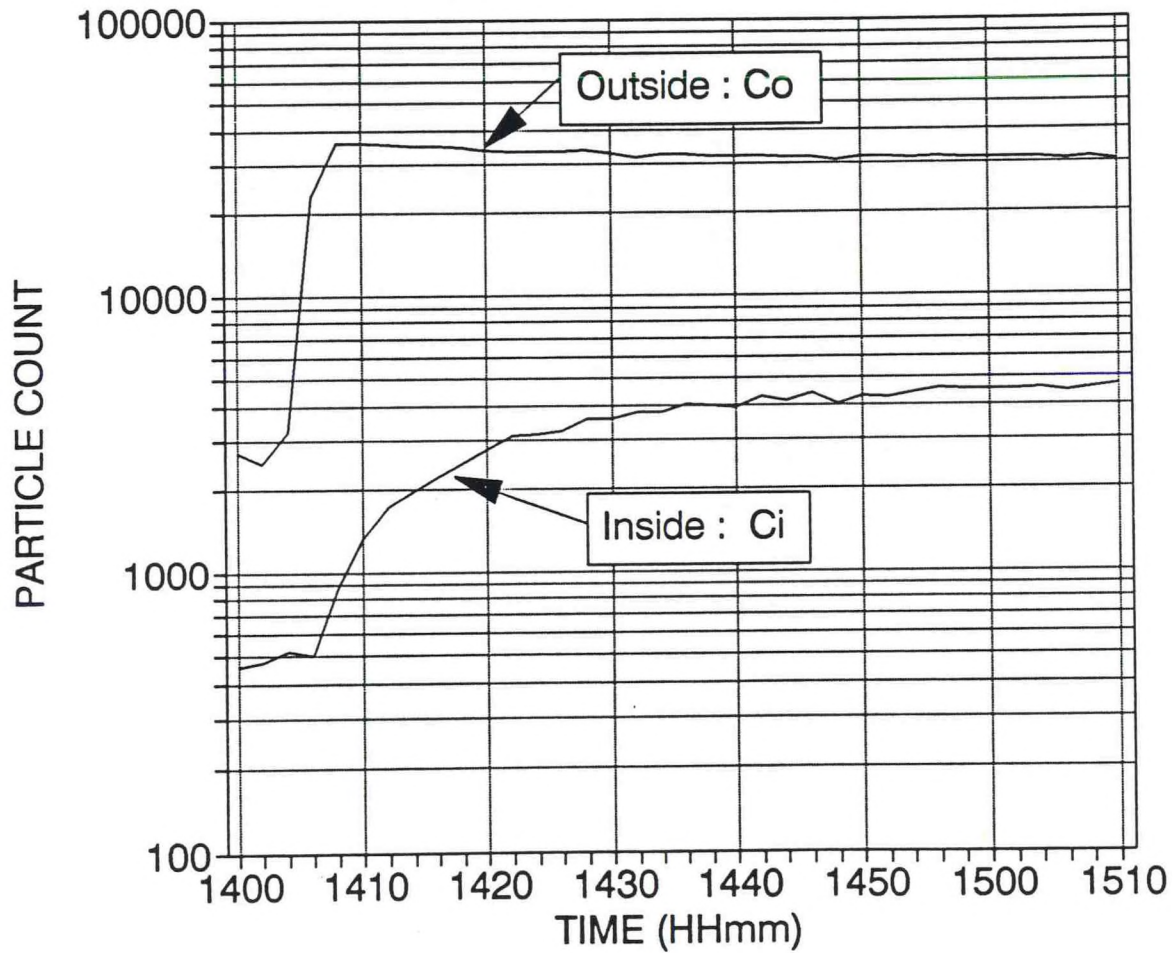
Fig. 5. 8/27/1400-1510. GM 4WD. Fan off, same run as Fig. 4. The outside concentration of particles decreases slowly despite the constancy of the alcohol (Fig. 4), but is sufficiently constant for the experiment. The increasing concentration of particles was measured in the front seat, and approaches an equilibrium I/O ratio of about 0.18 with fans off.
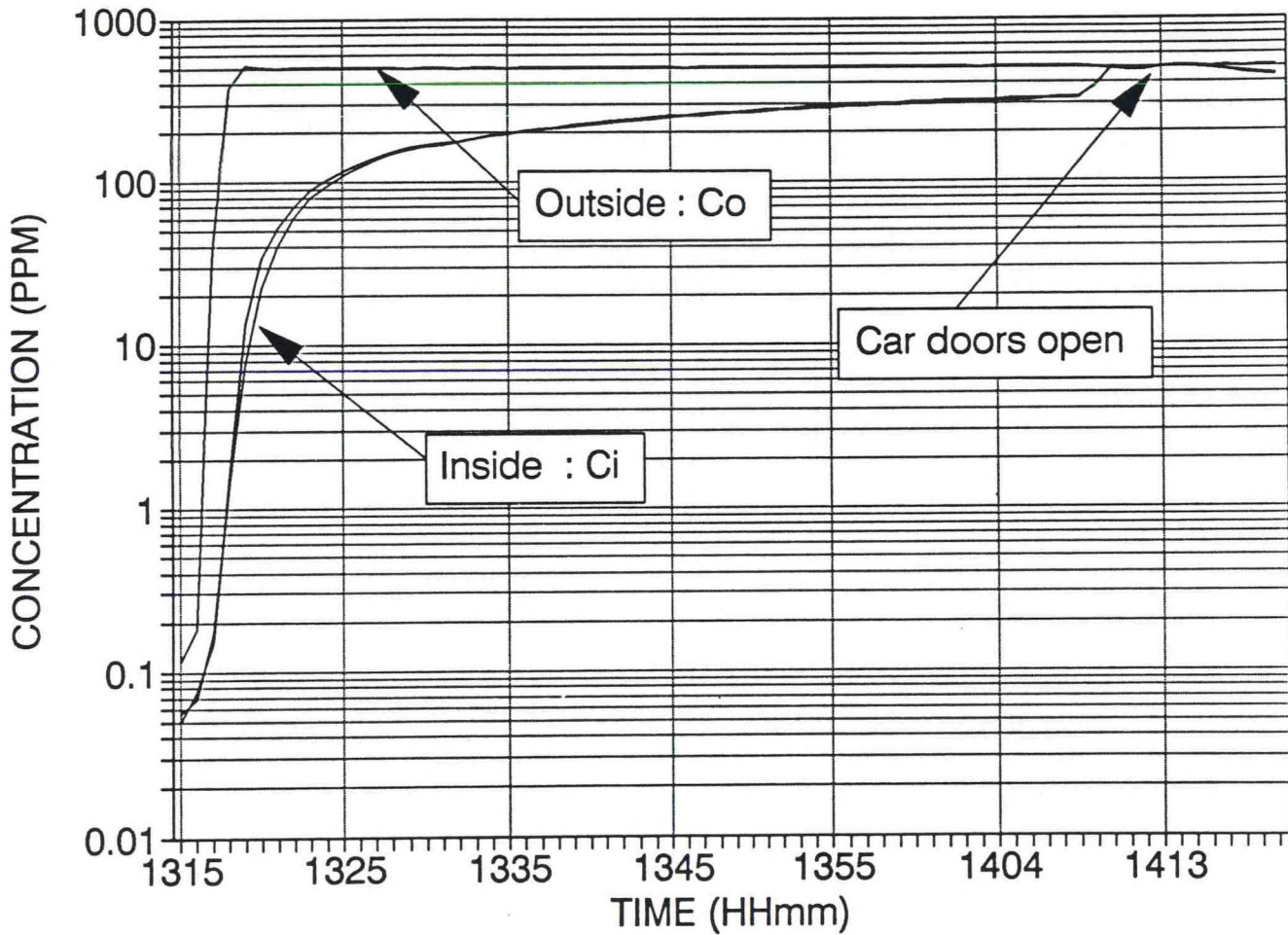
Fig. 6. 8/15/1315-. K car. AC on. Note the more rapid increase of alcohol inside the K car with the AC on, compared to Fig. 3 where the AC was off. The outside concentration was quite constant at 500 ppm. The data from this test were virtually identical to those from tests on two other dates.
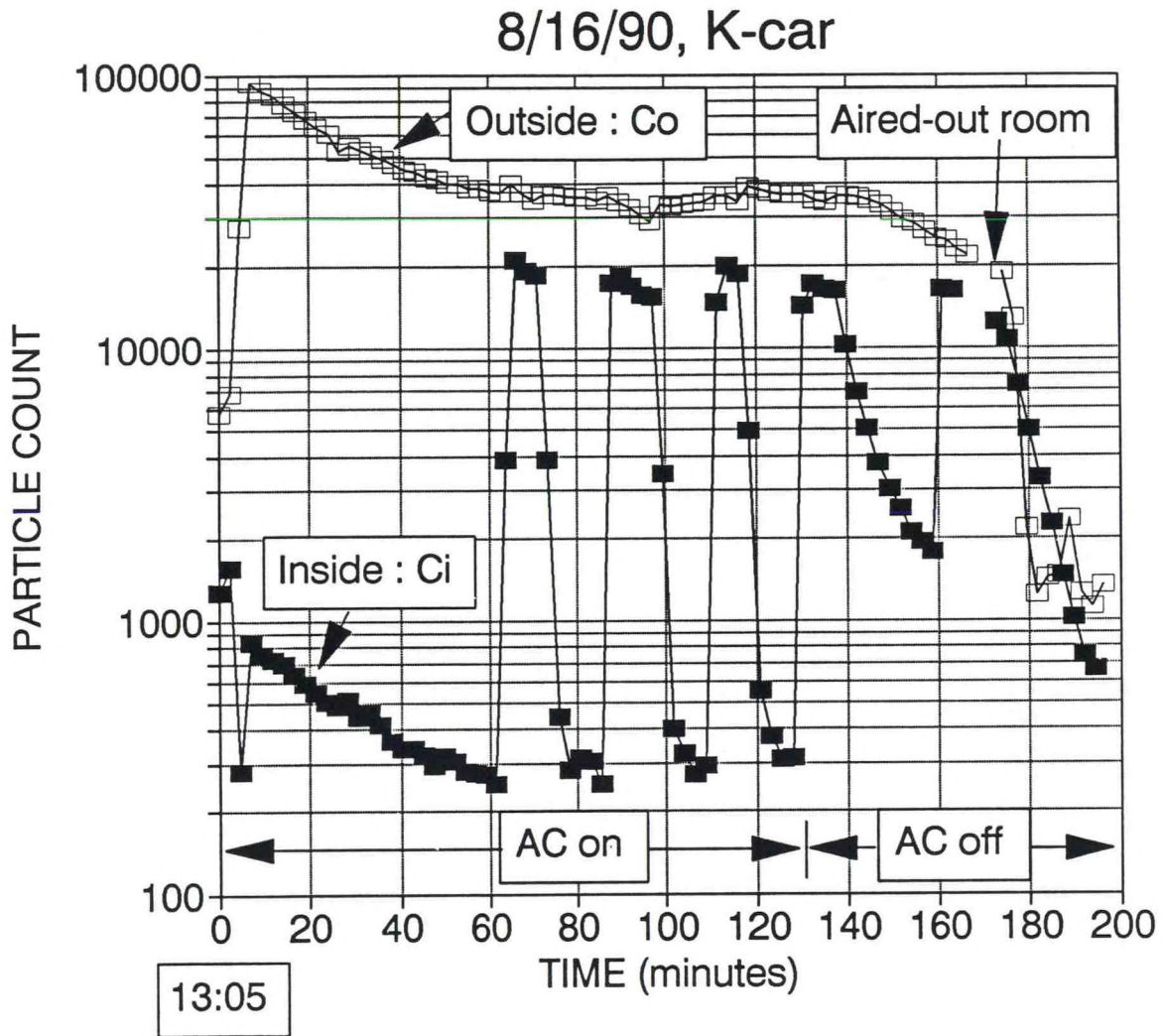
Fig. 7. 8/16/1305-. K car. Complete record of particle concentration during one experiment. Note the rapid attainment of the equilibrium I/O ratio with the AC on at the start of the experiment (1305), and also when the car doors are opened and then closed. This reaching of an equilibrium is more rapid when the AC is on than when off. The room was aired out at the end of this test. The relatively low inside concentration when car doors are closed made it difficult to generate enough particles to get good values of the I/O ratio through a natural exchange process. Therefore, the opening and closing of car doors was introduced into the experimental procedure. This also gives more accurate I/O ratios because the same particle sampler is used for both concentrations.

8/21/90, K-car, AC on
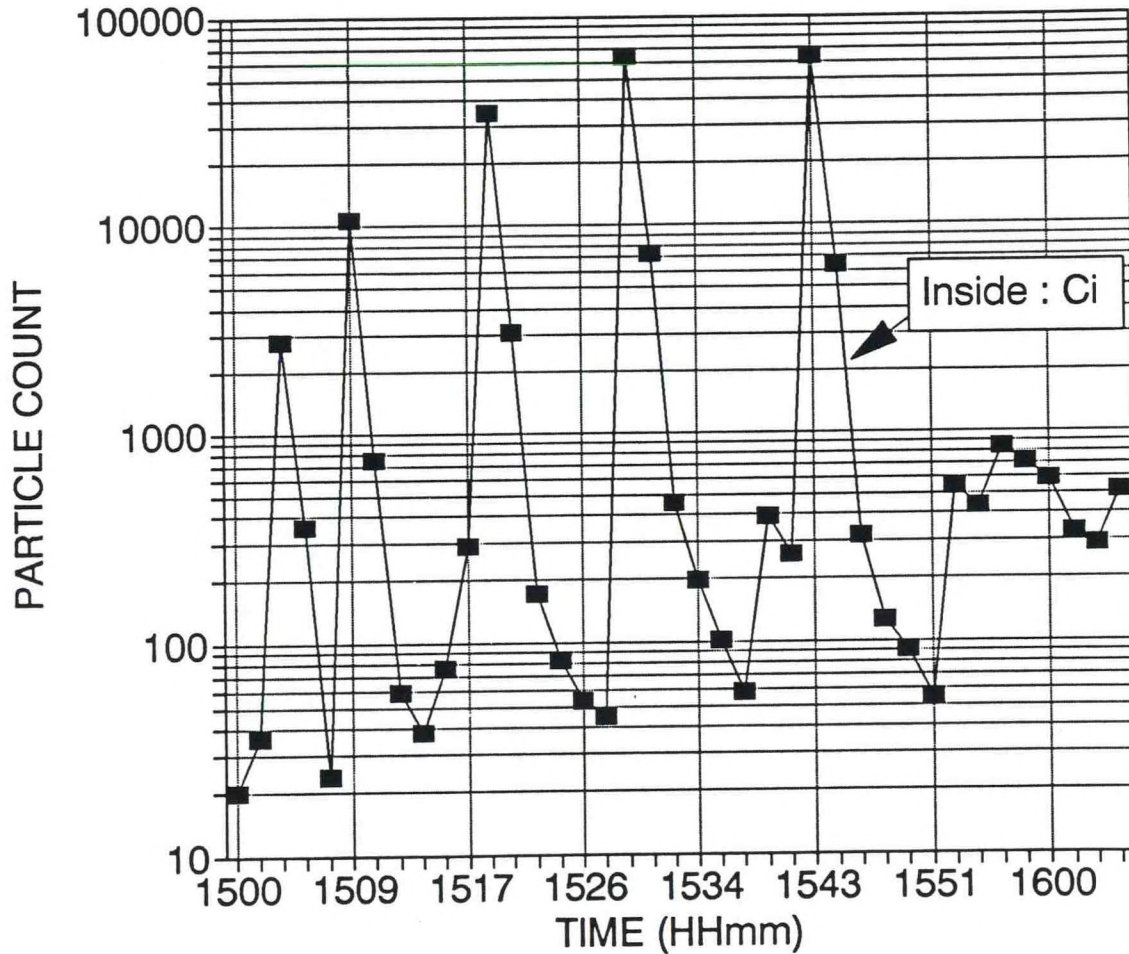
Fig. 8. 8/21/1505-1550. K car. AC on. In this experiment, the outside concentration was kept quite low with the room doors open. The sprayer was operated briefly inside the car at 1503, 1508, 1518:30, 1529, and 1542:30. The car doors were opened in advance of each spraying, and again at 1552. Note that the inside concentration drops 2 orders in magnitude in only 5 minutes with the AC on. From these tests, the parameter, b, for the K car was determined to be 55.9/hr with AC on. There were too few particles remaining in the sprayer to obtain useful data after about 1552.

8/16/90, K-car, AC on
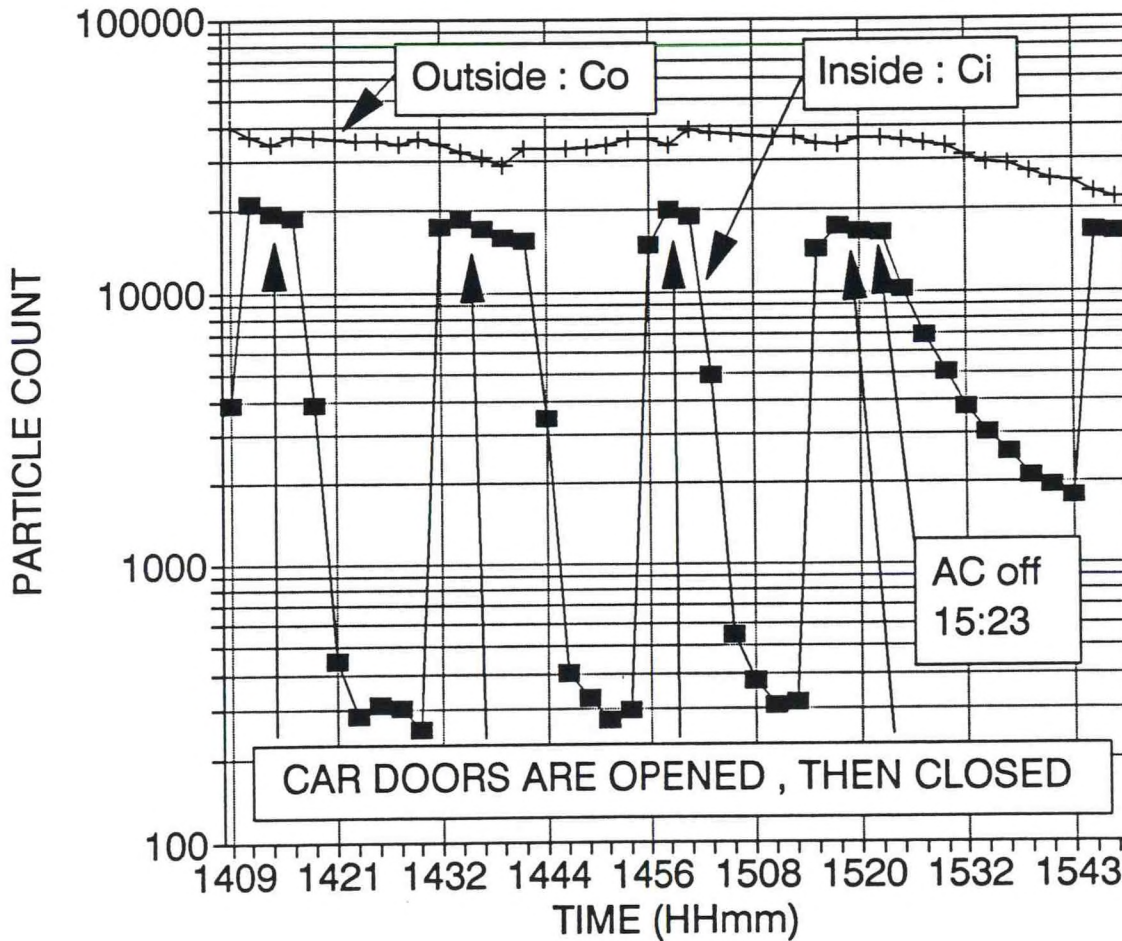
Fig. 9. 8/16. K car. AC on. Illustrating the rapid decrease of 2 micrometer particles inside with AC on, following equilibration with outside concentration and car door closing. The I/O ratios with AC on are about 0.015 in this test. The AC was turned off at 1523, and the I/O ratio subsequently approached 0.046, a value estimated from fitting Eqn. 6 to the data. That the I/O ratios with AC on (0.015) are only a little less than I/O ratios with AC off but AC fan on (0.02) in Fig. 11, suggests that condensation in the AC system does not play a strong role in removing particles.

8/24/90, K-car, AC off
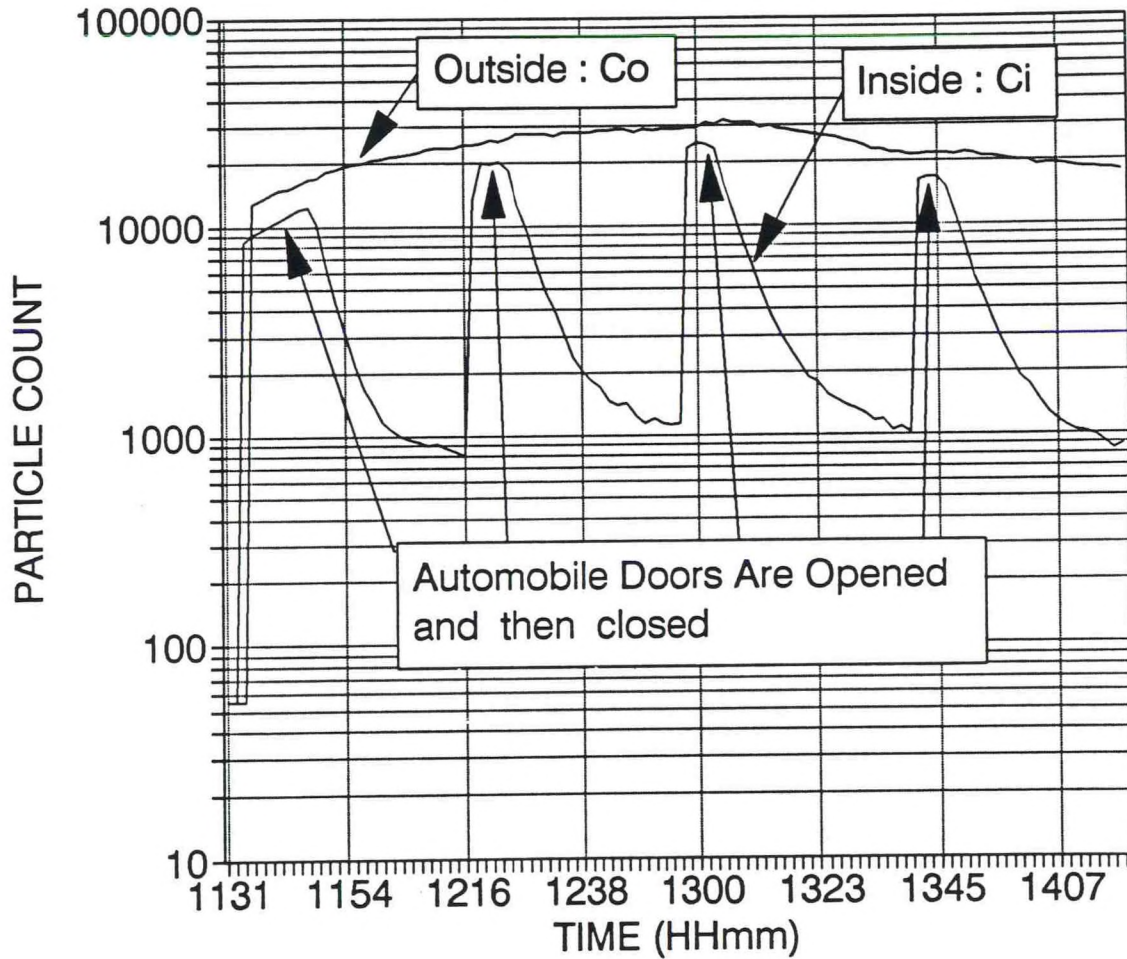
Fig. 10. 8/24/1140-1340. K car. AC off. The decreasing slope of inside concentration of particles following door closings is steep, but not as steep as with the AC on (Fig. 8), or the AC off but fan on (Fig. 11). The true outside concentrations are those given by the inside sampler when the car doors are opened. Using those values, the I/O ratios are about 0.04 with the AC off.

8/24/90, K-car, AC off, Fan on
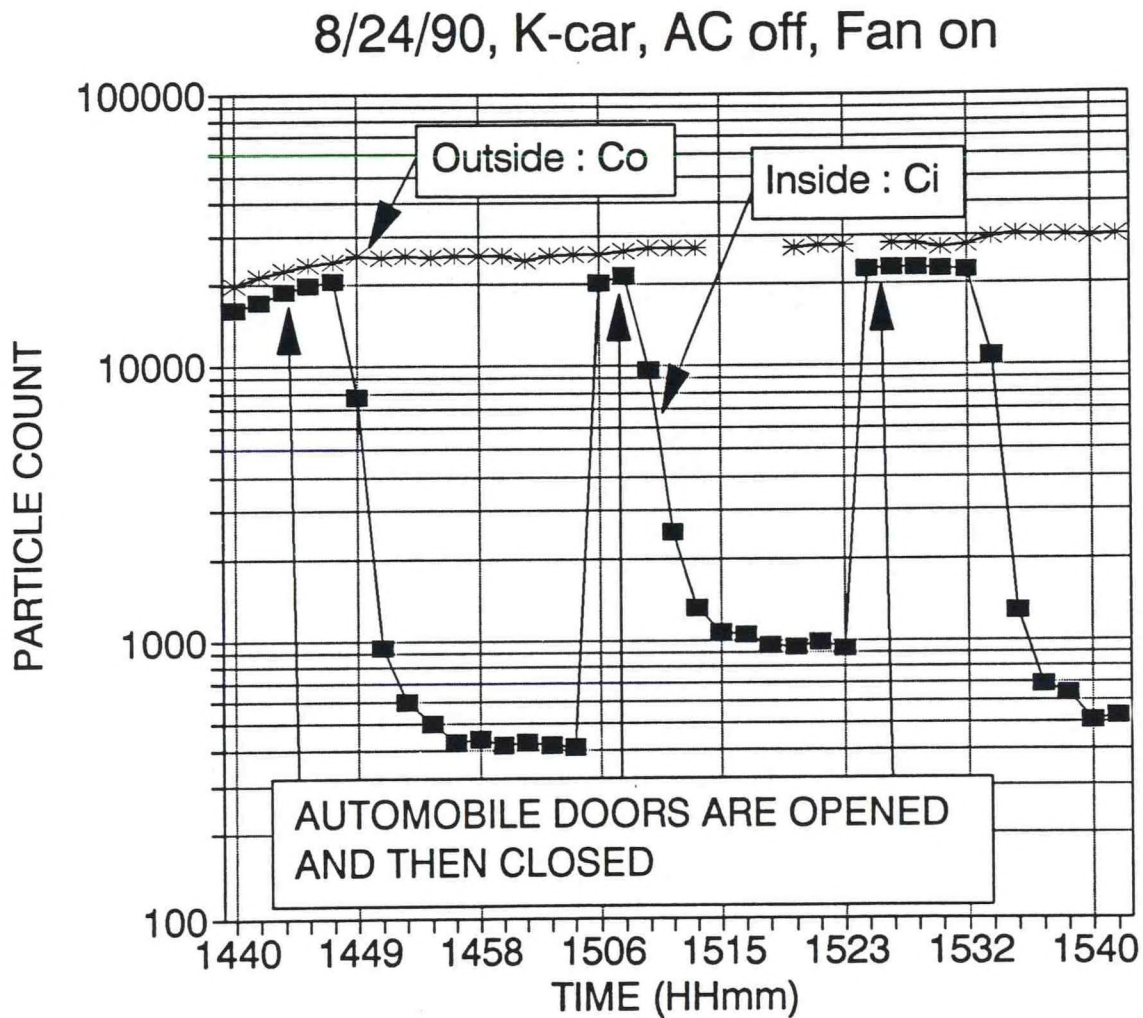
Fig. 11. 8/24/1445-1545. K car. AC off but the AC fan on. Illustrating the decreasing particles following equilibration with outside room air and door closings. The true outside concentration is that shown by the inside sampler when the doors are open. The I/O ratios at 1505 and 1541 were 0.02. The less steep slope from 1509 to 1523, and the higher I/O of 0.041 at 1524 are unexplained. It can be speculated that the fan had been turned off at 1508 and on at 1532, but such actions were not entered in the log. Compare to Fig. 9 where data for the same car with both AC on and off are shown.

Simulation of Experiment with AC on
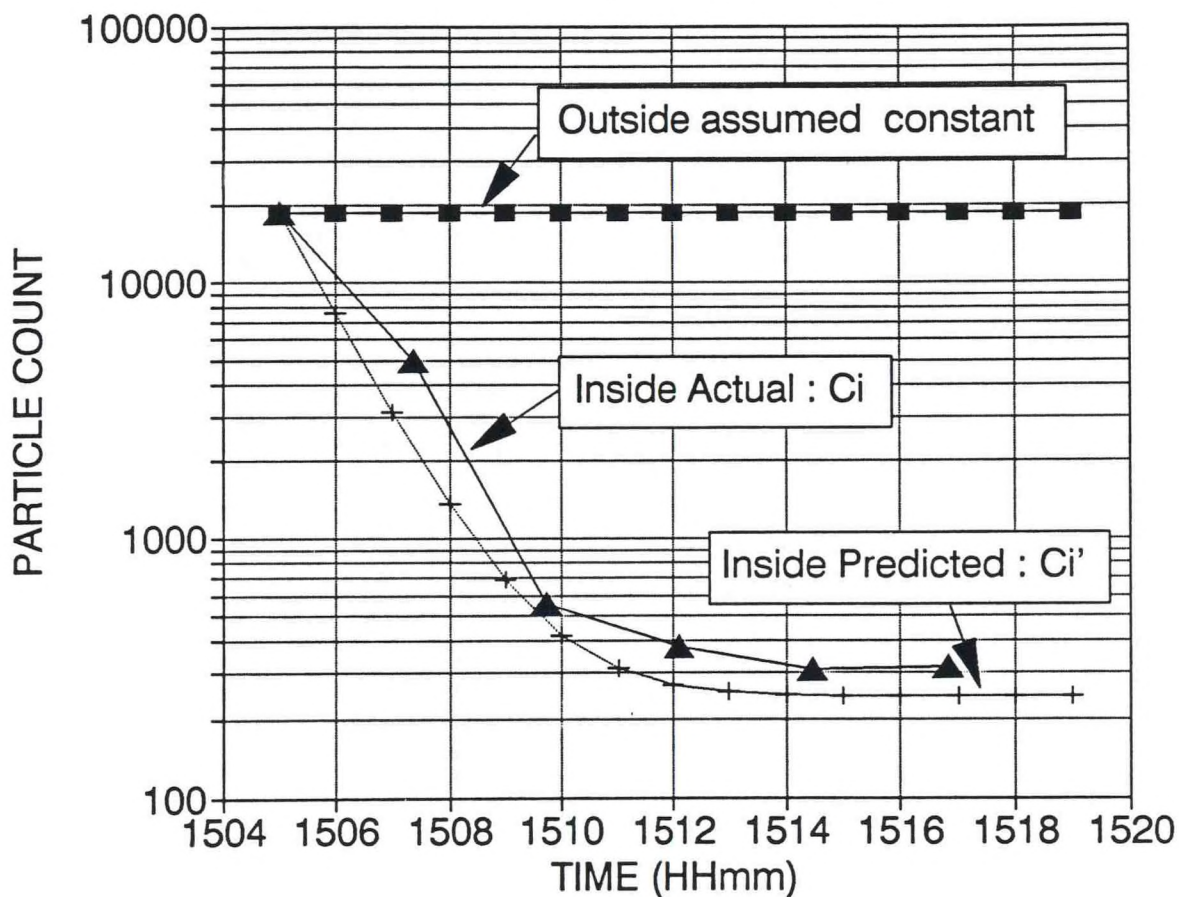
Fig. 12. 8/16/1505-. K car. AC on. Calculated inside particle concentration for comparison to the three curves in Fig. 9. Assumes leakage of 2.5/hr, deposition of 9.22/hr, recirculation of 62.2/hr, and a penetration factor of 0.29 for the AC system (a = 0.725, b = 55.88). The resultant I/O ratio (a/b) is 0.013. (Note, however, that the AC is believed to enhance deposition considerably above 9.22/hr, as discussed in text.)
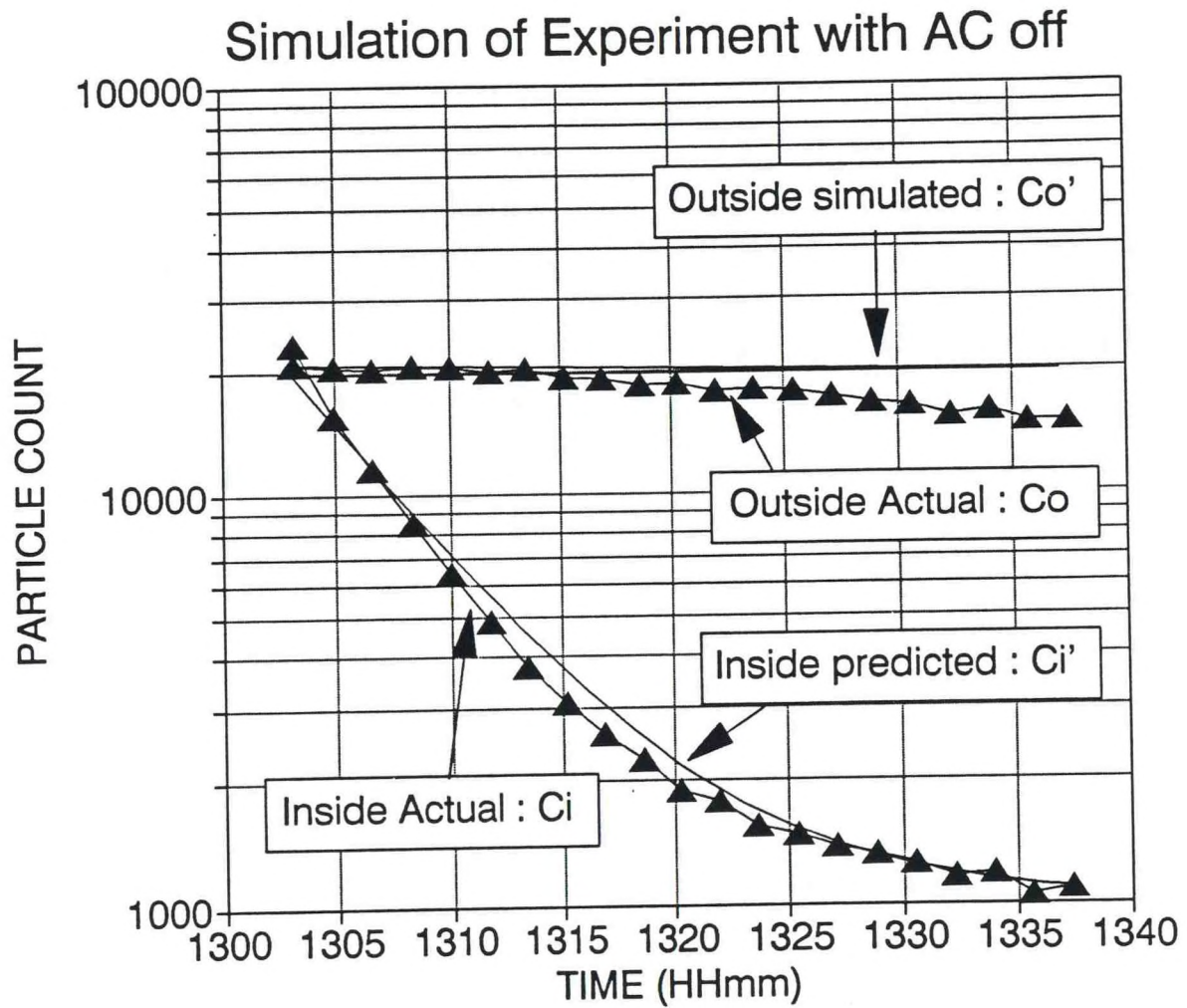
Fig. 13. 8/24. K car. AC off. Calculated interior concentration of particles for comparison to the curves in Fig. 10. Assumes a constant outside concentration, an exchange rate of 0.5/hr, and a deposition rate of 9.22/hr (a = 0.5, b = 9.72, a/b = I/O = .05).
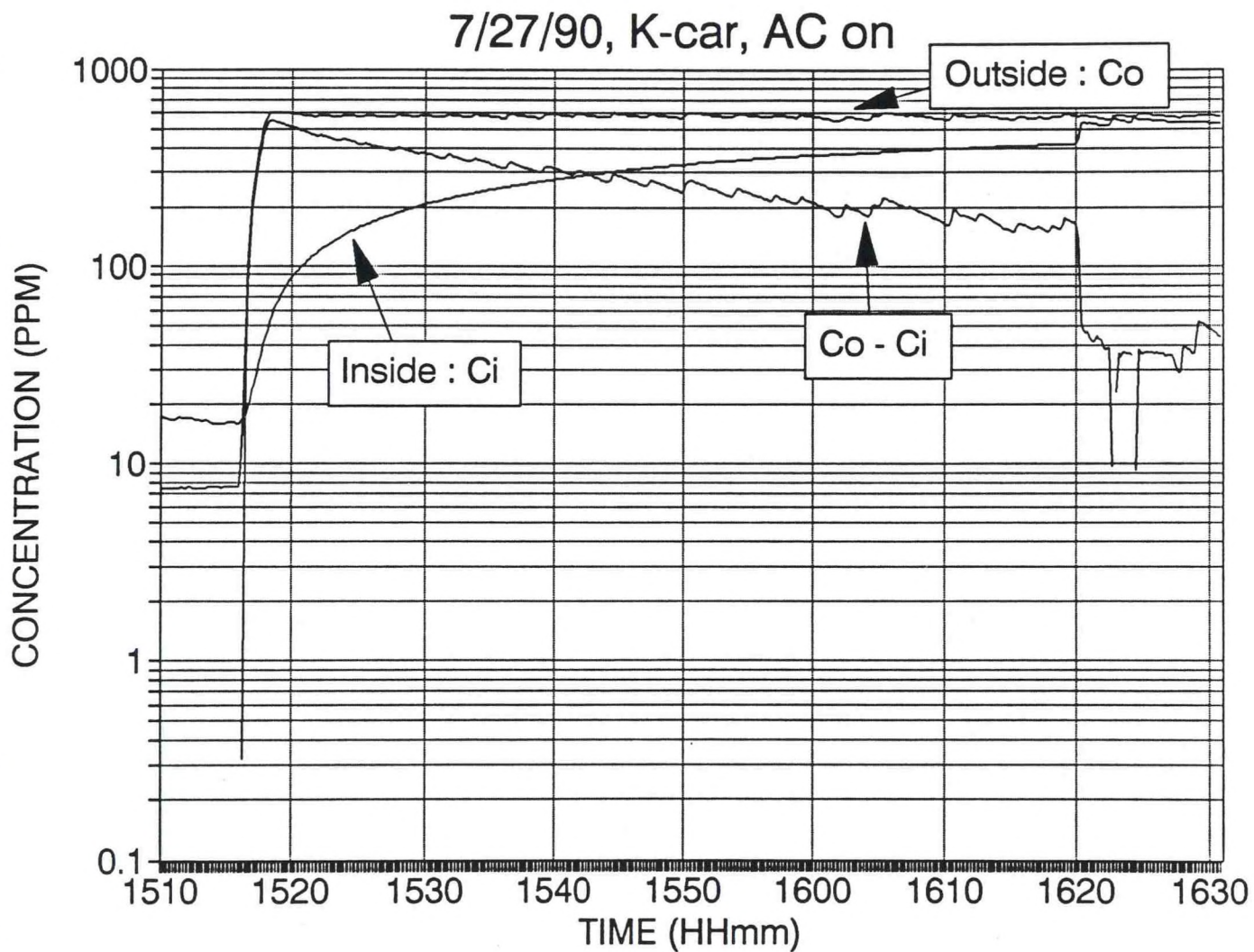
Fig. 14. 7/27/1518-. K car. AC on. Measured concentrations of isopropyl alcohol. The difference between inside and outside concentration should be linear with time on semi-logarithmic paper, if there were no deposition or second compartment. The slight non-linearity in this case suggests some deposition. Car doors were opened at 1620.
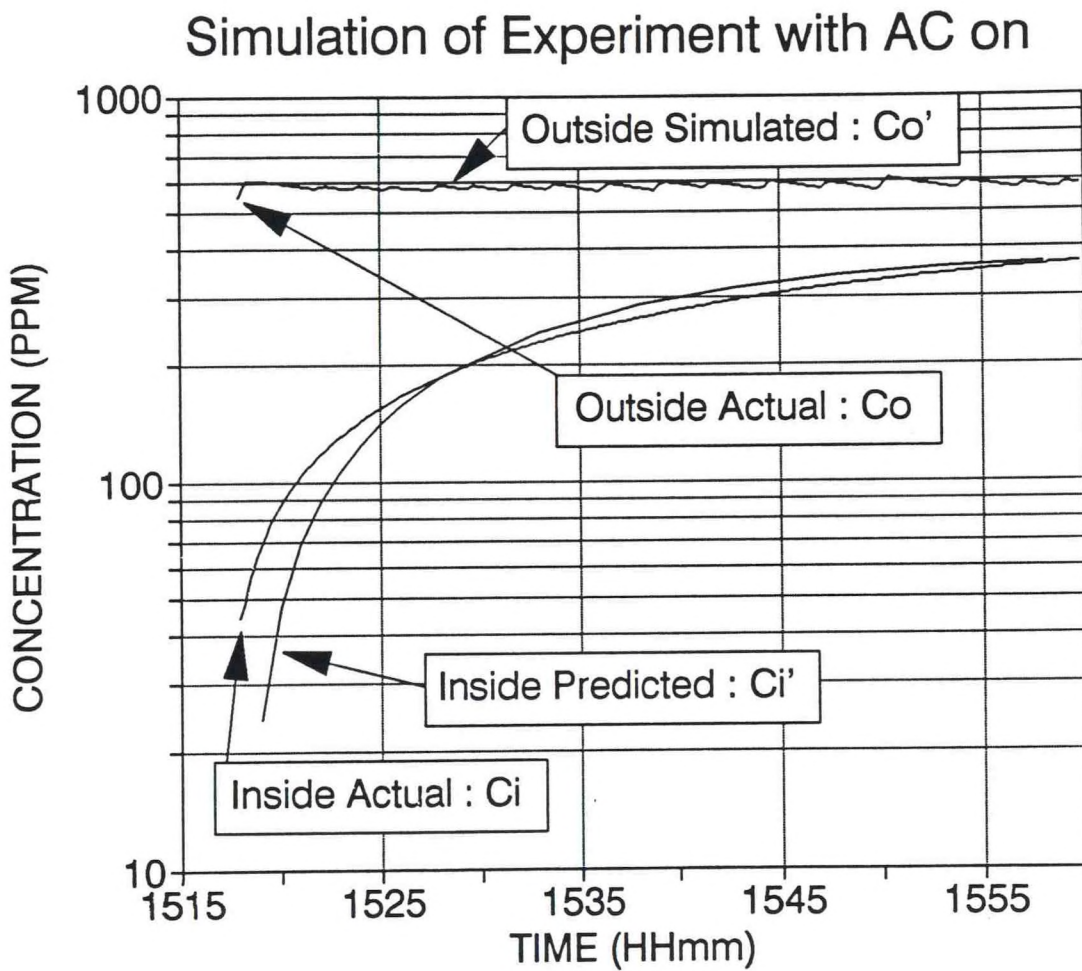
Fig. 15. 7/27/1518-. K car. AC on. Inside concentration of alcohol, calculated for comparison to Fig. 14. Calculations used an air exchange rate of 2.5/hr resulting from the AC operation, and a false irreversible alcohol deposition rate of 1.25/hr (a = 2.5 and b = 3.75).
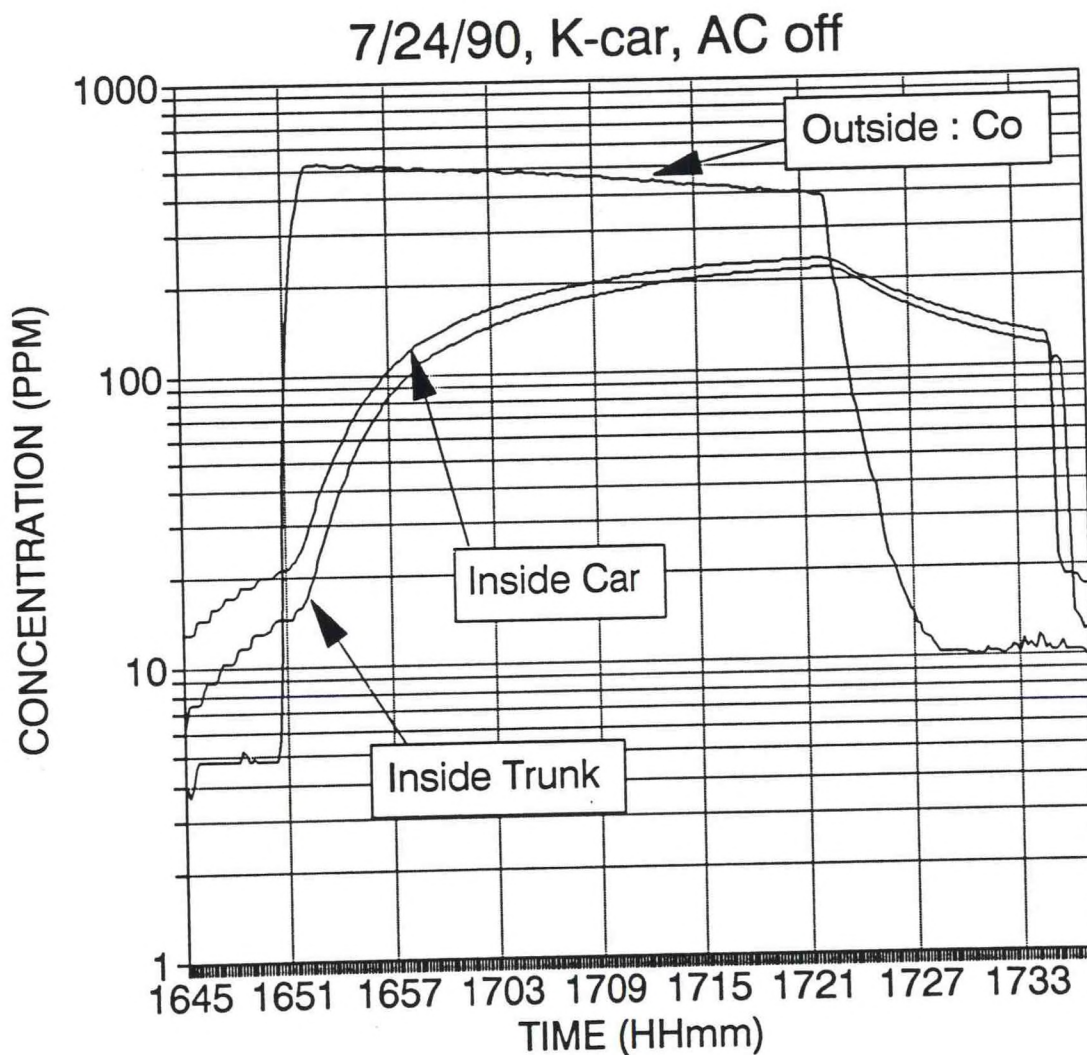
7/24/90, K-car, AC off

Fig. 16. 7/24/1645-. K car. AC off. Measured concentrations of isopropyl alcohol in the room, front seat and trunk. The tent was removed about 1653 to start the experiment. The indicated 10-20 ppm inside the car and trunk prior to generation at 1650 is due to non-zeroing of the instruments and small instrument drift. The inside concentration data show about the same exchange rates for the passenger compartment and trunk. There is an indication of off-gassing inside the car following airing of the room outside at 1722. The car and trunk doors were opened at about 1735.
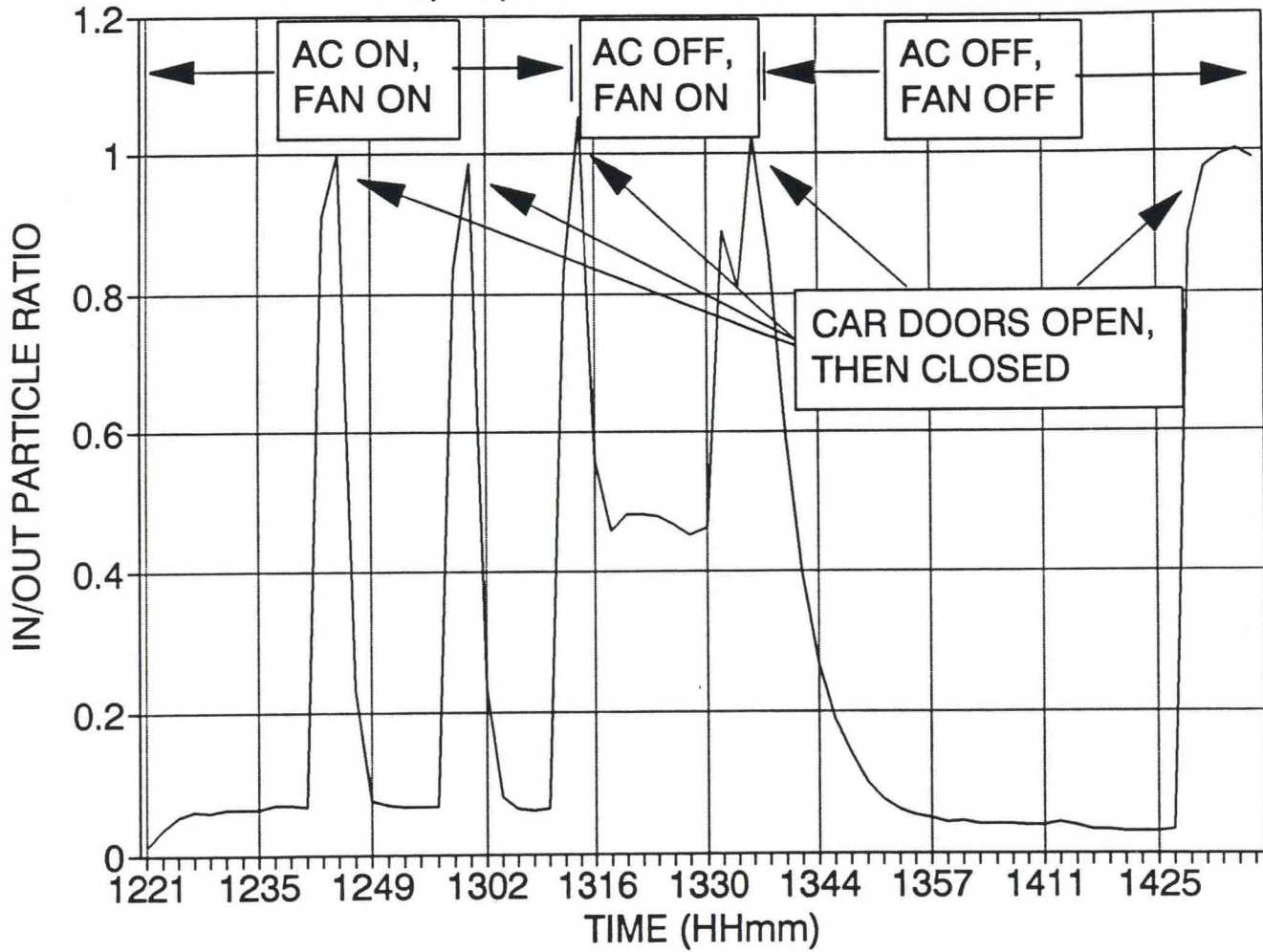
Fig. 17. 8/29/1221-1425. 1990 Oldsmobile. Inside particle concentrations, as a fraction of the outside concentration. Note the differences in I/O ratios with the AC on (0.08), the AC and AC fan off (0.05), and when the AC is off but vent open with the system fan on high setting (0.46).