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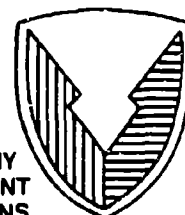## ENGINEERING
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CONTAMINATION HAZARD OF SECONDARY VAPOR
IN A COLLECTIVE SHELTER RESULTING
FROM ENTRY/EXIT OPERATION

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RESEARCH DIRECTORATE

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19 ABSTRACT (Continue on reverse if necessary and identify by block number)
A theoretical study of the effects of entry/exit procedures on the vapor hazard inside an NBC shelter was developed. The model assumes that soldiers will doff their contaminated overgarments in a vapor rich environment where some vapor can adsorb on their undergarments or skin. When the soldiers enter the air lock, some of the vapor desorbs. After a few minutes in the lock, they enter the shelter where the remaining vapor desorbs. The model calculates the time history of agent concentration in the air lock and shelter.

The model can be used to evaluate design criteria for chemical shelters and operational procedures for processing personnel through the shelter. *(Keywords...)*

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PREFACE

The work described in this report was authorized under Project No. 1L162706A553, CB Defense and General Investigation. This work was started in January 1986 and completed in April 1986.

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CONTAMINATION HAZARD OF SECONDARY VAPOR
IN A COLLECTIVE SHELTER RESULTING FROM ENTRY/EXIT OPERATION

1.   INTRODUCTION

A collective protection shelter is defined as an enclosure that is
pressurized with filtered air. The designed overpressure inside the enclosure
is such that it precludes penetration of unfiltered air into the enclosure
through the points of leakage. The shelter can be used as a rest and relaxation
(R & R) area for the troops in a contaminated battlefield, a command, control,
and communication center, or for other purposes. In all cases personnel will
need to enter and exit the shelter.

In a vapor-contaminated area the vapor will deposit on exposed "clean"
surfaces (such as exposed skin, exposed undergarments, etc.). After entry into
the shelter, the vapor can desorb and thus, potentially, create a vapor hazard
inside the shelter. This effect was already recognized by the British military
in their WWI doctrine, which stated that "No one may enter the protected room
if it is suspected that they have been ...... contaminated by the vapor......"[1]

The various branches of the armed services established doctrines for
entry into NBC shelters to minimize the carry over of agent vapors into the
shelter.[2,3] These procedures were generally based on "gut feeling."

This report presents a theoretical study of the effect of entry/exit
procedures on the vapor hazard inside an NBC shelter. The vapor concentration
in the shelter was calculated for different shelter configurations and varying
entry procedures.

2.   THEORETICAL BACKGROUND

A person preparing to enter a chemical shelter sheds his liquid-
contaminated clothing in a vapor-rich environment. The vapor is adsorbed onto
the freshly exposed surfaces (skin, undergarments). The person then enters a
ventilated air lock where the adsorbed vapor can evaporate. After staying a
few minutes in the air lock, the person moves into the shelter carrying with
him the remainder of the vapor that is still adsorbed on his body (undergarment).
This residual adsorbed vapor can then contaminate the shelter to an unacceptable
level. (Figure 1 describes, schematically, the different processes that affect
vapor concentration inside the shelter.)

The equations that govern the behavior of agent concentrations inside
an enclosure are:

$$V(dC/dt) = \sum_i [Kb \cdot Mb_i - Db \cdot Ab \cdot C] + [K \cdot M - D \cdot A \cdot C] - [F \cdot C] \qquad (1)$$

$$dMb_i dt = C \cdot Ab \cdot Db - Mb_i \cdot Kb \qquad (2)$$

$$dM/dt = C \cdot A \cdot D - M \cdot K \qquad (3)$$

where:

C = agent concentration in the enclosure

V = volume of the enclosure (m^3)

F = air flow rate into the enclosure (m^3/sec)

A = surface area of the enclosure (m^2)

Ab = surface area of the body (2 m^2)

M = total amount of vapors adsorbed on the enclosure surfaces (arbitrary units)

Mb = total agent vapors adsorbed on the body (arbitrary units)

D = deposition velocity of the agent onto the surfaces of the enclosure (cm/sec). Note that the deposition velocity is the flux of agent vapor into the surface per unit concentration and unit area

Db = deposition velocity of agent vapor onto the body (or worn garment) (cm/sec)

K = desorption rate constant from the surface of the enclosure (min^{-1}). (Note that the desorption process is assumed to be a first-order reaction in the total amount adsorbed)

Kb = desorption rate constant from the body (min^{-1})

t = time (seconds).

Equation 1 describes the rate of change of agent concentration in the enclosure. The terms in the first bracket on the right hand side represent the contribution (source and sink) of the amount deposited on the body. The terms in the second bracket represent the contribution (source and sink) of the agent deposited on the surface of the enclosure. The last term represents loss due to ventilation. It should be emphasized here that we assume that no other mechanism of vapor penetration into the enclosure exists.

Equation 2 describes the rate of change in the amount of agent deposited on the body.

Equation 3 describes the rate of change in the amount of agent deposited on the enclosure walls.

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Equations 1 through 3 were integrated numerically using a digital computer. (Note that Equation 2 is applied to each person that enters the enclosure). The computer program allows for staggered entry into the shelter. As personnel leave the air lock and enter the shelter itself, the program tracks the amount of agent that is carried over on their bodies.

3.   RESULTS AND DISCUSSIONS

The shelter dimensions for this study were as follows:

surface area of shelter:	51 m^2 (550 ft^2)
volume of shelter:	34 m^3 (1200 ft^3)
surface area of air lock:	26 m^2 (280 ft^2)
volume of air lock:	12 m^3 (430 ft^3).

The shelter is similar to a tactical concrete arch shelter that was upgraded to provide radiological and chemical protection. The shelter is described in more detail in an earlier report.[4]

An example of the development, with time, of vapor concentration in the air lock and shelter is shown in Figure 2. As can be seen, a steady-state concentration inside the air lock and the shelter is reached. The rate at which the steady state is reached depends on the entry frequency, length of time personnel stay in each compartment, and adsorption/desorption constants. The data for Figure 2 were calculated for an entry every 5 minutes, a stay in the air lock of 5 minutes, and a stay of 1 hour in the shelter. For the sake of simplicity, the outside concentration is presumed to be constant and the inside concentration is presented as a fraction of the outside concentration.

3.1   Effect of Air Lock.

The effect of the air lock on the concentration of the agent inside the shelter is shown in Figure 3. The steady-state concentration of the vapor inside the shelter is reduced by about 30% when personnel pass through the air lock before entering the shelter as compared to when they enter the shelter directly.

3.2   Effect of Air Lock and Shelter Size.

The effect of air lock size on the steady-state concentration of vapors in the air lock and in the shelter is shown in Table 1. Increasing the size of the air lock while maintaining the same flow rate has marginal effect on the vapor concentration in the air lock and no effect on the vapor concentration in the shelter itself. Similarly, changing the size of the shelter itself while maintaining the same entry procedures and the same airflow rate into the shelter will have no effect on the final concentration of agent vapor inside the shelter. This appears to be an unexpected result since the rate of ventilation (air change per hour) decreases as the volume of the enclosure increases. However, since the source (i.e., the rate at which agent is brought into the shelter) and sink (rate at which agent is exhausted from the shelter, which depends on the airflow rate) did not change, this is a logical result.

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Table 1. Effect of Air Lock Size on Vapor Concentration
in the Air Lock and in the Shelter

Air lock area m² (ft²)	Air lock volume m² (f³)	Noramlized air lock concentration*	Normalized shelter concentration*
26 (280)	12 (430)	2.70E-3	6.76E-3
42 (450)	24 (850)	2.78E-3	6.76E-3
16 (175)	6 (220)	2.62E-3	6.76E-3

*Normal concentration is the inside concentration divided by the outside concentration.

3.3 Effect of Airflow Rate into the Air Lock and Shelter.

Figure 4 shows the effect of airflow rate into the shelter on the steady-state concentration of the agent inside the shelter. As can be seen, the steady-state agent concentration in the shelter decreases exponentially as the airflow rate into the shelter increases.

Varying the airflow rate into the air lock will have similar effect on the agent concentration inside the lock, but will have only marginal effect on the final concentration of the agent in the shelter. For example, doubling the airflow rate into the air lock will cause a decrease of 0.6% in the final concentration in the shelter.

3.4 Effect of Length of Stay in the Air Lock.

The steady-state concentration of agent in the air lock and shelter are affected by the length of time that personnel stay in the air lock before moving to the shelter (Figure 5). Increasing the length of stay in the air lock results in an increase in the number of persons that are present in the air lock at one time. This, in turn, results in an increase in the steady-state concentration of agent in the air lock. However, the longer stay in the lock results in lower residual agent vapor being carried into the shelter, which results in lower steady-state concentration in the shelter itself.

3.5 Effect of Personnel Processing Strategies.

Different strategies can be employed in processing personnel into a collective protection system. For example, for a scenario that calls for a maximum of four persons staying in the air lock for 10 minutes, three different strategies can be employed (Table 2). Different processing strategies result in different steady-state concentrations of agent (relative to the outside constant concentration). The concentration in the air lock and shelter is

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greatest when entry into the protective collection system is staggered, i.e., one person processed every 2.5 minutes, and smallest when four persons are being processed simultaneously every 10 minutes.

Table 2. Effect of Entry Strategy on Agent Concentration
in the Air Lock and Shelter of a Collective
Protection System

Frequency of entry (minutes)	No. of persons entering	Normalized air lock concentration*	Normalized shelter concentration*
2.5	1	9.540E-3	9.826E-3
5.0	2	9.134E-3	9.588E-3
10.0	4	8.271E-3	8.906E-3

*Normalized concentration is the inside concentration divided by the outside concentration.

3.6   Effect of Adsorption and Desorption Rates of Agent Vapors on Shelter (Air Lock) and Body Surfaces.

Changing the deposition velocity of agent vapors onto the surfaces of the air lock and shelter has no effect on the final concentration of agent vapors in the air lock and in the shelter itself. However, the final, steady-state concentration is reached faster for a low deposition velocity (Figure 6).

The effect of the desorption time constant on the final concentration in the shelter is given in Table 3. (The desorption time constant is the reciprocal of the desorption rate constant). As noted in Figure 7, it takes longer to achieve a steady state at the higher desorption time constant; in fact, at a desorption time constant of 240 minutes, a steady state had not been reached after 3 hours of simulated run time. It is possible that at a longer simulated run time (probably 12 to 24 hours) there will be no difference in the final steady-state concentrations of agent in the shelter.

Note that even though the deposition velocity and desorption time constant were treated in this study as independent variables, they are related. A high deposition velocity indicates a strong affinity of the surface for the agent vapor and will result in slow desorption, i.e., a long desorption time constant.

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Table 3. Effect of Desorption Time Constant From
Shelter Surfaces on the Final Agent Vapor
Concentration in the Air Lock and Shelter

Desorption time constant (minutes)	Normalized concentration in air lock*	Normalized concentration in shelter*
15	2.70E-3	6.76E-3
30	2.70E-3	6.76E-3
60	2.69E-3	6.68E-3
120	2.64E-3	6.32E-3
240	2.50E-3	5.76E-3

*Normalized concentration is the inside concentration
divided by the outside concentration.

The effect of the affinity of the vapor for the body surfaces is
shown in Tables 4 and 5. As can be seen, the final steady-state concentration
in the air lock and shelter increases with increasing deposition velocity of
the vapor on the body surfaces. The effect of the desorption time constant
of the vapor from body surfaces is not that clear (Table 5 and Figure 8). It
appears that the steady-state concentration is low at high and low desorption
time constants and is higher for intermediate values. The explanation for
this behavior is that at a very fast desorption rate, more vapor will evaporate
from the body while the person is in the air lock. Thus total agent carried
into the shelter will be lower, hence the low steady-state concentration in
the shelter. On the other hand, when the evaporation rate is low enough, the
vapor is removed from the shelter as it is evaporating, again resulting in a
low concentration.

3.7   Effect of Time Spent Outside.

As expected, the vapor concentration in the air lock and shelter
increases as the length of time the body surfaces are exposed to the high vapor
concentration outside increases (Table 6). The longer stay outside results in
a larger amount of vapor being carried into the air lock and shelter.

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Table 4. Calculated Agent Concentration in the Air Lock and Shelter at Different Vapor Deposition Velocities on Body Surfaces

Deposition velocity (cm/sec)	Normalized concentration in air lock*	Normalized concentration in shelter*
0.1	2.70E-3	6.76E-3
0.01	2.74E-4	7.08E-4
0.001	2.74E-5	7.11E-5

*Normalized concentration is the inside concentration divided by the outside concentration.

Table 5. Effect of Desorption Time Constant from Body Surfaces on the Final Agent Vapor Concentrations in the Air Lock and Shelter

Desorption time constant (min)	Normalized concentration in air lock*	Normalized concentration in shelter*
15	4.24E-3	4.91E-3
30	2.70E-3	6.76E-3
60	1.53E-3	6.85E-3
120	8.15E-4	5.25E-3

*Normalized concentration is the inside concentration divided by the outside concentration.

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Table 6. The Effect of Length of Exposure Outside
on the Vapor Concentrations in the Air
Lock and Shelter

Time spent outside (min)	Normalized concentration in air lock*	Normalized concentration in shelter*
2.5	1.35E-3	3.30E-3
5	2.70E-3	6.76E-3
10	5.40E-3	1.35E-2

*Normalized concentration is the inside concentration
divided by the outside concentration.

4.   CONCLUSIONS

The model calculation confirms that evaporation of chemical agent
vapor from contaminated personnel can present a hazard in a collective pro-
tection shelter. The factors that control the final steady-state concentration
of the vapor inside the shelter are:

● Presence or absence of an air lock

● Affinity of the agent vapor for different surfaces, i.e., the
body (or undergarment) and shelter surfaces

● The flow rate of purified air into the shelter

● Length of time personnel stay in the air lock before moving
into the shelter

● Processing strategy

● Length of time personnel stay outside exposed to high vapor
concentration before entering the air lock.

5.   RECOMMENDATIONS

The hazard to personnel inside a chemical collective protection
shelter can be reduced substantially by proper application of materials and
development of correct entry procedures. We make the following recommendations:

a. Develop an undergarment that will have low affinity for the vapor
of chemical warfare agents.

b. Include an air lock for any chemical shelter.

c. Increase the total airflow into the shelter. The increased airflow rate will require larger filter/blower units with increased power consumption. This increase in the logistics burden must be taken into account by the combat planner.

d. Develop an entry procedure that will reduce the shelter contamination hazards, i.e.:

- Minimize the time personnel stay in a vapor-rich environment

- Maximize the time personnel stay in the air lock before entering the shelter itself

- Process personnel in a batch mode.

e. The model that is discussed in this report needs to be validated. Care must be exercised in the design and execution of the experimental program to prevent vapor penetration into the shelter through other mechanisms.

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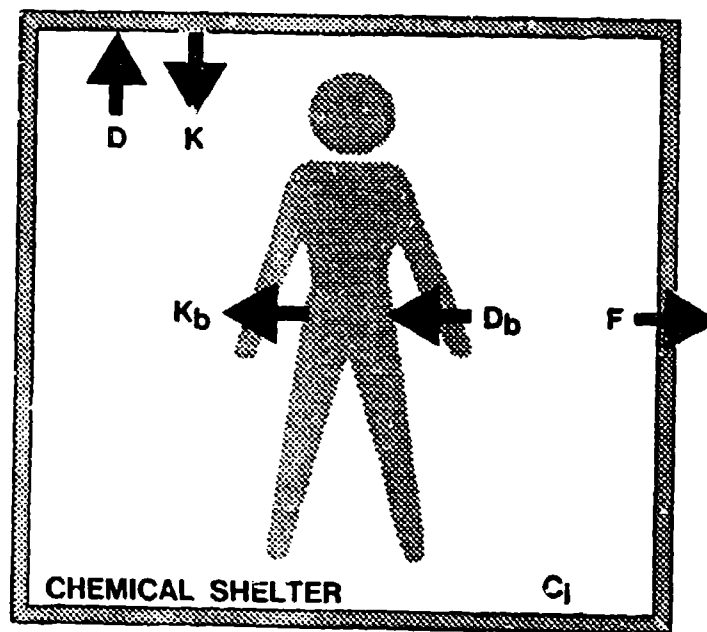
Figure 1. Factors Affecting Vapor Concentration in a Chemical Shelter
For explanation of the different factors see text.
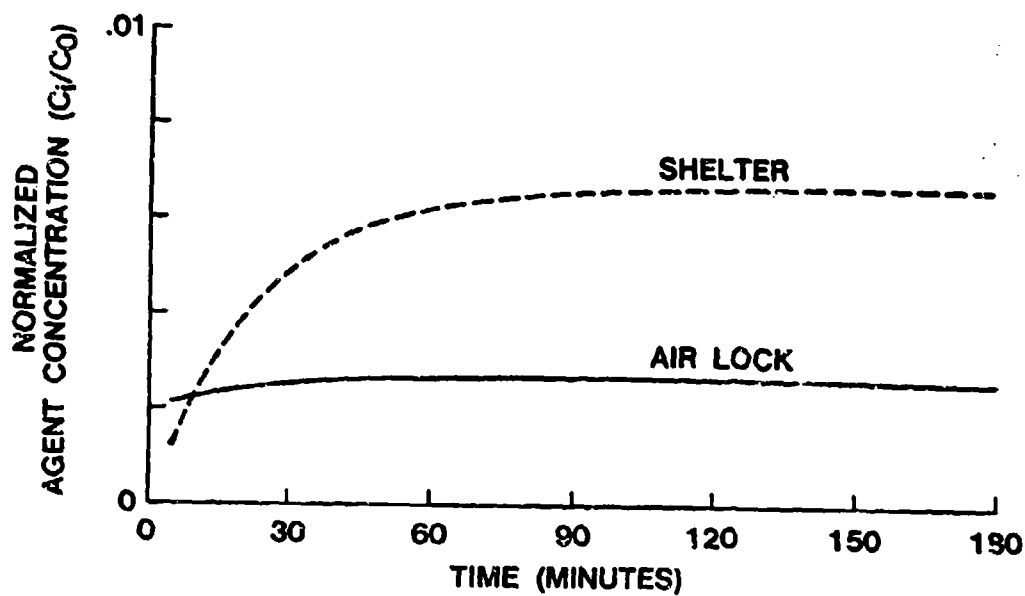
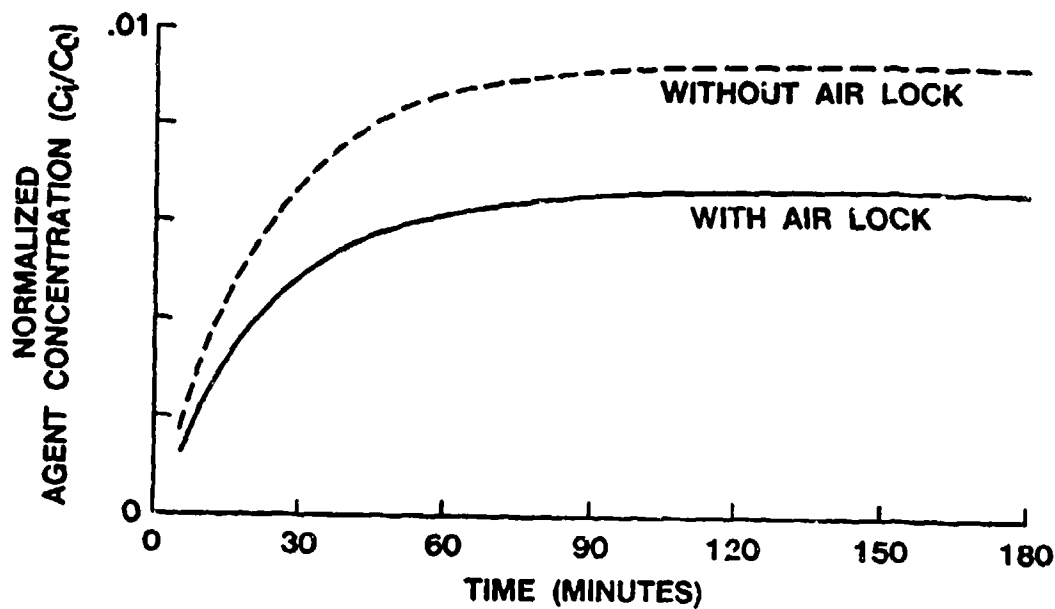Figure 2. Example of Agent Concentration Development in the Air
Lock and Shelter

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Figure 3. Effect of Air Lock on Agent Concentration Inside
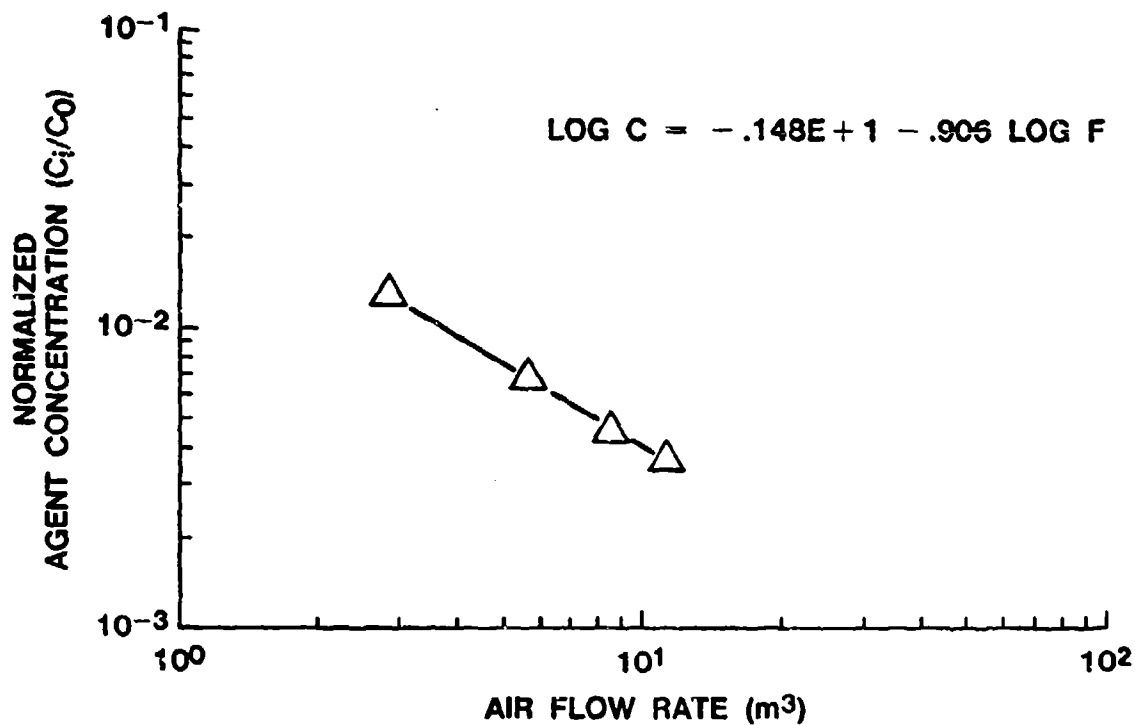a Collective Protection Shelter

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Figure 4. Vapor Concentration Inside a Shelter at Different
Airflow Rates

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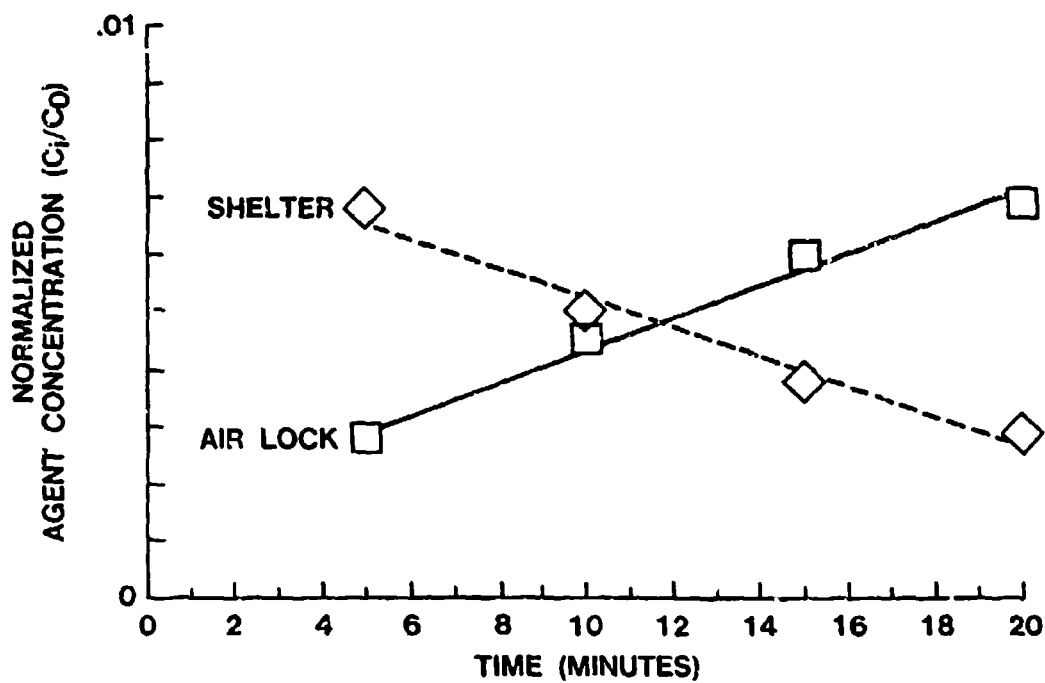
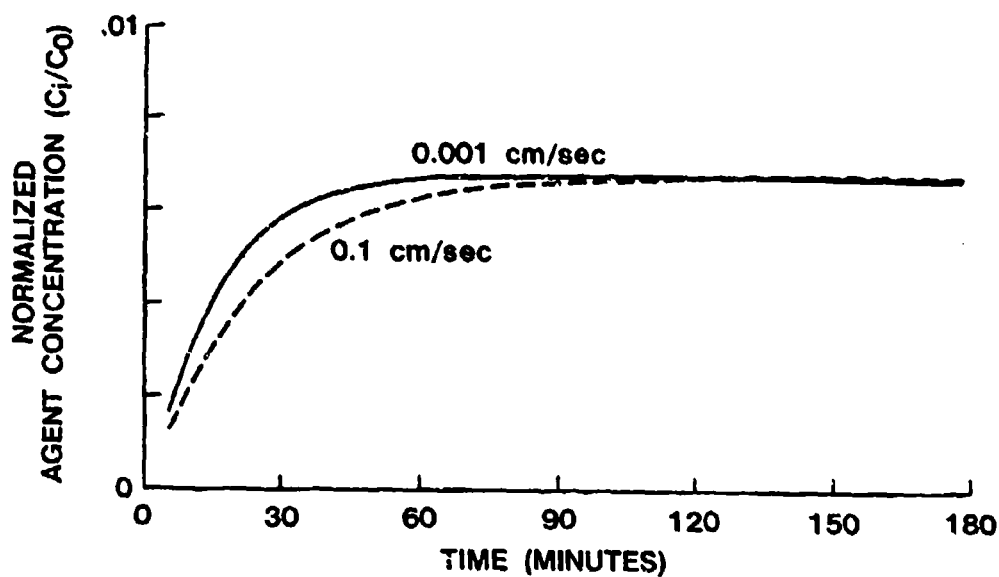Figure 5.   Concentration of Vapor in an Air Lock and Shelter

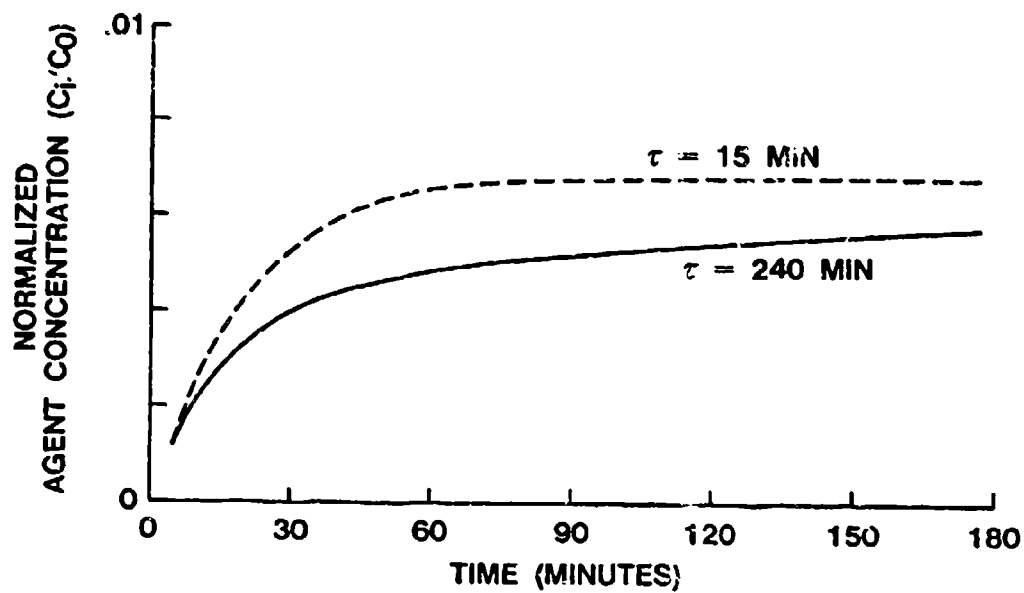Figure 6.   Effect of Deposition Velocity in Shelter

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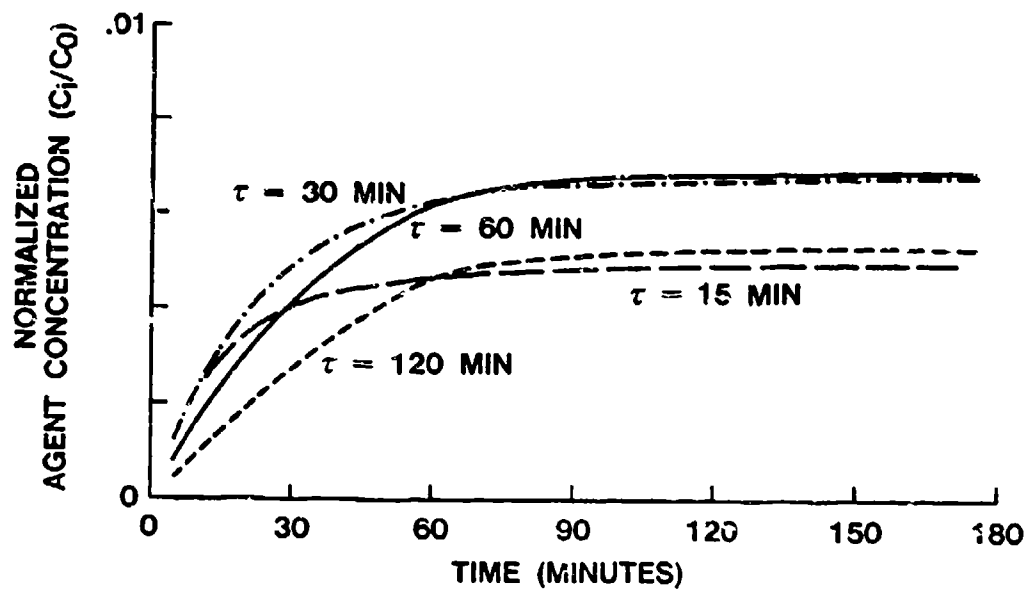Figure 7. Effect of Desorption Rate from the Shelter Walls

Figure 8. Effect of Desorption Rate from the Body

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