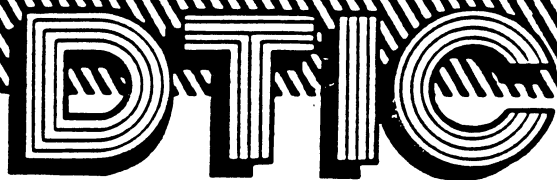


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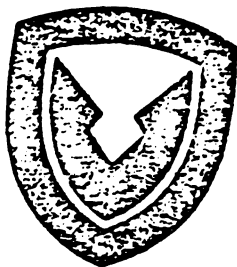
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LEVEL II

Technical Report

A SIMPLE METHOD FOR
PREDICTING CHEMICAL AGENT EVAPORATION

by

Kenneth S. K. Chinn

September 1981

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FOREWORD

• The word "model" instantaneously creates a certain mystical confusion as to its purpose and uses on one side of the scale and to a mystical analytical solution to all problems on the other.

The purpose of building a model is development of a device to analyze a series of relationships. The prerequisite for any model is a conceptual scheme and either information or assumptions about patterns and relationships. Thus, models are artificial structures and do not necessarily depict the nature of natural phenomena. Mathematics can provide a structure that simulates phenomena in the natural environment; it does not follow that mathematics expresses the truth about the natural environment. Alfred North Whitehead, English philosopher and mathematician, was quoted as saying, "There can be no true physical science which looks first to mathematics for the provision of a conceptual model. Such a procedure is to repeat the errors of the logicians of the Middle Ages."

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Table 1. Evaporation Times and Selected Physical Properties of Chemicals at 25°C.

Chemical	Evaporation Time (sec) ^a	Molecular Weight	Vapor Pressure (mm Hg)	Volatility (mg/m ³)
Acetone	82	58.08	222.2	694,060
Amyl alcohol	2,300	88.15	3.09	14,660
tert-Amyl alcohol	505	88.15	17.46	82,830
Benzene	133	78.11	94.34	396,550
Isobutyl acetate	305	116.16	19.00	118,700
Isobutyl alcohol	740	74.12	12.70	50,630
n-Butyl alcohol	1,080	74.12	7.38	29,430
sec-Butyl alcohol	565	74.12	18.19	72,560
Isobutyl isobutyrate	970	114.21	3.92	30,420
Cyclohexanol	9,200	100.16	1.27	5,390
Cyclohexanone	1,570	98.14	4.56	24,070
Diethylene glycol monobutyl ether	50,000	162.23	0.09	785
Diacetone alcohol	3,840	116.16	1.23	7,680
Diisobutyl ketone	2,430	142.23	1.71	13,080
Dimethyl formamide	2,280	73.19	3.70	14,560
Ethyl alcohol	280	46.07	56.94	141,170
Ethyl benzene	562	106.16	9.84	56,220
Ethyl ether	40	74.12	525.0	2,094,100
Ethylene glycol monoethyl ether	1,210	90.12	85.0	41,200
Ethylene glycol monomethyl ether	880	76.09	11.9	48,700

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I. INTRODUCTION

Dissemination of liquid chemical agents in the field results in formation of a wide range of droplet sizes. The droplets are subjected to atmospheric transport and diffusion, evaporation, coalescence, fallout, seepage, absorption, and possible degradation. Simultaneous consideration of all the variables which directly or indirectly influence the ultimate fate of the droplet spectrum is mathematically impractical.

Earlier investigations into the evaporation rates and lifetimes of assemblages of liquid agents have been based primarily on the rate of single droplet evaporation (1-6). Because droplet interaction, due to vapor concentration changes within the space occupied by droplet assemblages, can occur, a "cellular" model was developed by Zung (7) and further modified by Stuenkel (8,9). Alternatively, the evaporation rate model presented by Solomon et al. (10) [derived from equations presented in Chapter 4 of the Chemical Engineer's Handbook (11)] can be used for predicting the amount of agent evaporation from a source of liquid disseminated over the ground. However, the most frequently used models are the Porton Model 2515 (12,13), the Generalized Porton 2515 Evaporation Model (14), the Project Summit Model I or the Steuteville Model (15), and the Project Summit Model II developed by Brambaugh and Haney (16). Due to the complex array of parameters required and mathematical calculations involved in these models, a simple and direct method of estimating agent evaporation rates and lifetime of assemblages is proposed.

II. APPROACH

The initial step of the proposed method is concerned with prediction of the lifetime of agent assemblages under identical laboratory conditions. Data on evaporation rates of chemical agents of military interest, under identical laboratory conditions, are not available. Therefore, the times for 90 percent evaporation of pure chemicals as determined by the Shell thin film evaporimeter at 25°C and 0 percent relative humidity (17) and whose vapor pressures and physical properties were published by Othmer et al. (18), were used. Evaporation times and selected physical properties of 40 chemicals are listed in Table 1. The volatility was calculated by the following equation derived from the perfect gas law:

$$\phi = \frac{\text{Mwt} \times P \times 16,040}{^{\circ}\text{K}} \quad (1)$$

where

- ϕ = Volatility (mg/m³)
- Mwt = Gram-molecular weight
- P = Vapor pressure (mm Hg)
- $^{\circ}\text{K}$ = Absolute temperature

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The relationship between the time required to evaporate 90 percent of each chemical and its corresponding volatility at 25°C is shown in Figure 1. The data fit quite well into the relation:

$$\log t = 7.3698 - 0.9546 \log \phi \quad (2)$$

where t = Time in seconds for 90 percent evaporation

The correspondence is indicated by a high correlation coefficient of R = 0.988.

Accordingly, evaporation times of chemical agents and some of the simulants were estimated using Equation 2. The predicted times and pertinent physical properties are shown in Table 2. The vapor pressure of chemical agents and simulants was calculated according to Kirk-Othmer (19) and the volatility was calculated according to Equation 1. Among the chemical agents and simulants in Table 2, propylene glycol (PG) is the only chemical whose 90 percent evaporation time has been determined by the Shell thin film evaporometer. The PG 90 percent evaporation time of 11.11 hours (40,000 sec) in Table 1 is in fair agreement with the estimated time of 10.02 hours (36,072 sec) in Table 2.

The evaporation data for unthickened mustard (HD) at 18.3, 25.6, and 22.2-28.9°C (average 25.6°C), determined by McMahon et al. (20) (Table 3 and Figure 2), were used for HD evaporation rate evaluation. The calculated linear regression evaporation rates and those predicted from Equation 2 for the above temperatures are presented in Table 4.

Although the evaporation rates of GD and DMMP were determined by McMahon et al. (20), the rather rapid evaporation of GD and DMMP, the inappropriate and insufficient sampling time, and the fact that only one determination was performed on GD, prevent performance of an evaporation rate evaluation. Furthermore, under the similar laboratory procedures and conditions, there were sizable evaporation losses of 6.1 and 22.5 percent for thickened GD and thickened DMMP, respectively, at zero hour (21).

An indirect approach for evaluating the proposed method of estimating evaporation rates of agents and simulants is to compare the evaporation rate of agents and simulants to agent GB. Table 5 summarizes these calculated values together with those reported by Franke (22).

Thus far, the calculated values of the evaporation rates of HD and PG and the comparative evaporation rates of L, HD and GA to GB are in good agreement with those obtained from laboratory studies (17,20) and those reported by Franke (22), respectively. Whether Equation 2 is applicable to field trials requires verification. Because Equation 2 applies only to the so-called standard laboratory conditions of approximately 5.0 mm droplet size and a wind velocity of 1.8 meters per

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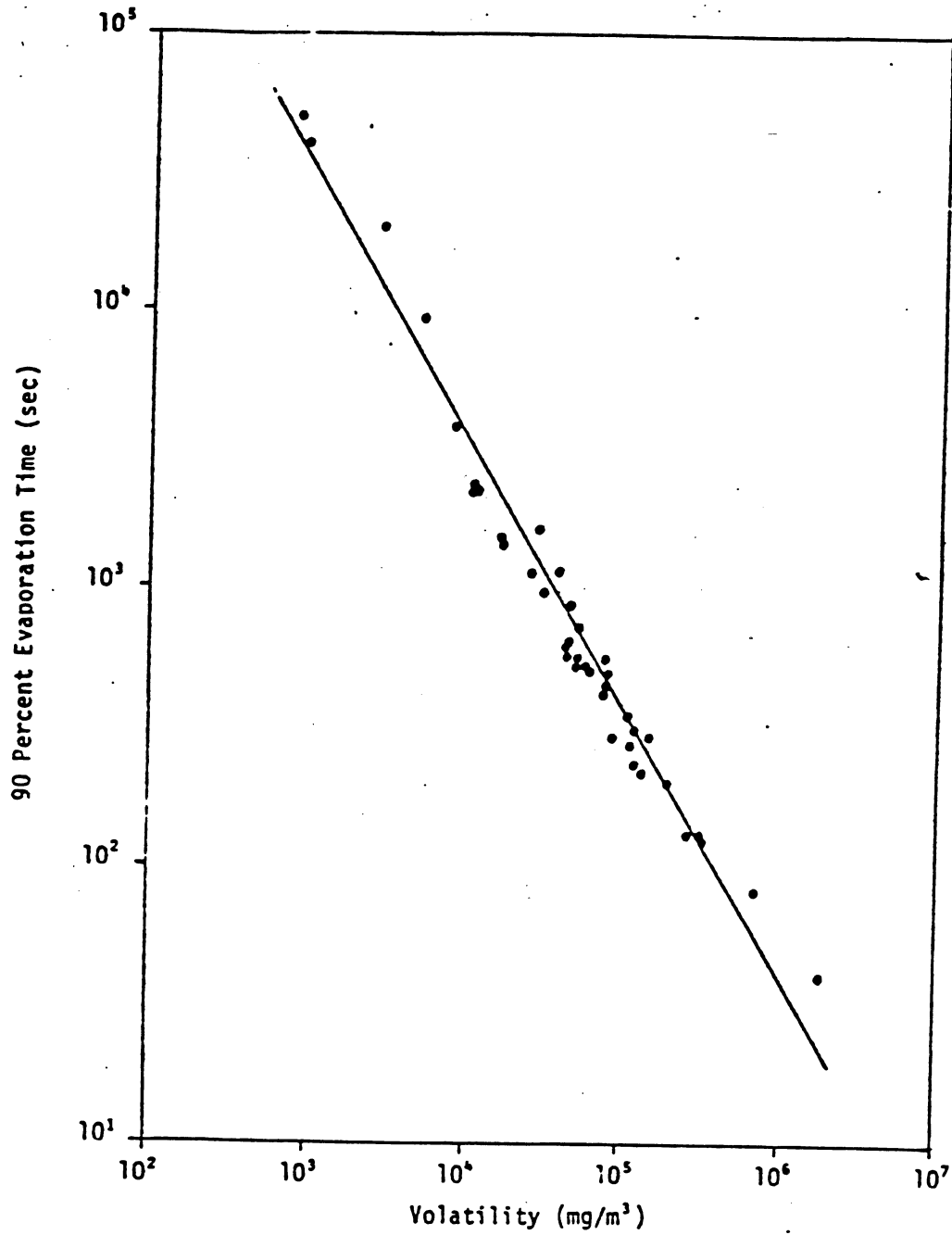


Figure 1. Relationship Between Volatility and 90 Percent Evaporation Time of Chemicals at 25°C.

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Table 2. Estimated 90 Percent Evaporation Time and Selected Physical Properties of Chemical Agents and Simulants at 25°C.

Chemical	Molecular Weight	Vapor Pressure (mm Hg)	Volatility (mg/m ³)	90 Percent Evaporation Time (hr)
<u>Agent</u>				
L	207.35	0.570	6,359	1.52
HD	159.08	0.110	939	9.46
HL (eutectic mixture)	186.4	0.370	4,009	2.37
HL (50/50 mixture)	183.22	0.310	3,291	2.86
GA	162.3	0.070	610	14.29
GB	140.1	2.775	20,909	0.49
GD	182.18	0.409	4,011	2.37
VX	267.38	0.00078	11.22	648.6
<u>Simulant</u>				
DMMP	124.0	0.583	3,885	2.44
DEM	160.0	0.338	2,908	3.22
PG	76.1	0.216	884	10.02

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Table 3. Cumulative Percent Weight Loss of Unthickened Mustard (HD) on Glass Slides (20).

Time (hr)	Weight Lost (%)		
	18.3°C ^a	25.6°C ^b	22.2-28.9°C ^c
0.5	3.3	4.8	7.6
1	5.5	10.5	12.7
1.5	9.1	17.5	18.3
2	12.0	22.9	24.0
3	17.9	31.5	30.2
4	23.6	38.9	38.3
5	28.9	45.5	44.1
6	34.3	- d	-
7	39.6	-	-

^a Relative humidity 46 percent and air flow rate 1.8 m/sec

^b Relative humidity 44 percent and air flow rate 1.8 m/sec

^c Relative humidity 45-52 percent and air flow rate 1.8 m/sec

^d Not determined

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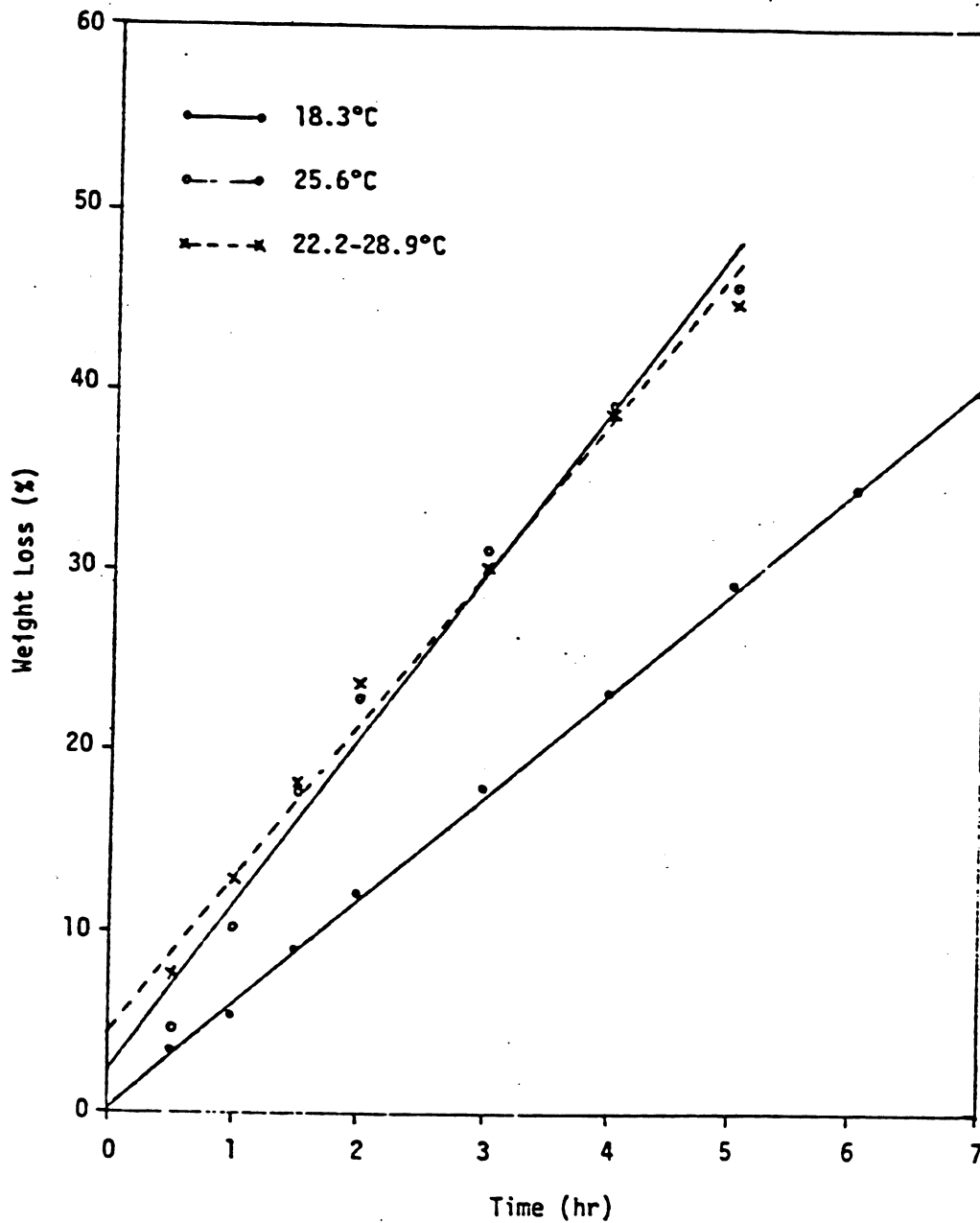


Figure 2. Evaporation Rate of Unthickened Mustard (HD) on Glass Slide at Various Temperatures with Wind Velocity of 1.8 m/sec (20).

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Table 4. Evaporation Rate of Unthickened Mustard (HD).

Temperature (°C)	Volatility (mg/m ³)	Evaporation Rate (%/hr)	
		Calculated ^a	Predicted
18.3	559	5.7	5.8
25.6	990	9.3	10.0
22.2-28.9 (25.6 average)	990	8.6	10.0

^a Calculated from McMahon, et al. (20)

Table 5. Evaporation Rate of Some Chemical Agents and Simulants as Compared to GB at 20°C.

Chemical	Calculated	Franke (Ref. 22)
HL (eutectic mixture)	5.0	- ^a
HL (50/50 mixture)	5.5	-
L	3.2	3.1
HD	20.8	21.4
GA	21.6	18.8
GD	5.0	-
VX	1505.0	-
DMMP	5.3	-
DEM	6.9	-
PG	22.2	-

^a Not reported

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second (m/sec) on a non-absorbing surface, it is necessary to introduce correction factors for drop size, wind velocity and surface variables.

If one assumes that the rate of droplet evaporation is a function of surface area to volume ratio (which is equal to $\pi d^2 / \frac{4}{3}\pi d$ or $6/d$, where d is the droplet diameter), then the drop size correction factor (D_f), calculated as $d/6$ and adjusting the 5.0 mm standard droplet as 1.0, will be those shown in Table 6. These factors are identical to those reported by Pasquill et al. (12).

The wind correction factor at various wind velocities can be calculated by the following equation:

$$\log U_f = 0.2404 - 0.7984 \log U \quad (3)$$

where

U_f = Wind correction factor

U = Wind velocity in m/sec at 2 m above ground

This equation is an adaptation of the Porton wind correction equation (12) but has been converted to metric units for consistency with the proposed method. Since 63 percent of the time, wind velocity in Central Europe averages 2.24 m/sec (23) and the laboratory wind condition was 1.8 m/sec, Equation 3 was adjusted to a wind velocity of 2.0 m/sec as the standard wind condition. The wind correction factors calculated using Equation 3 are identical to those reported in the Handbook for Chemical Hazard Prediction (24) if the 2.0 m/sec wind velocity is used as the standard wind velocity.

The most difficult correction factor to evaluate is the effect of the surface on which a chemical warfare agent may be deposited. The nature of the surface has an important bearing on the physical and chemical behavior of chemical warfare agents. An agent on grassland will probably evaporate faster than the same agent on permeable surfaces such as sand and soil, or from paved road and painted surfaces where chemical agents can penetrate by dissolution.

Empirical results derived from wind tunnel and field experiments indicated that HD evaporated approximately 2.5 times slower from sand than from grass (12) and a correction factor of 2.5 for chemical agents on sand was used by the Joint Technical Coordinating Group for Munitions Effectiveness (JTCG/ME) (13). Mayhood et al. (25) used ^{32}P labeled VX to determine the rate of ^{32}P disappearance from glass plate, sand and soil contaminated with one 500- μg droplet or 100 5- μg droplets of VX. They sampled the surfaces at various time intervals over 91 hours. Their laboratory results indicated that the 500- μg VX droplets evaporated 1.09 and 1.50 times slower from sand and soil than from glass plate, and the 5- μg VX droplets evaporated 1.27 and 2.67 times slower from sand and soil than from glass plate.

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Table 6. Drop Size Correction Factors (D_f).

Droplet Diameter (mm)	Surface Area to Volume Ratio (mm^{-1})	D_f
0.2	30.0	0.04
0.5	12.0	0.1
1.0	6.0	0.2
1.5	4.0	0.3
2.0	3.0	0.4
3.0	2.0	0.6
4.0	1.5	0.8
5.0	1.2	1.0

In view of the surface correction factors reported by Pasquill et al. (12) and those obtained from data reported by Mayhood et al. (25), it was concluded that surface correction factors remain undefined and certainly warrant further investigation. In addition, the surface correction factors may be dependent on droplet size as indicated by Mayhood et al. (25). For the present method, no correction factor was used.

Another correction factor is for the purity of the chemical warfare agents, in the vicinity of 90 percent (25-28). If the 10 percent impurity is assumed to be essentially non-volatile and in a homogeneous mixture with the chemical agent, then the term fractional activity or agent fraction (A_f) can be introduced as an indication of the relative tendency of the volatile agent to pass into the vapor state, as compared with the pure agent. The reciprocal of A_f would be volatile retarding index which could be calculated by the following equation:

$$\frac{1}{A_f} = \frac{A_r A_p + I_p}{A_r A_p} \quad (4)$$

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where

- A_f = Agent fraction
- A_r = Agent remaining, fraction of initial amount
- A_p = Initial agent purity, percent
- I_p = Initial impurity, percent

The evaporation rate of droplets is dependent on the droplet size (Table 6). However, in a field trial dissemination, the drop size correction factor (D_f) reflects only the mass median diameter of the droplet spectrum. As a result, 50 percent of the chemical agent would evaporate faster than estimates based on the mass median diameter of the droplet spectrum and 50 percent would evaporate slower. The differing evaporation rates require calculation of another correction factor. The volatile retarding index ($1/A_f$) at the 50 percent level ($1/A_{0.50}$) is used as a reference point and the ratio $1/A_f : 1/A_{0.50}$ (the same as $A_{0.50}/A_f$) calculated as the adjusted evaporation correction factor. This adjusted evaporation correction factor can be calculated by the following equation:

$$\frac{A_{0.50}}{A_f} = \frac{A_r A_p + I_p}{A_r A_p + 2 A_r I_p} \quad (5)$$

After combining the wind, drop size and adjusted evaporation correction factors to the basic evaporation equation, the evaporation time of agent droplets from field trials could be predicted by the following equation:

$$T_e = \frac{EtU_f D_f (A_{0.50}/A_f)}{90} \quad (6)$$

where

- T_e = Evaporation time for any percent of agent evaporation (hr)
- E = Agent evaporation (%)
- t = 90 percent of pure agent evaporation time (hr)
- U_f = Wind correction factor
- D_f = Drop size correction factor
- $A_{0.50}/A_f$ = Adjusted evaporation correction factor (Purity)

The proposed method was tested against the evaporation recovery data of GA measured in a field trial at a surface temperature of 39.9°C and wind velocity of 2.77 m/sec. The purity of GA was assumed to be 90 percent (26-28). Droplet size was not measured on the trial but a mass median diameter of 3.0 mm was assumed for the sprinkling can manifolds used, as was also assumed by the JTCC/ME for their evaluation of this GA trial (13).

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GA at 39.9°C has a vapor pressure of 0.162 mm Hg, corresponding to a volatility of 1346 mg/m³. The excellent agreement between the observed and the predicted values are presented in Table 7 and Figure 3. The step-by-step procedures for estimating GA evaporation in this GA field trial are detailed in Appendix A. The values predicted by the JTCG/ME using the Generalized Porton 2515 Evaporation Model (13) are also shown in Table 7 and Figure 3 for comparative purposes.

The evaporation method was further tested against data reported by Pasquill et al. which were used for the Porton Model development (12,13). The agent used in their field trial was HT with a mass median diameter of 1.0 µm at 15.6°C and with a wind velocity of 4.6 m/sec. HT is a mixture of 60 percent mustard and 40 percent 2,2'-bis-(2-chloroethylthio)-diethyl ether or oxygen mustard which is essentially non-volatile with a vapor pressure of 0.001 mm Hg at 120°C (22). If one assumes that HT mixture had a purity of 90 percent, then the mixture had 54 percent HD and 46 percent non-volatile substances.

HD has a vapor pressure of 0.0502 mm Hg at 15.6°C with a corresponding volatility of 443 mg/m³. The agreement between the observed and the predicted values are presented in Table 8 and Figure 4. The step-by-step procedures for estimating HD evaporation in this HD field trial are detailed in Appendix A. The values predicted by the original Porton Model which was derived from this field trial data (12,13) are also shown in Table 8 and Figure 4 for comparative purposes.

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Table 7. Comparison Between Predicted and Observed Evaporation Time of GA - Field Trial.

Percent Evaporated	Time (hr)		
	Observed	Predicted	
		Present Method	JTCG/ME
10	0.27	0.31	0.22
20	0.60	0.64	0.50
30	0.95	0.98	0.86
40	1.34	1.34	1.33
50	1.71	1.72	2.00
60	2.13	2.17	3.00
70	2.65	2.70	4.66
80	3.35	3.53	7.99
90	4.66	5.37	17.98

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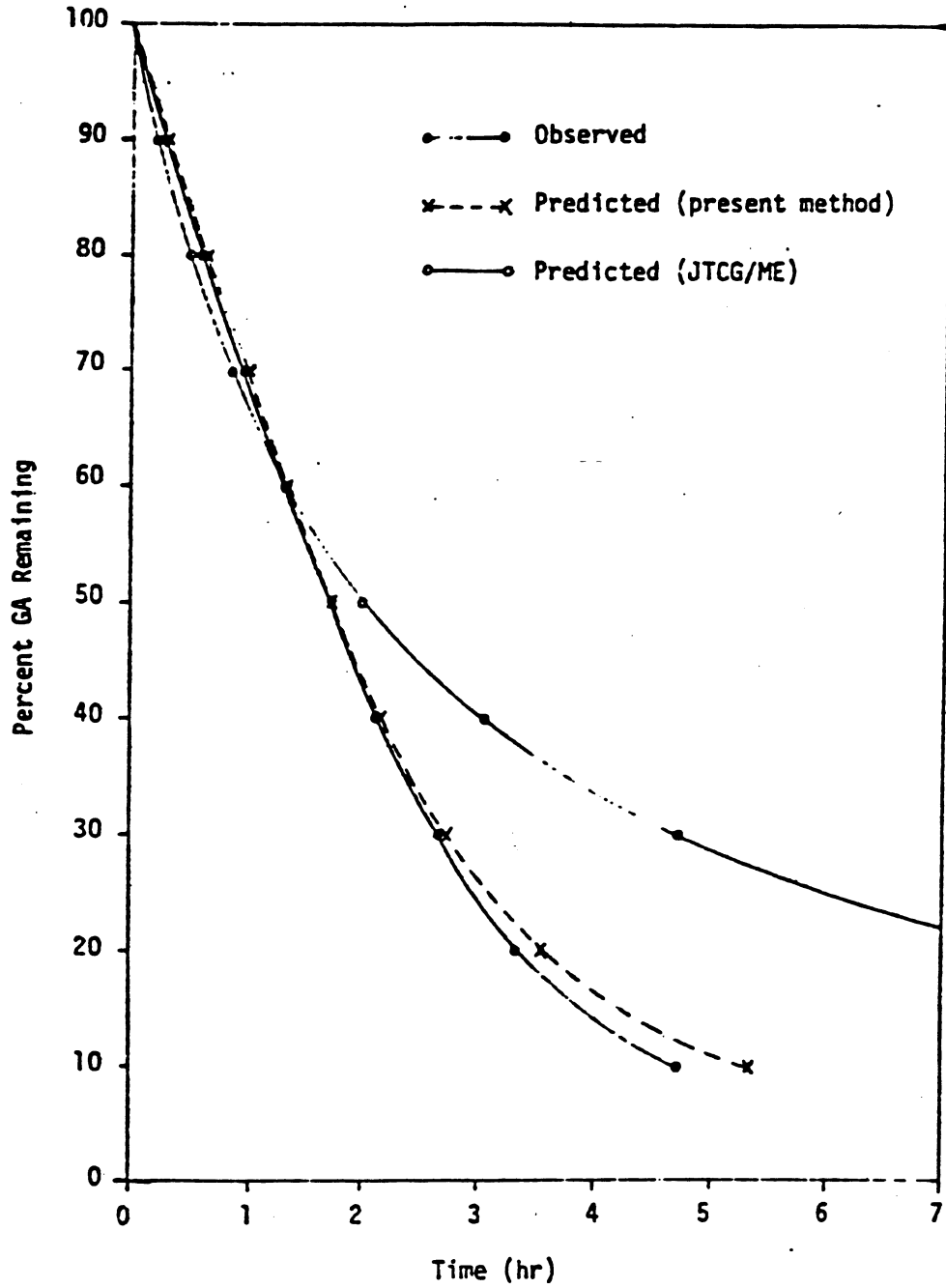


Figure 3. Observed Versus Predicted Evaporation of GA - Field Trial

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Table 8. Comparison Between Predicted and Observed Evaporation Time of Unthickened Mustard (HD) - Field Trial.

Percent Evaporated	Time (hr)		
	Observed	Predicted	
		Present Method	Porton Model
5	0.05	0.08	0.05
10	0.11	0.16	0.11
15	0.18	0.24	0.18
20	0.26	0.34	0.25
30	0.45	0.54	0.43
40	0.69	0.79	0.67
50	1.1	1.10	1.00
60	1.7	1.53	1.50
70	2.4	2.18	2.33
80	3.3	3.42	4.00
90	4.3	6.96	9.00

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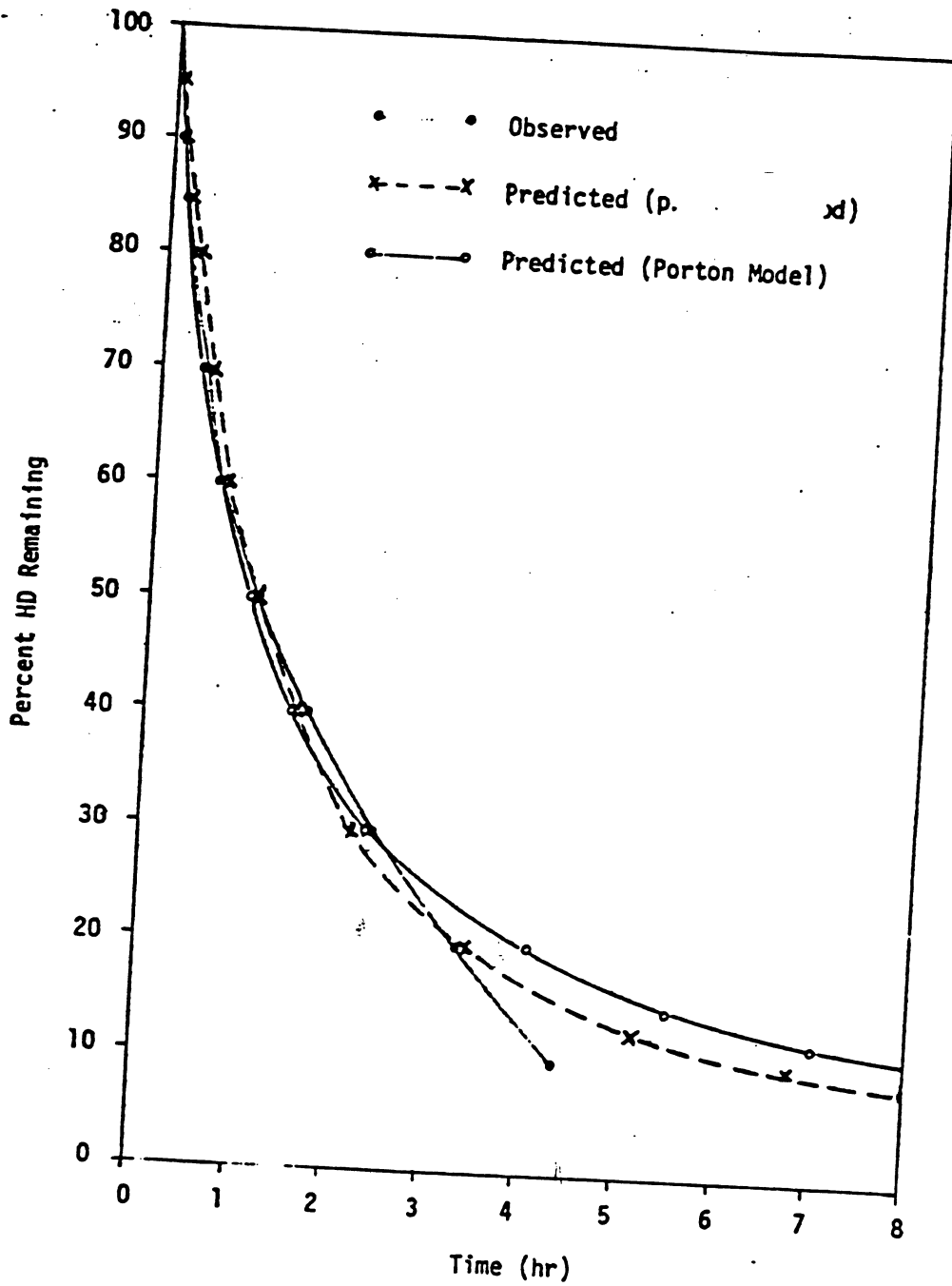


Figure 4. Observed Versus Predicted Evaporation of Unthickened Mustard (HD) - Field Trial.

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III. DISCUSSION

The approach used in this report was to minimize the number of variables required for prediction of liquid chemical agent evaporation without sacrificing the accuracy of the procedure. Most of the variation (97.6 percent) in liquid chemical agent evaporation time is due to the explicit relationship between chemical volatility and evaporation time (Figure 1) and is accounted for by Equation 2, using volatility.

The first step used to predict liquid chemical agent evaporation time is to determine the 90 percent evaporation time. Next, the wind correction factor (U_f) and drop size correction factor (D_f) are applied to the evaporation time. The evaporation rate is determined and expressed as percent per hour. An adjusted evaporation correction factor ($A_{0.50}/A_f$), which corrects for differences in evaporation within the droplet spectrum and the effect of non-volatile impurities, is then applied to obtain the predicted evaporation rate.

The proposed method compared quite well with actual observations. Furthermore, this method yields overall recoveries that are closer to the observed recoveries than the Generalized Porton 2515 Evaporation Model (14). However, values obtained are based on limited field trials. More data and further validation studies are required to determine how well the proposed method will predict under all conditions. Comparison of the proposed method to Project Summit Model I (15) and Project Summit Model II (16) could not be performed because the parameter values required for the Project Summit models were not determined in the field trials.

The proposed method is simple to use and its basic derivation does not depend on assumptions of variables which may or may not have any significant influence on agent evaporation. Furthermore, the proposed method satisfies the axiom "*essentia non sunt multiplicanda praeter necessitatem*" or "plurality should not be assumed without necessity" set forth by William of Ockham in the early 1300's which has come to be known as "Ockham's Razor".

IV. CONCLUSION

The proposed method for estimating chemical agent evaporation is direct and simple. It is reasonably easy for nontechnical people to use and understand. It appears that this model can be used to predict chemical agent evaporation in laboratory and field experiments.

V. RECOMMENDATION

To obtain a correction factor which may further improve chemical agent evaporation prediction in field trials, controlled laboratory studies should be conducted to evaluate the nature of surface types and their effect on relative persistency of chemical agents.

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SAMPLE PROBLEM SOLUTION

GENERAL

This appendix contains input information for the GA and HD field trials which were used for the proposed method verification. The step-by-step procedures to arrive at an estimated evaporation time of these two field trials were included to illustrate the use of the method.

I. GA FIELD TRIAL

A. Problem: Estimate the evaporation time of GA disseminated on grassland given the following conditions:

1. Ground temperature: 39.9°C
2. Wind velocity at 2 m above ground level: 2.77 m/sec
3. Mass median diameter: 3.0 mm
4. Agent purity: 90 percent
5. Volatility of GA at 39.9°C: 1345 mg/m³

B. Solution:

1. Find the 90 percent evaporation time of GA at 39.9°C.
 $\log t = 7.3698 - 0.9546 \log \phi$ (Eq. 1)
 $\log t = 4.3828$
 $t = 24,144 \text{ sec or } 6.71 \text{ hr}$
2. Find the wind correction factor for a wind velocity of 2.77 m/sec.
 $\log U_f = 0.2402 - 0.7984 \log U$ (Eq. 2)
 $\log U_f = -0.11308$
 $U_f = 0.77$
3. The drop size correction factor (D_f) is 0.6 (Table 6).
4. Find the 90 percent evaporation time of GA at the above conditions.
 $t = 6.71 \times 0.77 \times 0.6 = 3.1 \text{ hr}$
5. Find the evaporation rate.
 $\text{rate} = 90\%/3.1 \text{ hr} = 29.0\%/\text{hr}$

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6. Find the 20 and 70 percent evaporation times.

a. 20 percent evaporation: The evaporation rate of GA at the above conditions is 29.0%/hr (step 5); therefore, the 20 percent evaporation time is 0.69 hr (20%/29.0%/hr).

The adjusted evaporation correction factor is then calculated and applied to the evaporation time:

$$\frac{A_{0.50}}{A_f} = \frac{A_r A_p + I_p}{A_r A_p + 2 A_r I_p} \quad (\text{Eq. 4})$$

$$\frac{A_{0.50}}{A_{0.80}} = \frac{(0.80 \times 90) + 10}{(0.80 \times 90) + 2(0.80 \times 10)} = \frac{82}{88} = 0.932$$

$$20 \text{ percent evaporation time} = 0.69 \times 0.932 = 0.64 \text{ hr}$$

b. 70 percent evaporation: 70 percent evaporation is 2.57 hr (70%/29.0%/hr).

$$\frac{A_{0.50}}{A_{0.30}} = \frac{(0.30 \times 90) + 10}{(0.30 \times 90) + 2(0.30 \times 10)} = \frac{37}{33} = 1.121$$

$$70 \text{ percent evaporation time} = 2.41 \times 1.121 = 2.70 \text{ hr}$$

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II. HD FIELD TRIAL

A. Problem: Estimate the evaporation time of HD in a HT mixture disseminated on grassland given the following conditions:

1. Ground temperature: 15.6°C
2. Wind velocity at 2 m above ground level: 4.6 m/sec
3. Mass median diameter: 1.0 mm
4. HT mixture: 60 percent HD and 40 percent T
5. HT purity: 90 percent
6. HD volatility at 15.6°C: 443 mg/m³

B. Solution:

1. Find the 90 percent evaporation time of HD at 15.6°C.

$$\log t = 7.3698 - 0.9546 \log \phi \quad (\text{Eq. 1})$$

$$\log t = 4.8435$$

$$t = 69,750 \text{ sec or } 19.38 \text{ hr}$$

2. Find the wind correction factor for a wind velocity of 4.6 m/sec.

$$\log U_f = 0.2402 - 0.7984 \log U \quad (\text{Eq. 2})$$

$$\log U_f = -0.2889$$

$$U_f = 0.51$$

3. Drop size correction factor (D_f) is 0.2 (Table 6).
4. Find the 90 percent evaporation time of HD at the above conditions.

$$t = 19.38 \times 0.51 \times 0.2 = 1.98 \text{ hr}$$

5. Find the evaporation rate.

$$\text{Rate} = 90\%/1.98 \text{ hr} = 45.5\%/\text{hr}$$

6. Find the 30 and 80 percent evaporation times

a. 30 percent evaporation: The evaporation rate of HD at the above conditions is 45.5%/hr (step 5); therefore, 30 percent evaporation time is 0.659 hr (30%/45.5%/hr)

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The adjusted evaporation correction factor is then calculated and applied to the evaporation time:

$$\frac{A_{0.50}}{A_f} = \frac{A_r A_p + I_p}{A_r A_p + 2 A_r I_p} \quad (\text{Eq. 4})$$

$$\frac{A_{0.50}}{A_{0.70}} = \frac{(0.70 \times 54) + 46}{(0.70 \times 54) + 2(0.70 \times 46)} = \frac{83.8}{102.2} = 0.820$$

$$30 \text{ percent evaporation time} = 0.659 \times 0.820 = 0.54 \text{ hr}$$

b. 80 percent evaporation: 80 percent evaporation time is 1.76 hr (80%/45.5%/hr).

$$\frac{A_{0.50}}{A_{0.20}} = \frac{(0.20 \times 54) + 46}{(0.20 \times 54) + 2(0.20 \times 46)} = \frac{56.8}{29.2} = 1.945$$

$$80 \text{ percent evaporation time} = 1.76 \times 1.945 = 3.42 \text{ hr}$$

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