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EFFECTS OF CARBON MONOXIDE ON PERSONNEL

Presented

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by

Martin Mossa

System Safety Engineer

STECS-MT-S

Aberdeen Proving Ground, MD 21005-5059

EFFECTS OF CARBON MONOXIDE ON PERSONNEL

New weapons and the vehicles on which they mount have and will continue to become increasingly complex. These weapons are potentially more demanding, and challenges need to be addressed. One important challenge is the need to accurately monitor and control the amount of toxic substances, generated by weapon systems, that may endanger the soldiers who will operate the systems.

Toxic fumes generated from various sources can have debilitating effects on the efficiency of occupants and operators of vehicles and ground equipment. The insidious nature of these effects underscores the necessity for detecting, measuring, and eliminating these hazards to the extent possible. The overall problem that must be addressed is the potential exposure of soldiers to carbon monoxide (CO), ammonia (NH_3), oxides of sulfur (SO_2), oxides of nitrogen (NO_2), lead fumes (Pb), and other harmful substances. The exposures are likely to be relatively intense (above present Federal standards for occupational exposure), brief (1 hour or less), and rapidly repeated (as often as six times daily for periods as long as 14 days). Such exposures may occur when soldiers are trained to use various weapon systems or while in combat (ref 16).

While exposures to emissions from ammunition propellants may be encountered by soldiers in a variety of operational settings, the US Army's concern about the potentially harmful effects of various air pollutants has focused on exposures in various armored vehicles. Armored crewmen are vulnerable to the adverse effects of exposure to the toxicants mentioned because of the closely confined and sometimes poorly ventilated space inside the vehicles, and because of the proximity of personnel to the emission sources (ref 16).

Carbon monoxide (CO) is an invisible, odorless gas which gives no warning to its victims, although it is sometimes mixed with other more obvious gases. CO is one of the most dangerous industrial hazards and one of the most wide-spread. Approximately 2,000 persons die each year as a result of exposure to CO. At least 10,000 workers suffer from exposure to harmful levels of CO and those who experience milder effects number in the millions (ref 3). There is also good reason to believe that many cases, both fatal and nonfatal, go unreported or are incorrectly diagnosed each year. Motor vehicles account for 60 percent of all CO emissions annually. A lethal concentration of CO can be reached in a closed garage within 10 minutes. Concentrations of 25 parts per million (ppm) are commonly encountered on expressways in major metropolitan areas. During weather inversions, concentration could reach as high as 100 ppm (ref 23).The nonindustrial segment of the population most exposed to CO are tobacco smokers.

In 1973, the National Institute for Occupational Safety and Health (NIOSH) recommended a standard for CO exposure specifying an 8-hour time-weighted average (TWA) of 35 ppm with a ceiling value of 200 ppm. The recommended standard was designed for the safety and health of workers performing a normal 8-hour day, 40-hour week assignment; it was not designed for the population at large. The recommended TWA standard of 35 ppm CO is based on a carboxyhemoglobin (COHb) level of 5 percent, the amount of COHb that a person engaged in sedentary activity would be expected to inhale in 8 hours during continuous exposure. The ceiling concentration of 200 ppm is based upon the restriction of employees to noncontinuous exposures to CO above 35 ppm which would not be expected to significantly alter their level of COHb. The recommended standard does not take into consideration the smoking habits of workers since the level of COHb in chronic cigarette smokers has generally been found to be in the 4 to 5 percent range before CO exposure.

As of this date, the NIOSH standard has not been adopted by the Occupational Safety and Health Administration (OSHA). The OSHA standard (29CFR1910.1000(a)), based on a COHb level of about 6 percent, specifies a 50 ppm TWA for an 8-hour period (ref 6). No ceiling level is specified in this standard.

MIL-STD-1472C (ref 15) states "...that carbon monoxide in personnel areas shall be reduced to the lowest level feasible. Personnel shall not be exposed to concentrations of carbon monoxide (CO) in excess of values which shall result in carboxyhemoglobin (COHb) levels in their blood greater than the following percentages: 5 percent COHb (all system design objectives and aviation system performance limits); 10 percent COHb (all other system performance limits) ..."

While it is recognized that toxic gases, such as nitrogendioxide (NO_2), sulphur dioxide (SO_2), and other dangerous substances, can affect the health of personnel, this investigation was confined to the study of carbon monoxide.

The information contained in this report was developed through a search of existing available literature on the subject of CO and from data collected during toxic gas testing conducted at APG (ref 27). The APG instrumentation used to collect toxic gas data, discussed in this report, is housed in a mobile van and consists of four MSA LIRA 202 carbon monoxide analyzers, four HNU 200 ammonia analyzers, one TECO Model 14 nitrogen dioxide analyzer, and one TECO Model 40 sulfur dioxide analyzer. The electrical output from each analyzer is amplified and recorded on a paper chart by means of two SOLTEX Model KA-62, 6-pen recorders. The average CO concentration is monitored by the instruments and the COHb level is then calculated by an in-line updated so that it will have the capability to monitor vehicles on the move. An in-line computer will calculate and record TWA and COHb levels instantly.

The collected information from this investigation was combined and analyzed to determine the problems confronting personnel who would be exposed to the measured concentrations of CO. Analytical models obtained from the investigation were used to develop hypothetical situations that would represent real-world conditions. The information was also used by APG to determine requirements and specifications to update monitoring equipment used to measure CO during tests of weapons systems.

The first subjective sign of CO intoxication in a healthy subject can be in the form of a headache when the COHb level in the subject's blood reaches 10 to 20 percent. If exposure continues, symptoms may progress to dizziness, nausea, a feeling of weakness, mental confusion, impaired vision, and an awareness of palpitations and breathing difficulties before collapsing. The major effect of CO is due to its ability to impair oxygen transport by the blood, thus resulting in hypoxia (ref 1). Normally, oxygen from the lungs is carried through the body by the blood's hemoglobin. But when CO is inhaled, the hemoglobin (Hb) grabs the poison first, ignoring the available oxygen. Without oxygen passing through the bloodstream, the victim suffocates. At lower levels, the CO still takes over part of the oxygen-carrying capability of the blood. CO is a safety hazard as well as a health hazard. A person suffering from CO intoxication is likely to cause accidents, possibly injuring himself and others, while performing military functions such as operating vehicles, mechanical/electrical equipment, or weapon systems.

The affinity of Hb for CO is about 200 to 300 times as great as oxygen. The affinity constant (M) can be expressed as the number of moles of oxygen which must be present with each mole of CO in order to maintain an equilibrium saturation of Hb. The combination of Hb with CO forms a compound known as COHb. A normal male has about 15 grams of Hb per 100 ml of blood and each gram of Hb is capable of carrying 1.34 ml of oxygen. This results in the transport of 20 ml of oxygen per 100 ml of blood which represents a maximum oxyhemoglobin $(HbO_2)_{max}$ of 0.2 ml per ml of blood (ref 16). Because the Hb binding sites have a preference for CO, the HbO concentration is always less than $(HbO_2)_{max}$ by a value of (COHb) (ref 16). The relationship between the partial pressures of oxygen and CO in the lungs and their combinations with Hb can be expressed by the equation:

$$P_{co} \times M/P_{02} = COHb/O_2Hb$$

where

P_{co} and P_{02} = Partial pressures of CO and O_2, respectively

M = Affinity constant of CO for Hb

As with many other gases, the degree of harm from CO is a product of concentration (ppm) multiplied by the length of exposure (time). For a healthy nonsmoking male doing a sedentary type of activity (work effort = 1), the relationships in Table 1 have been proposed as a rough guide in estimating effects of exposure to CO (ref 12). However, if the work effort was to be increased to a moderate work level (work effort = 4) the level of COHb would increase to dangerous levels (see column 1) in Table 1.

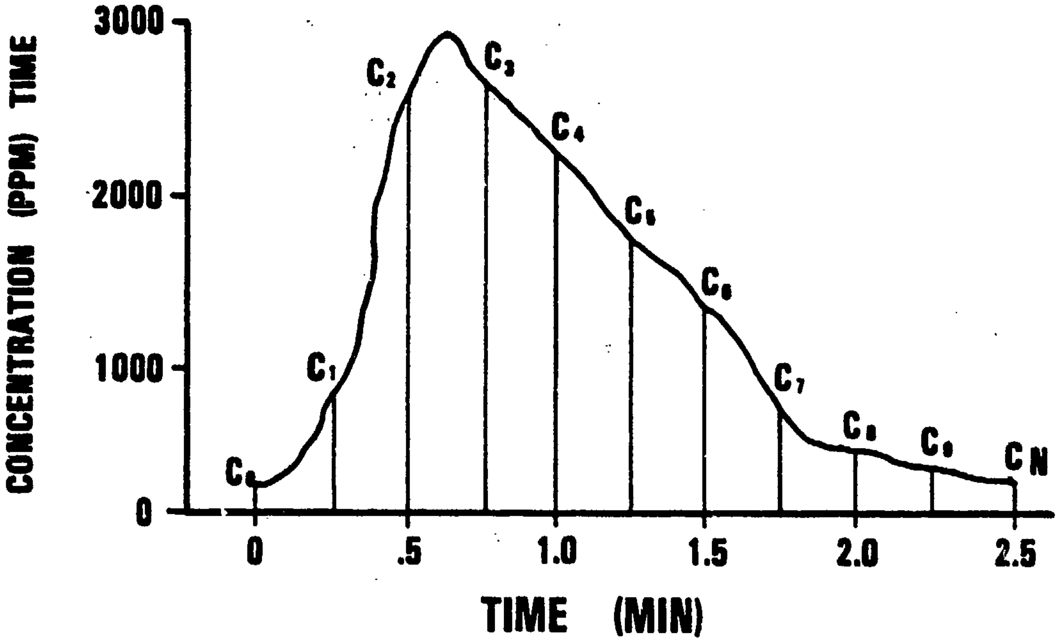
The exposure of 600 ppm-hour would cause the COHb level to rise dangerously to approximately 40 percent. In fact, the safe exposure would have to be less than 150 ppm-hour. It is obvious then that the OHSA standard of 50 ppm, TWA for 8 hours would not be valid when a 400 ppm-hour exposure is permitted for personnel who are working at moderate levels.

In the real world of toxic gas exposures, the amount of CO contaminating the atmosphere will not necessarily be constant. It is unlikely that a given concentration, say 50 ppm, can be measured steadily for a period of 8 hours. Measurements of CO and other toxic gases during testing at APG vary from a point near zero and rise steadily until a maximum peak is reached and then fall steadily when the source of CO has been removed. The scenario can be described by the typical exposure concentration curve in Figure 1 (ref 9).

PROBABLE EFFECTS OF EXPOSURE TO CO

CONCENTRATION (ppm) X TIME (HR)	COHb (%) WE = 1	PROBABLE EFFECT	COHb (%) WE = 4	PROBABLE EFFECT
300 ppm · hour	8.0	NO PERCEPTIBLE EFFECT	20.0	HEADACHE
400 ppm · hour	10.0	OSHA TWA	27.0	HEADACHE AND NAUSEA
600 ppm · hour	16.0	JUST PERCEPTIBLE EFFECT	40.0	DANGEROUS TO LIFE
900 ppm · hour	24.0	HEADACHE AND NAUSEA	60.0	FATAL
1,500 ppm · hour	39.0	DANGEROUS TO LIFE	$>$ 60.0	FATAL

TABLE 1



TYPICAL EXPOSURE CONCENTRATION CURVE

$$A = \int_{t=0}^{tn} f(t)dt$$

$$A = h/3\left[(C_0+C_n) + 4\,(C_1+C_3+\ldots+C_{n-1})+2(C_2+C_4+\ldots+C_{n-2})\right]$$

A = AREA UNDER THE CURVE (AVE. CONCENTRATION)

h = TIME INTERVAL BETWEEN POINTS

N+1 = No. OF POINTS

C = CONCENTRATION AT TIME t_n

FIGURE 1

The area under the curve represents the average concentration of CO over a period of time. The greater the number of points used, the greater the degree of accuracy in calculating the area. The area is calculated as follows:

$$h = 0.25 \text{ minute}$$

$$A = 0.25/3 \left(\left(100 + 260\right) + 4\left(900 + 2,600 + 1,600 + 600 + 300\right) + 2\left(2,600 + 2,100 + 1,200 + 400\right)\right) = 3,080\text{ppm}$$

The COHb level for a person, exposed to this concentration for a period of 2.5 minutes and doing level 4 type of activity, would be approximately 11.58%. This person would be considered over-exposed, and some action to prevent or reduce this exposure would need to be taken. It has also been recognized that when a person performs exercise or work during CO inhalation, the maximum work time before exhaustion will be reduced, depending both on COHb and exercise levels. Two important parameters to be considered are the diffusion rate (D_L) of CO through the lungs (ml/min) and the ventilation rate (V_a) (ml/min). The following assumptions listed in Table 2 have been made for various levels of activity (ref 15).

ASSUMPTIONS FOR VARIOUS LEVELS OF ACTIVITY

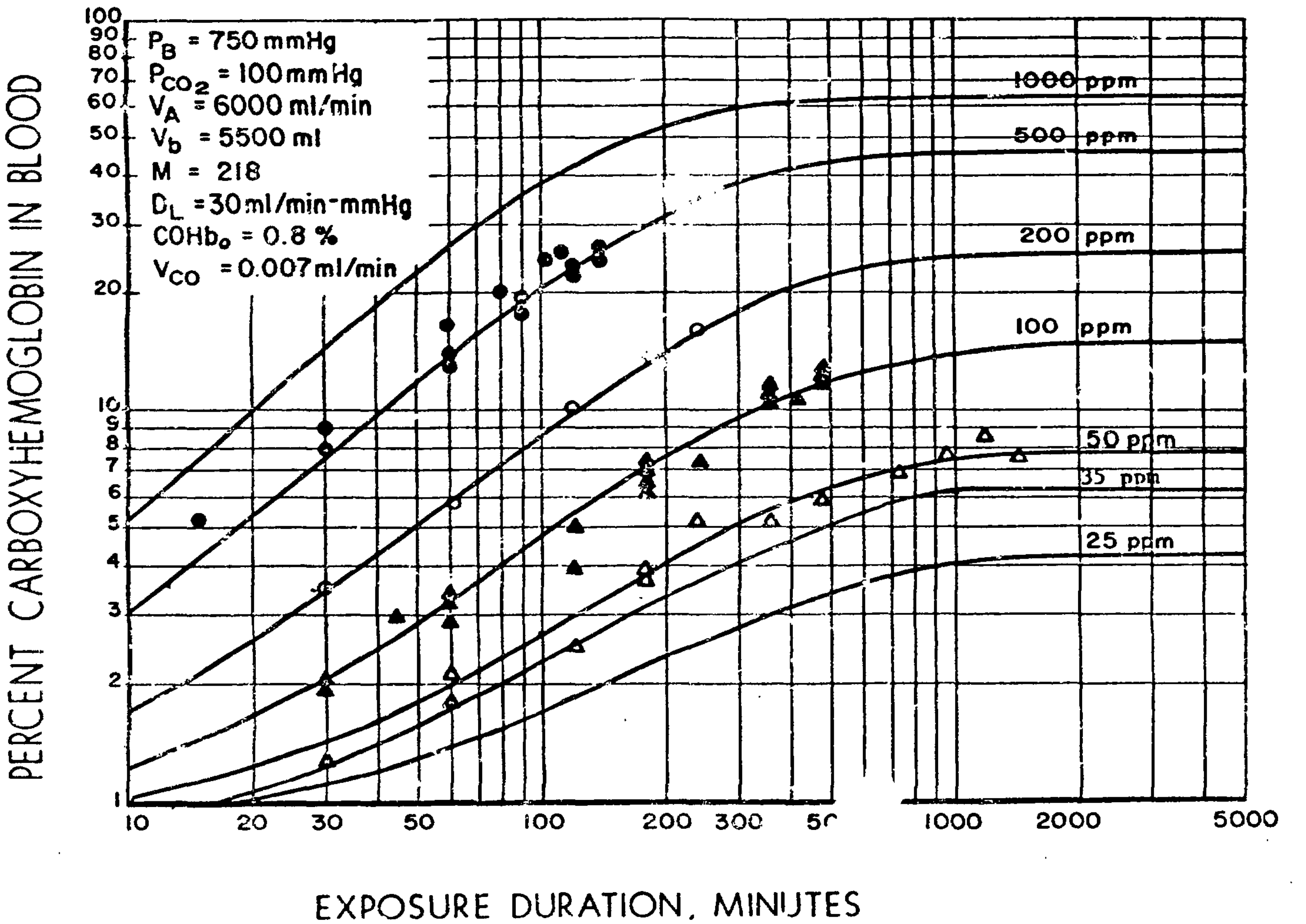
WCRK EFFORT	TYPE OF ACTIVITY	DIFFUSION RATE (D_L)	VENTILATION RATE (V_a)
1.	SEDENTARY	30 ml/min	6,000 ml/min
2.		35 ml/min	12,000 ml/min
3.	LIGHT WORK	40 ml/min	18,000 ml/min
4.	MODERATE WORK	50 ml/min	24,000 ml/min
5.	HEAVY WORK	60 ml/min	30,000 ml/min

TABLE 2

The rate at which the blood becomes saturated with CO is therefore directly proportional to cardiac output. Consequently, a person working vigorously will note the onset of symptoms and signs much more quickly than one who is sedentary or at rest (i.e., a person running around in a building seeking an escape route from a fire will be overcome more quickly than will someone sleeping (ref 15).

In 1965, Coburn et al (CFK) (ref 1) published a definitive study on the role of endogenous CO production rate, pulmonary CO diffusing capacity, and other recognized variables. The CFK equation was later tested by Stewart et al (ref 1) and Peterson and Stewart (ref 1) in experiments with human volunteers. It was concluded that the ability of the CFK equation to predict the effects of CO exposure on blood COHb levels was astonishingly good in normal young adult males (ref 1). This equation was later used in a number of studies, one of which was published by NIOSH in 1972, recommending a standard for occupational exposure to CO. The standard has not yet been adopted by OSHA; however, the CFK equation as published by NIOSH has been used extensively in various Government standards to predict levels of COHb resulting from CO exposure. COHb saturations obtained during experimental human exposure to CO by Stewart et al (ref 19) are imposed on the theoretical absorption curves (fig. 2). The results of the comparisons showed that the experimental data fit the CFK (ref 5) model very well.

ABSORPTION OF CARBON MONOXIDE



Stewart, R. D., et al: Experimental Human Exposure to Carbon Monoxide. Arch. Environ. Health. 21:154-164, 1970.

FIGURE 2

CFK equation. The CFK equation (ref 18) has become a model for estimating changes in COHb concentration in the blood. The equation once integrated takes the following form:

$$\frac{\dfrac{[COHb]P_{CO_2}}{[O_2Hb]M} - V_{CO}\left[\dfrac{1}{D_L} + \dfrac{P_B - P_{H_2O}}{V_A}\right] - P_{I_{CO}}}{\dfrac{[COHb]_0 P_{CO_2}}{[O_2Hb]M} - V_{CO}\left[\dfrac{1}{D_L} + \dfrac{P_B - P_{H_2O}}{V_A}\right] - P_{I_{CO}}} = e^{-\dfrac{P_{CO_2} t}{MV_b [O_2Hb] \frac{1}{D_L} + \frac{713}{V_A}}}$$

has been rearranged for programming as follows:

$$\text{CO in air (ppm)} = \frac{1316\ [(AC - V_{CO}B + a\ (V_{CO}B - AD)]}{1 - a}$$

where

$$A = \frac{P_{C-O_2}}{M[O_2H_b]}$$

$$B = \frac{1}{D_L} + \frac{P_L}{V_A}$$

$C = [COHb]_t$ = COHb concentration (ml CO/ml blood) at time t.

$D = [COHb]_0$ = "background" COHb (ml CO/ml blood) at time = 0.

V_{CO} = Rate of endogenous CO production (ml/min)

$$a = e^{-\frac{tA}{VbB}}$$

V_b = blood volume

$P_{C-O_2} = PO_2$ in capillaries (mm Hg)

$[O_2Hb]$ = oxyhemoglobin conc. (ml/ml blood)

M = CO/O_2 affinity for Hb

CFK Equation Continued

V_a = ventilation rate (ml/min)

D_L = 30 ml/min-mmHg

V_{CO} = 0.007 ml/min

V_b = 5,500 ml

$P_c - O_2$ = 100 mm Hg

(O_2Hb) = 0.2 ml/ml blood

M = 218

P_b - 760 mm of mercury

The empirical equation in MIL-STD-759A (ref 10) used to predict the rise in COHb in humans was also derived from the CFK equation and was transformed as follows:

$$\%\,COHb_t = \%\,COHb_o \left(e^{-t/2398B}\right) + 218 \left(1 - e^{-t/2398B}\right)\left(.007B + CO_{ppm}/1316\right)$$

where

$\%COHb_t$ = Predicted COHb

$\%COHb_o$ = Initial COHb

t = Exposure in minutes

COppm = CO exposure in parts per million

B = $1/D_L + (Pb - 47)\ V_a$

ABSORPTION OF CARBON MONOXIDE

As levels of COHb increase, the proportion of absorbed CO decreases due to an increase in the average back pressure of CO in the blood of the lung capillaries. Theoretically, the rate of CO uptake would be proportional to the difference between alveolar CO partial pressure (P_{CO}) and the average back pressure of CO in the blood of lung capillaries. Both values rise during the course of exposure. The back pressure rises slowly at first and then rapidly as Hb saturation increases. As the saturation increases, alveolar P_{CO} rises because progressively less CO is extracted by the blood from the inspired air; when equilibrium between P_{CO} in the capillaries and the alveoli is reached, absorption ceases (ref 1). Figure 3 shows the COHb for resting adults exposed to constant concentrations of CO of 10, 50, and 100 ppm for 30 hours

When the CO exposure is terminated, the level of COHb will fall to its pre-exposure level. The rate of excretion is assumed to be equal to approximately 250-minute biological half-life.

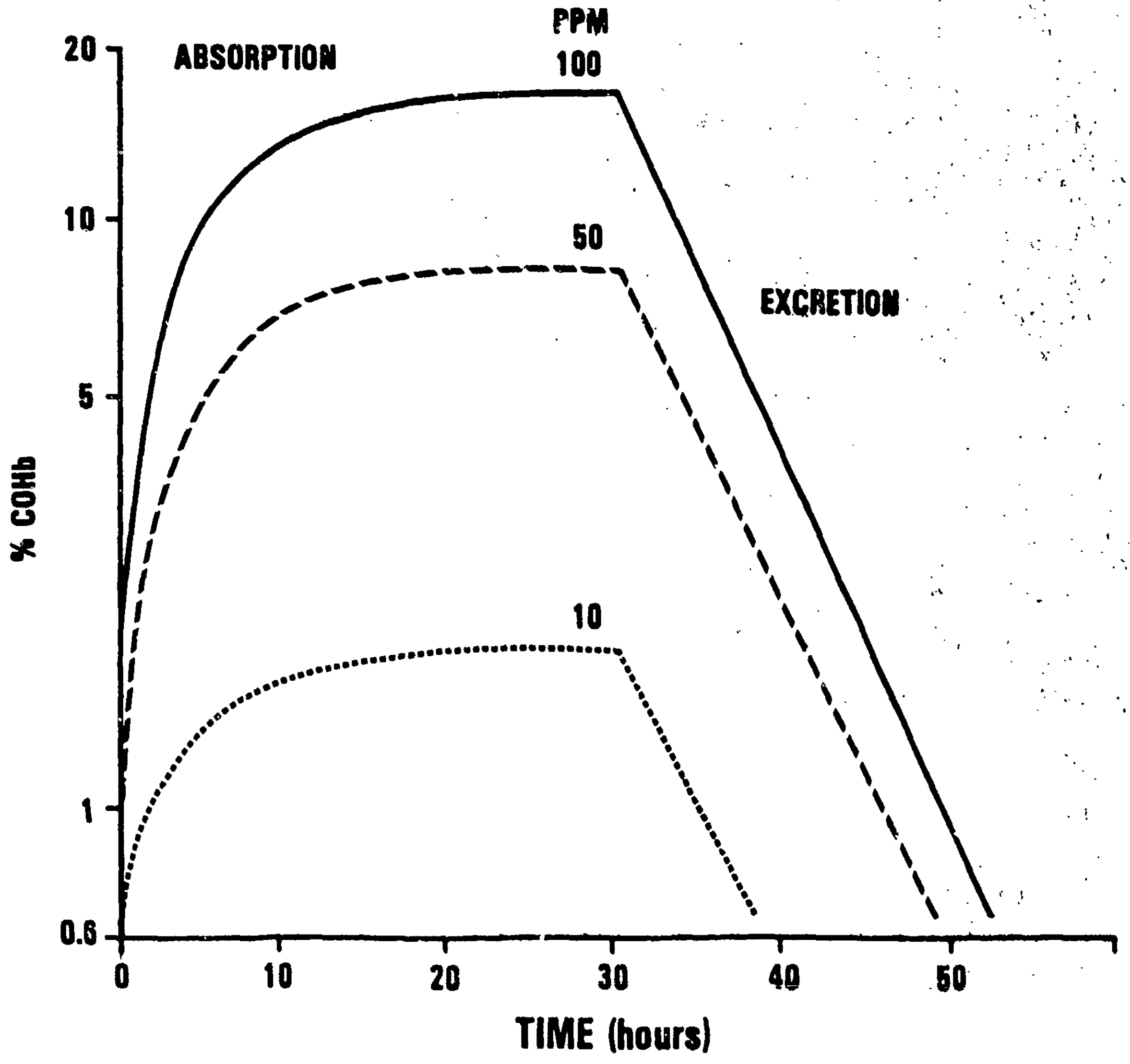


FIGURE 3

It is therefore apparent that unless the partial pressures of CO and O_2 are taken into consideration, the CFK equation would not show that a level of equilibrium has been reached.

While the Stewart tests showed that the experimental data fit the CFK equation very well, those data compared to the modified CFK equation showed that the level of COHb may overpredict (ref 23). Therefore, because of the variables that must be considered when calculating COHb levels with the CFK equation, the results are sometimes questionable. Furthermore, MIL-STD-1472C and MIL-HDBK-759A have recognized the difficulty in obtaining actual blood COHb levels in the operational environment. A method using breath alveolar CO concentrations of test subjects was demonstrated by Stewart, et al (ref 6). The accuracy and simplicity of this techinique has opened a practical field method for the rapid estimation of blood COHb levels in occupational groups (ref 6).

The Stewart methodology does not address CO exposure profiles. It estimates the blood COHb levels resulting from the summation of previous CO exposures (ref 6). Thus, this method is ideally suited to the biological monitoring program in the operational setting.

<u>Elimination of CO</u>. Most of the CO is eliminated unchanged through the lungs and is similiar in many ways to absorption. Elimination is rapid at first, but the last traces are eliminated very slowly. CO is eliminated exponentially; so it is useful to discuss the elimination rate in terms of biological half-life. The normal elimination of CO is quite slow because of its greater affinity for Hb than that of oxygen. The rate of excretion of CO can be calculated with the

CFK equation. The value of $COHb_o$ in equation (7) would be the highest $COHb_t$ level following the exposure, and the COHb would be the level to which it falls following a given time period. The rate of excretion using equation (7) is based on a biological half-life of 250 minutes for a healthly person at rest in an atmosphere of fresh air (free of contaminants). It is interesting to note that the biological half-life can be reduced by administering 100 percent oxygen by a tight fitting mask. The biological half-life is thus reduced to approximately 80 minutes. The biological half-life can be further reduced to about 24 minutes by administering 100 percent oxygen in a hyerbaric setting of 3 atomospheres of pressure (ref 22).

It is also interesting to note that the function $e^{-t/2398B}$ in equation (7) is equal to e^{-ta/V_bB} from equation (6). Both of these terms represent the decay of COHb. Consequently, both the terms are equal to the decay equation used to measure the amount of decay of radioactive material. The following equation (ref 32) can thus be substituted to calculate the elimination of CO from the blood.

$$N_t = N_o e^{-kt}$$

where

N_t = Final COHb level

N_o = Initial COHb level

K = Disintegration factor

= 0.693/Half-Life or 0.693/250 = 0.0028

t = Time (min)

Comparing this with the equation from MIL-HDBK-759A, we find that the function $e^{-t/2398B} = e^{-0.0028t}$ which equals the above equation for the decay of COHb in an atmosphere of fresh air.

To calculate the amount of time needed to purge the COHb level to a normal level of approximately 1 percent or to some other designated level, the decay formula can be transposed as follows:

$$t\ (\text{min}) = \frac{\log_e N_t - \log_e N_o}{-K}$$

The computer program illustrated in this paper is a revision of a program to calculate COHb levels at various crew stations in armored vehicles (ref 26). This program is written in FORTRAN IV language, and a simulated scenario was run to produce the printout. The commander, driver, and loader crew stations were assigned average CO concentrations of 507, 497, and 473, respectively, and COHb level was calculated for each time period listed in the left-hand column. The program was run at work levels equalling one and four for comparison (see printouts). The gunner's position was assigned a concentration of 50 ppm to demonstrate the COHb levels associated with OSHA'S standard. This data is plotted on a graph (Figure 4). A difference of almost 2 percent COHb can be expected in a nonsmoking healthy male person.

LEVEL OF COHb DURING EXPOSURE OF 50 PPM OF CO

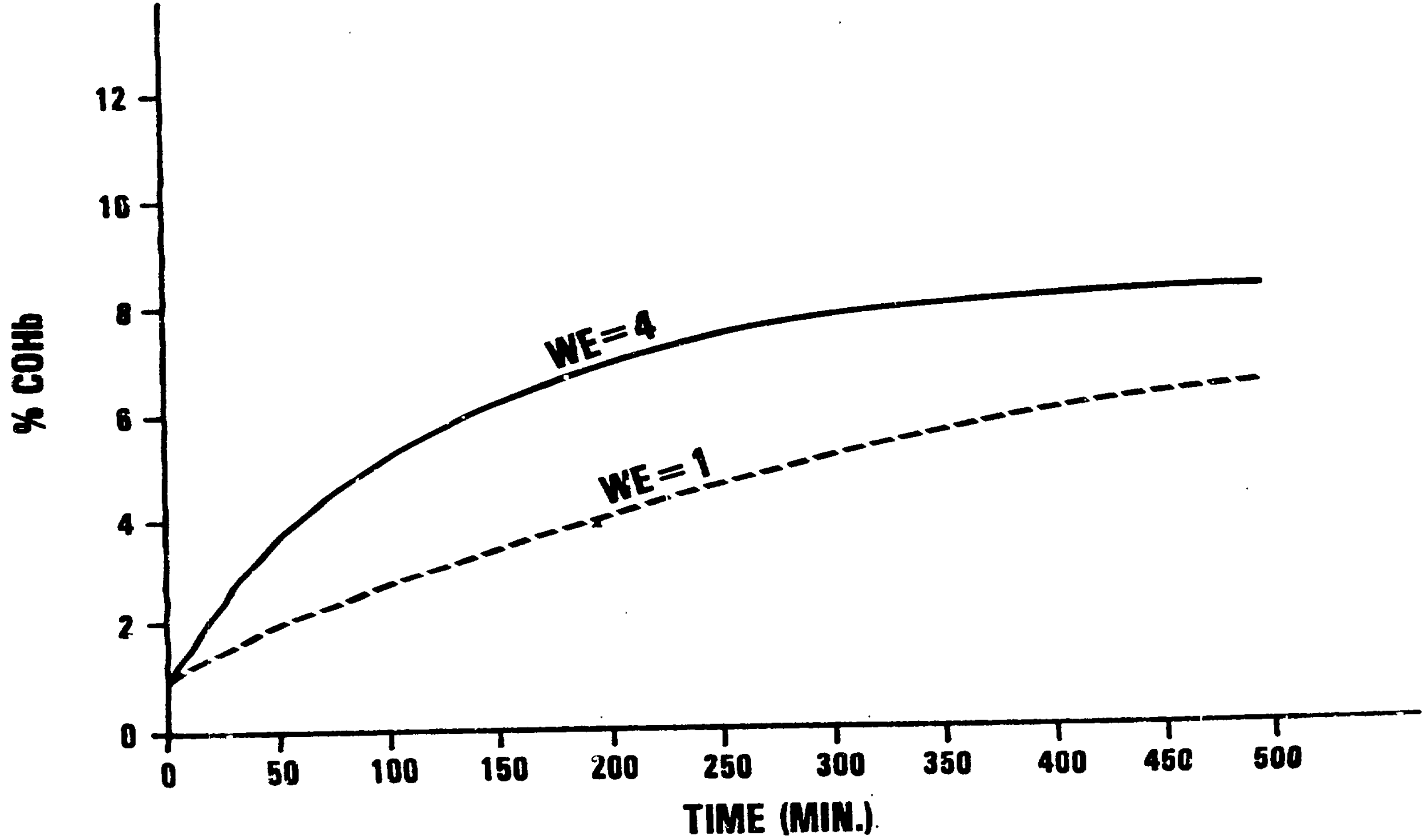


FIGURE 4

```
$CONTROL USLINIT,FILE=1
C  PROGRAM COHB3 REVISED 'FROM TECH NOTE 1-80(S.STEINBERG,AUTHOR)'
       PROGRAM COHB3
       DIMENSION COO(4),COHBT(4),PPM(4),IBWS(4),DL(5),
     +    VA(5),B(5),DCOHB(4)
      CHARACTER*70 HDR
       DATA     DL/30.0,35.0,40.0,50.0,60.0/,
     +       VA/6000.0,12000.0,18000.0,24000.0,30000.0/
      DISPLAY 'SET TOF'
      ACCEPT IDUM
      IN=1
100     READ  (IN,110) HDR,PB,COO
110     FORMAT (A70/F3.0,4(1X,F4.2))
      LINES=0.0
        TIME=0.0
        HTIME=0.0
290     WRITE (6,300) HDR,PB
300     FORMAT (1H1,'SCENERIO:',A70/
     +         20X,'BAROMETRIC PRESSURE=',F6.1,' (MM HG)'/
     +        T4,'CUM TIME',T15,'D-TIME',
     +         T23,'-------- COMMANDER --------',
     +         T51,'--------- DRIVER ----------',
     +         T79,'--------- LOADER ----------',
     +         T107,'-------- GUNNER ----------'/
     +         T17,'MIN',
     +         4('   WE CO-PPM D-COHB T-COHB  ')/)
         WRITE (6,350) HTIME,TIME,COO
350      FORMAT (1X,F5.2,1X,F6.1,7X,4(19X,F8.2,1X))
         DO 400 I=1,5
400      B(I)=1.0/DL(I) + (PB-47.0)/VA(I)
500      READ (IN,510) TI,(IBWS(J),PPM(J),J=1,4)
510      FORMAT (F5.1,4(1X,I1,1X,F5.0))
         IF (TI.LT.0..OR.IBWS(1).EQ.0.) GO TO 715
         IF (TI.EQ.0.0) GO TO 100
         DO 600 K=1,4
         TERM=EXP(-TI/2398.0/B(IBWS(K)))
         COHBT(K)=COO(K)*TERM + 218.0*(1.0-TERM)*(.007*B(IBWS(K))
     +    +PPM(K)/1316.0)
600      DCOHB(K)=COHBT(K) - COO(K)
         TIME=TIME+TI
         HTIME=TIME/60.0
         LINES=LINES+1
         IF(MOD(LINES,50).EQ.0) WRITE(6,675)HDR
675      FORMAT (1H1,'SCENERIO: ',80A1/
     +          T4,'CUM TIME',T15,'D-TIME',
     +           T23,'--------COMMANDER--------',
     +            T51,'---------DRIVER----------',
     +        T79,'---------LOADER----------',
     +           T107,'--------GUNNER----------'/
     +           T3,'HRS',T10,'MIN',T17,'MIN',
     +           4('   WE CO-PPM D-COHB T-COHB  ')/)
          WRITE (6,700) TI,
     +    (IBWS(M),PPM(M),DCOHB(M),COHBT(M),M=1,4)
700       FORMAT (12X,F7.1,4(I4,F8.0,F7.2,F8.2,1X))
710      GO TO 500
715      STOP
720      END
```

SCENERIO:TEST COMPUTER PROGRAM COHB3

BAROMETRIC PRESSURE= 760.0 (MM HG)

D-TIME	COMMANDER				DRIVER				LOADER				GUNNER			
MIN	WE	CO-PPM	D-COHB	T-COHB	WE	CO-PPM	D-COHB	T-COHB	WE	CO-PPM	D-COHB	T-COHB	WE	CO-PPM	D-COHB	T-COHB
				1.00				1.00				1.00				1.00
15.0	4	507.	9.82	10.82	4	497.	9.63	10.63	4	473.	9.16	10.16	4	50.	.87	1.87
30.0	4	507.	18.48	19.48	4	497.	18.11	19.11	4	473.	17.23	18.23	4	50.	1.64	2.64
60.0	4	507.	32.85	33.85	4	497.	32.20	33.20	4	473.	30.62	31.62	4	50.	2.91	3.91
90.0	4	507.	44.02	45.02	4	487.	42.27	43.27	4	473.	41.04	42.04	4	50.	3.90	4.90
114.0	4	507.	51.14	52.14	4	487.	49.10	50.10	4	473.	47.67	48.67	4	50.	4.53	5.53
120.0	4	507.	52.71	53.71	4	487.	50.61	51.61	4	473.	49.14	50.14	4	50.	4.67	5.67
135.0	4	507	56.30	57.30	4	487.	54.05	55.05	4	473.	52.48	53.48	4	50.	4.99	5.99
150.0	4	507.	59.46	60.46	4	487.	57.09	58.09	4	473.	55.43	56.43	4	50.	5.27	6.27
180.0	4	507.	64.71	65.71	4	487.	62.13	63.13	4	473.	60.33	61.33	4	50.	5.73	6.73
240.0	4	507.	71.97	72.97	4	487.	69.10	70.10	4	473.	67.09	68.09	4	50.	6.38	7.38
300.0	4	507.	76.36	77.36	4	487.	73.31	74.31	4	473.	71.18	72.18	4	50.	6.76	7.76
330.0	4	507.	77.85	78.85	4	487.	74.74	75.74	4	473.	72.57	73.57	4	50.	6.90	7.90
360.0	4	507.	79.01	80.01	4	487.	75.86	76.86	4	473.	73.65	74.65	4	50.	7.00	8.00
390.0	4	507.	79.91	80.91	4	487.	76.72	77.72	4	473.	74.49	75.49	4	50.	7.08	8.08
420.0	4	507.	80.61	81.61	4	487.	77.40	78.40	4	473.	75.15	76.15	4	50.	7.14	8.14
480.0	4	507.	81.58	82.58	4	487.	78.33	79.33	4	473.	76.05	77.05	4	50.	7.23	8.23
420.0	4	507.	80.61	81.61	4	487.	77.40	78.40	4	473.	75.15	76.15	4	50.	7.14	8.14
450.0	4	507.	81.16	82.16	4	487.	77.92	78.92	4	473.	75.65	76.65	4	50.	7.19	8.19

SCENERIO:TEST COMPUTER PROGRAM COHB:
BAROMETRIC PRESSURE= 760.0 (MM HG)

D-TIME MIN		COMMANDER WE CO-PPM	COMMANDER D-COHB	COMMANDER T-COHB		DRIVER WE CO-PPM	DRIVER D-COHB	DRIVER T-COHB		LOADER WE CO-PPM	LOADER D-COHB	LOADER T-COHB		GUNNER WE CO-PPM	GUNNER D-COHB	GUNNER T-COHB
				1.00				1.00				1.00				1.00
15.0	1	507.	3.35	4.35	1	497.	3.28	4.28	1	473.	3.12	4.12	1	50.	.30	1.30
30.0	1	507.	6.57	7.57	1	497.	6.44	7.44	1	473.	6.12	7.12	1	50.	.59	1.59
60.0	1	507.	12.62	13.62	1	497.	12.37	13.37	1	473.	11.76	12.76	1	50.	1.14	2.14
90.0	1	507.	18.19	19.19	1	487.	17.47	18.47	1	473.	16.96	17.96	1	50.	1.64	2.64
114.0	1	507.	22.33	23.33	1	487.	21.44	22.44	1	473.	20.82	21.82	1	50.	2.02	3.02
120.0	1	507.	23.32	24.32	1	487.	22.39	23.39	1	473.	21.74	22.74	1	50.	2.11	3.11
135.0	1	507.	25.73	26.73	1	487.	24.71	25.71	1	473.	23.99	24.99	1	50.	2.32	3.32
150.0	1	507.	28.05	29.05	1	487.	26.93	27.93	1	473.	26.15	27.15	1	50.	2.53	3.53
180.0	1	507.	32.40	33.40	1	487.	31.11	32.11	1	473.	30.21	31.21	1	50.	2.93	3.93
240.0	1	507.	40.11	41.11	1	487.	38.51	39.51	1	473.	37.39	38.39	1	50.	3.62	4.62
300.0	1	507.	46.65	47.65	1	487.	44.79	45.79	1	473.	43.49	44.49	1	50.	4.21	5.21
330.0	1	507.	49.53	50.53	1	487.	47.56	48.56	1	473.	46.18	47.18	1	50.	4.47	5.47
360.0	1	507.	52.19	53.19	1	487.	50.11	51.11	1	473.	48.66	49.66	1	50.	4.71	5.71
390.0	1	507.	54.64	55.64	1	487.	52.46	53.46	1	473.	50.94	51.94	1	50.	4.93	5.93
420.0	1	507.	56.90	57.90	1	487.	54.63	55.63	1	473.	53.04	54.04	1	50.	5.14	6.14
450.0	1	507.	58.97	59.97	1	497.	56.62	57.62	1	473.	54.98	55.98	1	50.	5.33	6.33
480.0	1	507.	60.89	61.89	1	487.	58.46	59.46	1	473.	56.77	57.77	1	50.	5.50	6.50
510.0	1	507.	62.65	63.65	1	487.	60.15	61.15	1	473.	58.41	59.41	1	50.	5.66	6.66
540.0	1	507.	64.27	65.27	1	487.	61.71	62.71	1	473.	59.92	60.92	1	50.	5.80	6.80
600.0	1	507.	67.15	68.15	1	487.	64.47	65.47	1	473.	62.60	63.60	1	50.	6.06	7.06

EXAMPLES

Example 1

Assume that a nonsmoking individual was exposed to 6,000 ppm of CO for a period of 1 minute. This individual was doing sedentary level or work while exposed. His physical characteristics were as follow:

Ventilation rate (V_a)	= 6,000 ml/min.		t	= 1 min
Diffusion rate (D_L)	= 30 ml/min.	where	B	= 0.15
Blood volume (V_b)	= 5,500 ml		%$COHb_t$	= 0.8% (nonsmoker)
Using CFK equation			ppmCO	= 6,000 ppm

$$\%COHb_t = 0.8 \left(e^{-1/(2398)(.15)}\right) + 218 \left(1 - e^{-1/(2398)(.15)}\right)\left((.007)(.15) + 6{,}000/1{,}316\right)$$

$$= 0.8\ (0.997) + 218\ (0.0027)(4.56)$$

$$= \underline{3.48}\%$$

Example 2

Assume that the same individual (example 1) was exposed, except that he was a chronic smoker and was doing heavy work at the time of exposure.

then

$$\%COHbt = 5 \left(e^{-1/(2398)(.04)}\right) + 218 \left(1 - e^{-1/(2398)(.04)}\right)\left((.007)(.04) + 6{,}000/1{,}316\right)$$

$$= 5\ (0.989) + 218\ (0.011)\ (4.56)$$

$$= \underline{15.88\%}$$

The difference in %COHb level following the same exposure level and time due to difference in work activity in addition to being a smoker is significant. The individual in example 2 could possibly be subjected to symptoms of COHb such as headaches, and his ability to perform work safely could be affected.

Example 3

At APG, toxic-fumes investigations are conducted to determine the concentration of toxic gases to which a crew is exposed to when executing sustained rates of weapons fire during various vehicle conditions and defensive or offensive scenarios. The study scenario is usually representative of anticipated operational situations. The ideal scenario encompasses periods when maximum sustained rates of fire are achieved by weapons systems and the crew space environmental control system is maximally stressed to remove firing contaminants. This ensures the crew exposure to maximum design concentrations of toxic gases or fumes at the time of high workload requirements. This ideal scenario represents a "worst-case" operational situation and during stationary fire or fire-and-maneuver exercises.

A toxic fume investigation is also conducted to determine the concentration of toxic gases resulting from the operation of vehicles and other engine-driven equipment.

A typical firing condition test matrix is usually represented in Table 4. (The scenario may vary according to the needs of the system being tested.)

FIRING CONDITION TEST MATRIX

Condition[a] No.	Rounds Fired: 25 mm[b]	Rounds Fired: 7.62 mm	Hatches[c]	Crew Ventilator[d]	Personnel Heater[e]
1	5	—	Closed	On	Off
2	5	—	Closed	Off	Off
3	5	—	Open	On	Off
4	10	—	Open	On	Off
5	10	—	Closed	On	Off
6	5	—	Closed	On	On
7	10	—	Closed	On	On
8	10	—	Closed	On	On
9	1	—	Closed	On	On
10	1	—	Open	On	On
11	—	23	Closed	On	On
12	—	21	Open	On	On
13	—	23	Open	On	Off
14[f]	135	200	Closed	On	On
15[g]	210	300	Closed	On	On

[a] During all firing conditions the engine was operated at 1400 rpm (tactical idle) with the exception of conditions 11, 12 and 13 when it was operated at 700 rpm (normal idle).

[b] The 25 mm was fired at high rate (≈182 rds/min) during all conditions, with the exception of condition 10, when it was fired at low rate (≈92 rds/min).

[c] Driver" hatch and the two rear doors were closed during all conditions; only the two turret hatches were either opened or closed.

[d] The crew ventilator (located on top of hull behind the driver) pulls air out of the vehicle, causing negative pressure within the vehicle.

[e] Heater operated on high setting.

[f] 3-Minute scenario.

30-Minute scenario.

TABLE 4

Based on the data collected during each firing trial, the information is used to calculate the COHb level of each crew member. Each test condition is evaluated to determine whether any of the crew would be exposed to harmful concentrations of CO or other toxic fumes. Figures 5 and 6 represent the results of the test data for conditions 8 and 15 (all hatches closed and heater and vent on). This evaluation is presented for each condition.

Figure 5 shows that the concentration of CO was minimal for positions 2, 3, and 4 and would not raise the COHb of those crew members. Therefore, no firing restrictions are necessary for these positions. However, position 1 was restricted to 140 trials (1400 rounds of 25mm ammo) because the COHb level of COHb was predicted to reach 10 percent at that time. Approximately 6 hours would be needed to fire the 1400 rounds and over 6 hours would be needed to permit the crewmembers' COHb level to reduce to 1 percent. Consequently only two such missions (2,800 rounds) could be permitted during a 24 hour period.

COMPUTED CARBOXYHEMOGLOBIN (COHB) LEVELS

AVERAGE FIRING CONDITION B

BAROMETRIC PRESSURE: 760.0 MM HG

	POSITION 1	POSITION 2	POSITION 3	POSITION 4
AVERAGE CO LEVEL, PPM	63.00	39.00	39.00	49.00
TIME OF FIRE MISSION, MINUTES	2.48	2.30	.93	2.28
COMPUTED COHB LEVEL AFTER FIRST TRIAL, %	1.20	1.00	1.00	1.00
NUMBER OF TRIALS TO REACH 10% COHB	140	****	****	****
COMPUTED COHB LEVEL AFTER N TRIALS, %	10.00	1.00	1.00	1.00
COMPUTED COHB LEVEL AFTER N+1 TRIALS, %	10.01	1.00	1.00	1.00
TIME FOR COHB TO DECAY TO 1%, HRS	6.20	0.00	0.00	0.00
NUMBER OF ALLOWABLE MISSIONS PER 24 HRS	2	****	****	****

CREW POSITIONS:

POSITION 1: DRIVER
POSITION 2: CENTER OF TURRET
POSITION 3: LEFT SIDE CREW
POSITION 4: RIGHT SIDE CREW

**** NOTE: NO FIRING RESTRICTIONS WITH RESPECT TO CO

TABLE 5

Figure 6 represents condition 15 where both the 25mm and 7.62mm weapons were fired simultaneously for 30 minutes (210 rounds of 25mm and 300 rounds of 7.62mm). It was predicted that the COHb level would have reached approximately 6 percent for each crew member. Two trials would have raised the COHb level to slightly under 10 percent. Consequently, a total of about 7.5 hours would include the firing and decay times, permitting three such missions within 24 hours.

COMPUTED CARBOXYHEMOGLOBIN (COHB) LEVELS

AVERAGE FIRING CONDITION 15

BAROMETRIC PRESSURE: 750.0 MM HG

	POSITION 1	POSITION 2	POSITION 3	POSITION 4
AVERAGE CO LEVEL, PPM	107.00	106.00	100.00	109.00
TIME OF FIRE MISSION, MINUTES	42.48	42.21	41.29	43.18
COMPUTED COHB LEVEL AFTER FIRST TRIAL, %	6.04	5.96	5.58	6.21
NUMBER OF TRIALS TO REACH 10% COHB	2	2	2	2
COMPUTED COHB LEVEL AFTER N TRIALS, %	9.56	9.44	8.82	9.83
COMPUTED COHB LEVEL AFTER N +1 TRIALS, %	12.03	11.89	11.11	12.35
TIME FOR COHB TO DECAY TO 1%, HRS	6.08	6.05	5.87	6.15
NUMBER OF ALLOWABLE MISSIONS PER 24 HRS	3	3	3	3

CREW POSITIONS:
- POSITION 1: DRIVER
- POSITION 2: CENTER OF TURRET
- POSITION 3: LEFT SIDE CREW
- POSITION 4: RIGHT SIDE CREW

TABLE 6

In conclusion, then, it is apparent that the Army as well as industrial workers need to be concerned with the effects of CO on personnel. The nature of the build-up of some of the effects underscores the necessity for detecting, measuring, and as much as possible, eliminating this hazard. The military is at the forefront of technology and procedures for controlling CO, and recognizes that more needs to be done. Non-military agencies such as OSHA need to update standards and serve as a conduit to advise industry and government agencies about the hazard of CO and the latest means of protection.

REFERENCES

1. Alarie, Y. and Zullo, P., Predicting Carboxyhemoglobin for Different Patterns of Carbon Monoxide, Proceeding of the Symposium on Carbon Monoxide, December 12-13, Mellon Institute of Carnegie-Mellon University, Pittsburgh, PA.

2. Burlington, R. S., Handbook of Mathematical Tables and Formulas, Handbook Publishers, Inc., Sandusky, OH.

3. Carbon Monoxide, Job Health Hazard Series, US Department of Labor, Occupational Safety and Health Administration, June 1975.

4. Code of Federal Regulations, Title 29, subpart Z, Occupational Safety and Health Administration (OSHA), Part 1910.1000, 7 November 1978.

5. Coburn, R. F., Forster, R. E., and Kane, P. B., Consideration of the Physiology and Variables that Determine the Blood Carboxyhemoglobin Concentration in Man, Journal Clinica Institute, Volume 41, 1965.

6. Dalton, Bruce A. MD, Biological Monitoring of Crewman Exposed to Carbon Monoxide in Specific Military Tactical Vehicles, Proposal Medicine Residency Project, APG.

7. Collison, H. A., Rodkey, R. L., and O'Neal, J. D., Determination of Carbon Monoxide in Blood by Gas Chromatography, Clin. Chem., 14,162 (1968).

8. Lucas, T. A., Final Report, Methodology Investigation of Toxic Gas Measurements during Weapons Firings from Vehicles While MOving, TECOM Project No. 7-CO-PB9-AP1-002, US Army Aberdeen Proving Ground, Report No. APG-MT-5896, September 1983.

9. MIL-HDBK-759A, Human Factors Engineering Design for Army Material, 30 June 1981.

10. MIL-STD-800, Carbon Monoxide Detection and Control in Aircraft, 21 July 1958.

11. MIL-STD-1472C, Human Engineering Design Criteria for Military Systems, Equipment and Facilities, 2 May 1981.

12. Meyers, R. A., Linberg, S. E., and Crowley, R. A., Carbon Monoxide Poisoning: The Injury and Its Treatment, Maryland Institute of Emergency Services Systems, University of Maryland, Baltimore, MD, November 1979.

13. Mossa, M., Final Report, Methodology Investigation of the Effects of Carbon Monoxide on Personnel, TECOM Project No. 7-CO-RD3-AP1-004, US Army Aberdeen Proving Ground, Report No. APG-MT-5728, February 1983. (Distribution controlled by TECOM, ATTN: DRSTE-AD-M. AD 071 323L.)

14. National Institute for Occupational Safety and Health (NIOSH), Criteria for a Recommended Standard - Occupational Exposure to Carbon Monoxide, 1972.

15. Nightingale, T. E., Biological Effects of Short High Level Exposure to Gases: Carbon Monoxide, Phase Report, US Army Medical Research and Development Command, Fort Dietrich, MD, June 1980.

16. Peterson, J. E. and Stewart, R. D., Absorption and Elimination of Carbon Monoxide by Inactive Young Men. Arch. Environ. Health 21:165-171, 1970.

17. Peterson J. E. and Stewart R. D., Predicting the Carboxyhemoglobin Levels Resulting from Carbon

18. Stewart, R. D., Peterson, Y. E., Baretta, E. D., Bachan, R. T., Hosko, M. Y., and Hermann, A. A., Experimental Human Exposure to Carbon Monoxide. Arch. Environ. health 21:154-162, 1970.

19. Stewart, R. D., Petersen, J. E., Baretta, E. D., Bachand, R. T., Hosko, M. J., and Hermann, A. A., Experimental Human Exposure to Carbon Monoxide. Arch of Environ. Health, 19/0, 21, 154-164.

20. Stewart, R. D., Fisher, T. N., Hosko, M. J., Baretta, E. D., and Hermann, A. A., Experimental Human Exposure to High Concentrations of Carbon Monoxide. Arch. of Environ. Health, 1973, 26, 1-7.

21. Stewart, R. D., Stewart, R. S., Stamen, W., and Seller, R., Rapid Estimation of Carboxyhemoglobin Level in Fire Fighters, JAMA 235:390-392, 1976.

22. Stewart R. D., The Effect of Carbon Monoxide on Humans, Department Environmental Medicine, Medical College of Wisconsin, 1975.

23. Steinberg, S., The Prediction of COHb Blood Levels in Armored Combat Vehicles Crewmen in a Combat Scenario, Presentation at IATC Working Group, Fort Detrick, MD, 18 May 1983.

24. Steinberg, S. and Nielsen, D., A Proposal for Evaluating Human Exposure to Carbon Monoxide Contamination in Military Vehicles, March 1977, AMCMS Code 672716.H700011, US Army Human Engineering Laboratory, Aberdeen Proving Ground, Maryland.

25. Steinberg, S., A Computer Model for Evaluating the Effects on Fighting Vehicle Crewmembers of Exposure to Carbon Monoxide Emissions, Technical Note 1-80, January 1980, AMCMS Code 612617.H7000011, US Army Human Engineering Laboratory, Aberdeen Proving Ground, Maryland.

26. Workinger, G. F., Toxic Fumes Investigation of Light Armored Vehicle (LAV), During the Technical Feasibility Test, 11 December 1982.