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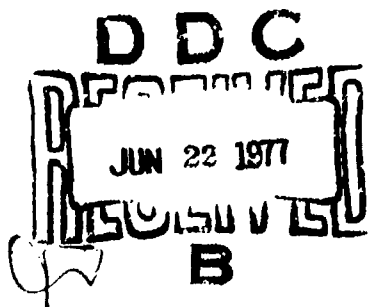
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Technical Memorandum 11-77

A PROPOSAL FOR EVALUATING HUMAN EXPOSURE TO CARBON
MONOXIDE CONTAMINATION IN MILITARY VEHICLES

Seyrnour Steinberg
Gerald D. Nielsen

March 1977
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) Carbon monoxide (CO) is considered the most frequent and predominant toxic element present in military vehicles. Exposure to CO can potentially degrade soldiers' performance and be injurious to their health. Presently, the Army evaluates the severity of CO toxic hazard to weapon system crews by applying the same Occupational Health and Safety Administration (OSHA) standards used when evaluating toxic hazard to the industrial/civilian community. A more realistic method of evaluation for Army personnel is proposed which accounts for the CO actually inspired by the exposed individual by predicting the carboxyhemoglobin (COHb) in the blood at any time during and subsequent to the exposure. The prediction (calculated by an empirical equation) is based upon (Over)		

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20. Abstract (Continued)

knowledge of the ambient CO concentration, the duration of the exposure and the physical exertion of the exposed person. COHb blood content is closely related to the medical effects of CO exposure and is the prime basis for both the evaluation procedure and the standard proposed in this report.

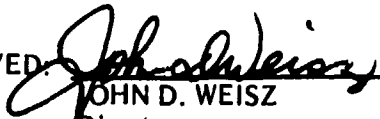
Additional subjects discussed in this report include the chronology of civilian and military standards and limits governing CO exposure, the test requirements including details which are necessary to implement the proposed evaluation method and suggested areas for future research for reducing CO exposure and potentially improving vehicle design. Also included is an example which applies the COHb equation (for predicting COHb blood content) to some hypothetical data.

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**A PROPOSAL FOR EVALUATING HUMAN EXPOSURE TO CARBON
MONOXIDE CONTAMINATION IN MILITARY VEHICLES**

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March 1977

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A PROPOSAL FOR EVALUATING HUMAN EXPOSURE TO CARBON MONOXIDE CONTAMINATION IN MILITARY VEHICLES

INTRODUCTION

Recent Army materiel development programs involving enclosed vehicles such as the mechanized infantry combat vehicle (MICV) and XM1 tank, and their integral weapons systems, have prompted a critical examination of the present method for evaluating human exposure to toxic gases such as carbon monoxide (CO). This examination is motivated, in part, by the need for an accurate and realistic method of evaluating brief, high-concentration exposures. Although other toxic substances (ammonia, sulphur dioxide, nitrogen dioxide, methane) may be present in and about vehicles, and their hazards may also require reassessment, they are not discussed in this report. It is limited exclusively to assessing the hazards of CO, which is considered the most significant toxic gas present in operating vehicles (13, Scharf *et al.* in 15).

The severity of CO exposure is a function of a number of factors, among which are: the vehicle's operating characteristics, the individual's proximity to the source of the toxicant, his respiration pattern (i.e., rate and volume), work stress level, and cumulative prior exposure. These and other factors determine the level of carboxyhemoglobin (COHb) in an individual's blood and the particular consequence(s), if any, of the exposure. Although the particulars of exposure may vary greatly, it is helpful to characterize most exposure situations as one of the following: (a) a long duration, fairly constant concentration representative of a moving or stationary vehicle with engine running, or (b) a brief, high-level concentration which results from firing weapons from an operating vehicle. Figure 1 presents hypothetical examples of these types of exposure. The constant level exposure is typical of that expected in a truck, enclosed vehicle, helicopter or aircraft cockpit enclosure, or even by a troop squad using a moving vehicle for protective cover. In addition to its occurrence when firing weapons from an operating vehicle, the high-level exposure may also be hazardous to the operating crews of machine guns, automatic rifles and artillery pieces. In this report we are primarily concerned with providing a means of evaluating CO exposure severity for enclosed vehicle crew members. Such an exposure involves multiple combinations of both types (a) and (b) above during a complete mission; an example of these exposures for one crew member during a hypothetical mission is detailed in Appendix B.

Normally, CO concentration levels are measured during vehicle testing. The test results are then interpreted to determine whether the measured levels constitute a hazard to the vehicle occupants. The hazard determinations are based upon a regulatory standard for CO. The Army currently uses MTP 2-2-614, 18 June 1968 (see reference 26 for update draft) to describe test procedures and to evaluate the results of "Toxic Hazard Tests for Vehicles." The regulatory standard used in the MTP is appropriate for the industrial community; an industrial exposure, however, is relatively constant over lengthy periods and may not necessarily be appropriate for evaluating the enclosed military vehicle with changing exposures as described above. In addition, the industrial community standard is specifically oriented to the 8-hour work day and 40-hour work week. Military operations cannot conform to such restrictive schedules except for certain peacetime operations or when not maintaining 24-hour readiness. It is therefore necessary that a separate evaluative method be devised for CO exposure which will be applicable to Army personnel for all military operations. This method, if possible, should encompass consideration of the amount of CO inspired by a vehicle crew member and not depend solely upon the ambient CO concentration as it now does. The amount of CO absorbed is directly related to the onset and character of both the physical and perceptual effects experienced by the exposed person (see

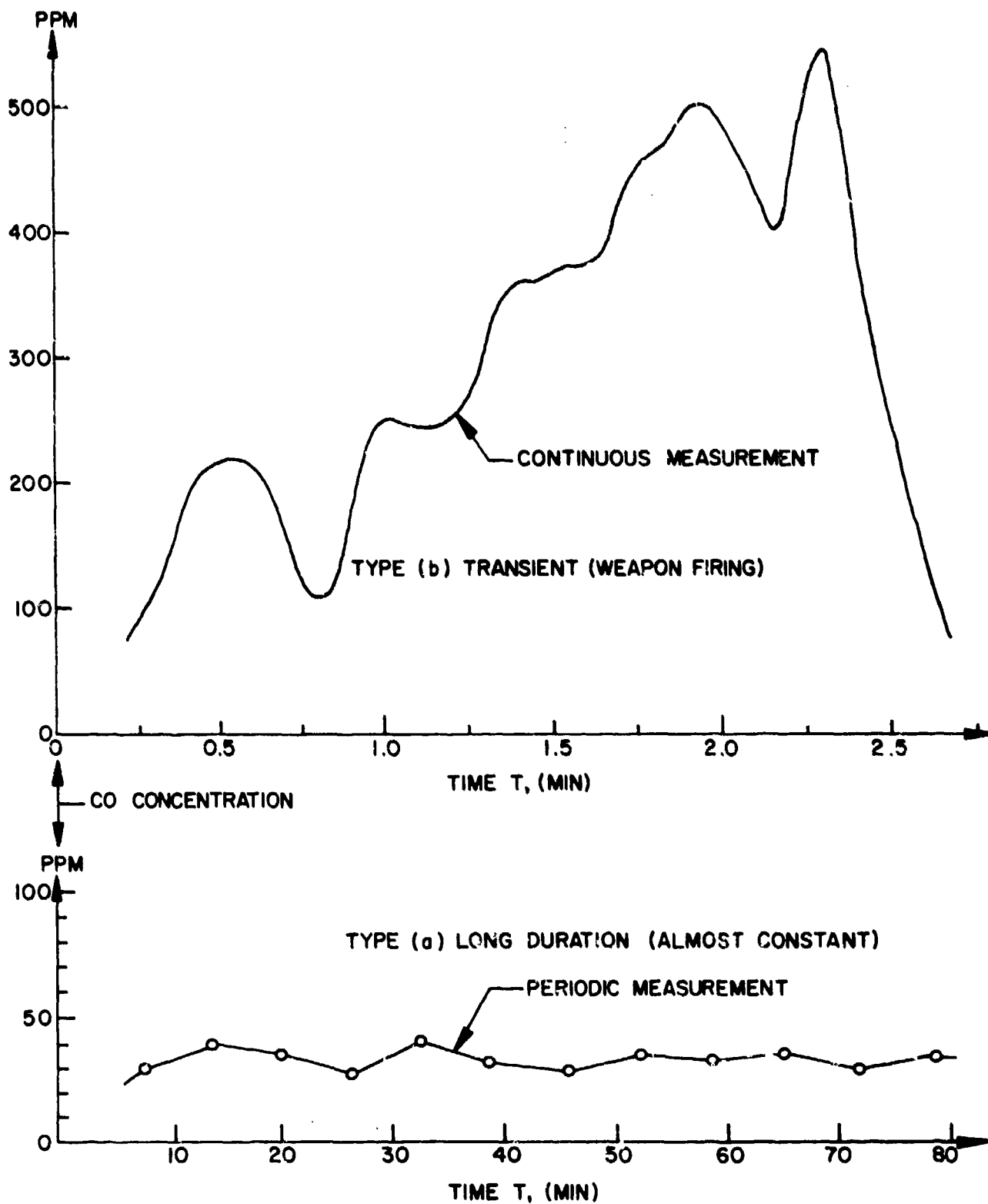


Figure 1. Hypothetical CO exposure types.

references 2, 16, 22, 23, 13, 15, 6, 5). The absorption rate, which is partly a function of the work activity level (14) of the individual, determines the content of carboxyhemoglobin (COHb) in the blood. We have concluded that the COHb blood content represents a more appropriate measure of CO exposure hazard and can conveniently be related directly to environmental concentration. By combining the level of CO exposure (equipment design dependent) with human activity (human performance dependent), one is able to measure effectively the degree of hazard to the vehicle crew. If the system designer accounts for both equipment performance requirements and the required human performance (both being design criteria) during design, the product will be superior in overall performance to the system designed solely on the basis of vehicle performance and subsequently evaluated against an industrial community standard for CO exposure.

Based upon the foregoing discussion, the objectives of this document are to:

1. Present a chronology of the present Army CO standard, demonstrating the need for a better method of evaluating CO exposure severity;
2. Propose a practical evaluation procedure for determining safe human exposure to a carbon monoxide environment resulting from the operation of military vehicles and their weapons;
3. Describe the test procedure and data specifications required by the above evaluation procedure;
4. Outline the general research requirements which will permit positive refinement and optimization of the evaluation method.

CHRONOLOGY OF THE PRESENT STANDARD

According to Brumbaugh and Jones (6), medical researchers in the late 19th century recognized the ill effects of human exposure to CO. These effects were described in terms of the apparent physical influence upon the exposed individual as a function of both exposure level and duration. They suggested the use of four simple equations to define five individual hazard zones of CO exposure including "death," "dangerous to life," "headache and nausea," "perceptible effects" and "no perceptible effects" in their 1921 publication (6). Figure 2 illustrates these hazard zones defined by Henderson et al. (14). They noted that "physical exertion and increased breathing" would decrease the exposure time for the onset of any of the deleterious physical symptoms noted above.

Table 1 (26, 8, 21) is an alternate means which has been used to describe the effects of CO exposure on humans. Average values from this table have been plotted on Figure 2 for comparative purposes. As can be seen, the curve lies completely in the "death" zone of Figure 2 and the tabular descriptions obviously do not correlate with Henderson's findings. It is possible that such differences are due to uncertainties of the experimental results upon which both documents are based. Also superimposed on Figure 2 are time weighted average values corresponding to both 50 and 35 ppm CO exposure levels so that the reader may contrast these levels with the physical symptom zones. The relevance of these points to the existing OSHA standard (19) will be discussed later in this report.

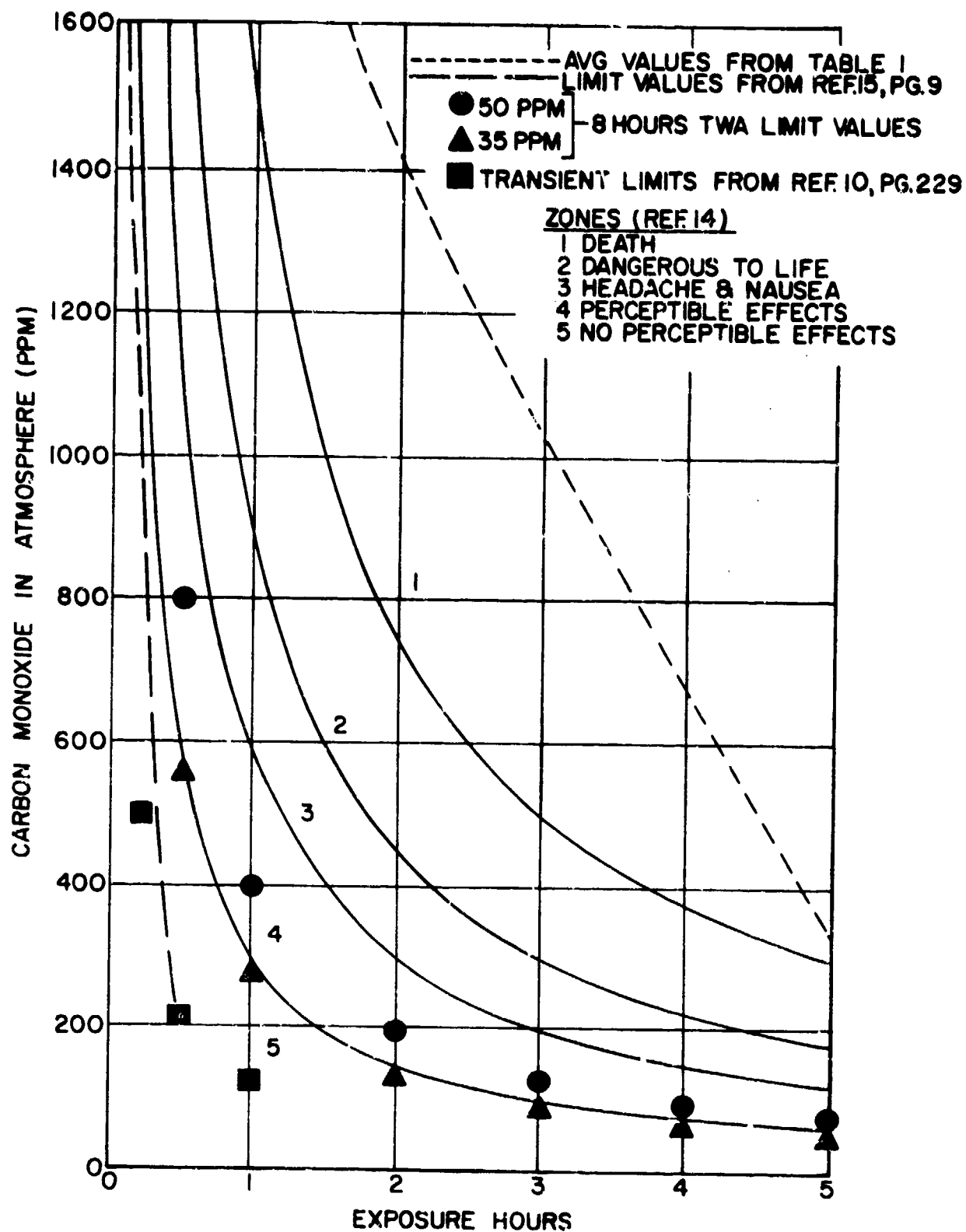


Figure 2. Limits and effects of carbon monoxide exposure on human beings.

TABLE 1^a

Physiologic Response to CO Exposures in Healthy Subjects

Carbon Monoxide Concentration in Air (ppm)	Carboxyhemoglobin Saturation In Blood (%)	Exposure Time	Symptoms
0-100	0-17		No appreciable effect, except occasional slight tightness across forehead and slight flushing.
200-300	23-30	5-6 hours	Throbbing temporal headache, generalized weakness, dizziness, dimness of vision, nausea, vomiting
400-600	36-44	4-5 hours	Same as above, with muscular incoordination and collapse.
700-1,000	47-53	3-4 hours	As above, with increased pulse and respiration
1,100-1,500	55-60	1½-3 hours	Coma with intermittent convulsions and Cheyne-Stokes respiration.
1,600-2,000	61-64	1-1½ hours	As above, depressed heart action and respiration, possible death.
5,000-10,000	73-76	2-15 minutes	Death

^aFrom references 26, 8, 21

Author's Reliance on Precedents

It is particularly noteworthy that the curves of Figure 2 (14) and the descriptive presentation in Table 1 appear in several documents (see references 3, 17 and 25 for Figure 2; references 26, 8, 21 for Table 1). These documents either do not indicate the original source for the curves or table, or the origin is incorrectly noted, as is the case in reference 3 which presents the curves. If the curves in references 3, 17 and 25 are compared carefully, one will note that they are similar but not identical. Furthermore, the curves in these references do not precisely match the accurately duplicated curves of Figure 2 which were drawn from equations given in the original source (14). In contrast, the wording in the descriptive table is identical in all three noted references. These facts can lead to the conclusion that the documents' authors merely followed the patterns set by their predecessors; the curves cannot be precisely drawn without the equations, and errors were obviously made in copying from a preceding document. In contrast, prose may simply be copied. The authors (presumably) trusted the authenticity of each preceding

source in spite of the potential of incurring error or using generalized descriptive tabulations, both representing qualitative information of questionable value.

Contradictory Standards and Criteria

For many years, the military services have neglected to adopt a consistent standard relating to CO exposure. In 1943, LTC Hatch *et al.* (13) reported that the maximum permissible CO concentration was 500 ppm for 30 minutes; it is unclear whether repeated exposures were permitted. In addition, we do not know whether longer exposure at lower levels was permissible. MIL-STD-800 (11) allows (once per mission) a maximum CO concentration of 6000 ppm for a maximum duration of 1-minute in the cockpit areas of Army and Air Force aircraft. The Navy (in the same document) also permits transient exposures in accordance with a tabulated schedule; by contrast, the maximum 1-minute exposure is 800 ppm, but it is unclear as to whether multiple exposures are permitted during a mission. A recent Navy publication (21), however, reverts to the Army/Air Force permissible CO transients stated in MIL-STD-800. MIL-HDBK-759 (10) which superseded HEL STD S-2-64A (24) suggests (for tank design) maximum transients of 500, 215 and 125 ppm CO for 10-, 30- and 60-minute exposures, respectively; the time weighted average (TWA) limit value for an 8-hour exposure is likewise 50 ppm. A TWA is calculated by summing the product of each CO concentration and its duration, and dividing that sum by the total exposure time to determine an average value. Again, it is not clear (MIL-HDBK-759) whether the permissible maximum transient exposures are acceptable more than once per mission. These transient values noted for tank design guidance are also plotted in Figure 2. Dr. G. L. Hody reports (15) that CO exposure limits of 8000, 1000 and 200 corresponding to 1-, 10- and 30-minute exposures respectively, were selected by the Advisory Center on Toxicology of the National Research Council in 1969 "to protect against visual impairment" of occupants of the UH-1B Armed Helicopter which is also plotted in Figure 2.

Unrealistic Standard

The basis for the present Army standard for safe human exposure to CO is the industrial standard (19) as amended by reference 9, which originated in the Office of the Surgeon General (OSG). This Army standard uses a TWA value of 35 ppm CO based on an 8-hour exposure and also allows transient exposure values in accordance with reference 11, as mentioned in the preceding paragraph. It is noteworthy, however, that reference 19 presently permits a threshold limit value (TLV) exposure of 50 ppm for the industrial community. Since both 35 ppm (8, 9) and 50 ppm (19) are used as standards, these values for an 8-hour work day have also been plotted on Figure 2. The excellent correlation of these values with the "no perceptible effects" and "perceptible effects" zones suggested by research conducted over 50 years ago (14) is apparent. It should be remembered, however, that the effects zones are based upon the individual being exposed while exerting little physical effort and breathing normally. Since these standards assume the exposed person is sedentary, they will be unrealistic for situations in which he is under physical or emotional stress.

Need for an Improved Evaluative Method

As stated in the Introduction section, it is unrealistic to evaluate CO exposure hazard for the type (b) exposure (Figure 1) using the current regulatory standards and design guides such as references 19 and 10 respectively. The designer must have good design criteria in order to design effective weapons systems. The human factors engineer needs the means to evaluate the system from the viewpoint of impact on humans; in effect, he must be in a position to recognize good design and he must be able to provide design guidance to ensure an appropriate man/machine combination. The present regulations and evaluation procedure (26) do not meet these goals and require revision.

Proposed Method of Evaluation

The evaluation of CO exposure severity can be divided into two parts which are somewhat independent of each other: (1) obtaining the necessary measurements relating to the conditions of exposure, and (2) interpreting the measurements in terms of their effects on the exposed individual(s). Army evaluation of CO exposure has heretofore neglected an important factor in each of these two parts. First, the measurements must include the respiratory parameters of the exposed human so that the exposure data are complete, and second, the predicted effects of exposure should include an evaluation of possible decrements in performance of the exposed human.

Equation to Calculate COHb

In order to determine what measurements are required, consider the conditions of military exposure to CO. Soldiers within enclosed vehicles may be subjected to wide extremes of CO concentrations, which are primarily due to the firing of weapons. Further, it is well documented (23, 18, 7, 20) that the intake of CO by the human body is directly related to the amount of CO respired during the exposure period. That is, if twice the volume of air is respired (CO concentration constant), about twice as much CO will be absorbed. The fluctuations in respiratory volume and in CO concentration which characterize the military exposure to CO must be incorporated in the evaluative procedure if it is to be accurate. Table 2B (Appendix B) provides examples of the effects of varying the respiratory volume. The most direct means of accounting for varying CO concentration and respiration is to calculate the resultant level of COHb the imposed conditions would produce. We believe the level of COHb is the measure most closely related to the effects of CO exposure (e.g., references 13, 7, 8). It is typically assumed (18, 8) that the mechanism of CO toxicity is the reduction in the oxygen-carrying capacity of the blood caused by the union of CO to hemoglobin (COHb). Although there is recent evidence (12) that CO toxicity may not be directly related to COHb under certain laboratory conditions, COHb nevertheless remains the most appropriate measure of exposure severity under typical exposure conditions (18, 8). Fortunately, there is general agreement (23, 18) on a function relating COHb to CO concentration and respiration (7). Although the experimental data which resulted in the empirical equation were not obtained for very brief, high level CO concentrations which precisely typify the military exposure, we have compared predictions of COHb made by use of the equation to experimental data reported in reference 23. The experimental conditions of reference 23 reasonably exemplified the military CO exposure in that the test subjects were exposed to high-level exposures for brief periods. The comparison showed the calculations (Appendix A equation) conservatively predicted the actual results. Appendix A presents this equation in a form we consider most useful in evaluating CO exposure. Assuming that the required data can be obtained, it is relatively simple to use the method demonstrated in Appendix B to generate predicted levels of COHb. These COHb levels can then be interpreted with relation to their potential effects on the exposed person.

Safe COHb Range

There are at least two important aspects to be included in assessing the effects of particular levels of COHb: (1) health hazards, and (2) decrements in performance. To some extent, these aspects correspond to peacetime and wartime conditions of CO exposure, in that even though war may overshadow long-term health considerations, performance is then crucial. Although the present standards described in the Unrealistic Standard section implicitly set a maximum allowable level of COHb on the basis of health considerations, there is still considerable uncertainty as to precisely where the limit should be set. Reference 18 provides an extensive review of research concerned with this question. Two examples from this review will be sufficient to typify the range of this evidence. The most reliable result relating low levels of COHb to deleterious effects on human health is a demonstration that 5% COHb reduces the physical work which can be performed by subjects with coronary heart disease prior to the onset of angina pectoris (see pg. III-18 in reference 18). In contrast, the strongest evidence for an absence of effect over a long-term exposure is provided by tunnel workers who have been exposed regularly to CO over their working careers. They experienced levels of 13% COHb without detectable influence on their health (see page 3 in reference 8). Although it can be argued that some process of selection may have eliminated those tunnel workers susceptible to the effects of CO, one can logically counter that the soldier, like the tunnel worker, is also part of a select grouping in that environmental conditions he encounters (basic training, physically demanding workload, regular physical examinations, etc.) would tend to eliminate those individuals having circulatory or respiratory deficiencies.

COHb Limits Based on Health Considerations

In summary, our search of the literature resulted in the following scale for the effects of particular levels of COHb: below 5% COHb, the effects on health are minimal and probably undetectable. Between levels of 5 and 10%, the effects which have been observed are minor and generally confined to individuals with respiratory/circulatory deficiencies. Between 10 and 15% COHb levels, there may be detectable short-term effects on healthy people, but the classification of these effects as a hazard to health is debatable. Thus, it is not currently possible to justify precisely any recommended maximum for COHb. However, where a potential hazard exists, the limits must be set conservatively. In view of the lack of effects on the tunnel workers, and of the lack of evidence that a population similar to the soldier population would be affected, we conclude that levels of COHb below 10% are not hazardous to health. The probability of encountering any minor risk is logically reduced as the frequency of exposure is reduced. In cases where the exposure reaches or exceeds 40 hours per week on a continued basis, a lower COHb level limit is desirable. Accordingly, we suggest that a level of COHb averaging no more than 5%, but not to exceed 10%, represents a safe long-term level.

COHb Limits Based on Performance Considerations

Performance, as well as health, must receive consideration in evaluating CO exposure; in battle a soldier's life may depend upon his performance. Unfortunately, the literature relating COHb (or CO concentration) to decrements in performance shows as much variability as that describing the medical effects of CO exposure. Some researchers have found performance decrements resulting from COHb levels as low as 5%, others have shown no decrement with 20% COHb levels (see references 4 and 18 for summary). It may be that the type of task, subjects and experimental design account for these divergent results. MIL-HDBK-759 states on page 229 that no significant effects on performance are noted at levels of COHb up to 10%. An additional problem lies in relating the experimental tasks on which performance decrements have been demonstrated to the abilities required of particular soldiers. To summarize the findings reviewed in reference 18, tasks involving visual detection and discrimination, vigilance and decision seem most sensitive to impairment caused by exposure to CO. However, if COHb does not exceed 10%, the magnitude of these effects is unlikely to be unobjectionable, based on the available literature. A reduction of COHb levels below our recommended limit of 10% is not justified based upon the uncertainty of short-term behavioral effects of CO exposure.

Proposed Evaluation Scale

Merging health and performance considerations results in the following scale for evaluating CO exposure severity: we conclude that long-term regular exposure should not exceed a 5% COHb average; occasional levels up to 10% COHb are not considered hazardous to the soldier population. COHb levels above 10% may compromise human performance. These recommendations can be contrasted to previous standards which set limits for CO in ppm. By stating limits in terms of COHb, our recommendations are moved a step closer to the primary concern of any such standard, namely, the effects of CO upon the exposed human. In addition, by expressing limits in these terms and calculating the resultant level of COHb by the equation of Appendix A, we have accounted for the actual CO absorbed by the exposed individual, which is significantly more effective and realistic than the current procedure. A natural fallout of establishing these limits is that equipment design (exhaust system or weapons) may also be evaluated; design deficiencies may become apparent and improvements can be identified. The equipment user may thus be rewarded with a better design.

VEHICLE TEST REQUIREMENTS

The primary test objective is to measure carbon monoxide concentrations within the crew/occupant compartment of military vehicles under typical operating conditions including weapons system firing, to determine whether the vehicle conforms to the CO toxic hazard limits for occupants specified in the preceding section. The proposed toxic limits are expressed in terms of the percentage of COHb present in the exposed individual's blood. The COHb content is calculated by using the equation presented in Appendix A and exemplified in Appendix B. The calculation requires knowledge of the measured CO concentration level, its duration and an estimate of physical work effort of the exposed individual.

For purposes of document consistency and clarity, the specified testing requirements which follow are oriented to an enclosed type vehicle such as a personnel carrier or tank where operational variations are numerous and both transient and steady-state exposure conditions are encountered.

Test Variables and Conditions

The sequential organization of test variables and conditions into a test program comprises the test matrix. The test-program design ultimately determines the degree of success achieved in meeting the test objectives and fulfilling the test requirements. With regard to CO measurement, the test design should involve a detailed and systematic variation of test conditions to provide critical exposure levels for each crew member. The exposure measurements should encompass vehicle tests oriented to specific mission profiles and conditions consistent with a battle scenario. That is, operational limits for all weapons and other vehicle equipment should be both specified and included in each planned test event. If, for example, a model combat situation for a tank involves the firing of the main gun at maximum rate of fire for 2 minutes with the vehicle stationary (engine idling), hatch closed, and ventilating blowers operational, the test program should include this set of conditions. Alternately, if the above model combat situation was changed to a moving vehicle (maximum engine power), it might be necessary to reduce the main gun fire rate to be compatible with a moving vehicle. Basically, the organization of the test matrix should reflect real situations; it should not be based solely upon the maximum operational capability of individual items of equipment if it is unrealistic to do so or if such an occurrence is extremely unlikely. If performed, such tests should be categorized as "emergency" in contrast to anticipated normal operations.

The following listing exemplifies some of the variables and conditions upon which the test matrix is based:

Test Matrix Variables and Conditions

<u>Factors Influencing CO Exposure</u>	<u>Test Condition(s)</u>	
Vehicle	Stationary	Moving
Main Engine	Off, idling	1/2 power, full power
Auxiliary Engine	Stopped	Running
Heaters	Off	On
Ventilators (powered/unpowered)	Off/Closed	On/Open
Hatches	Closed	Open
Main Gun Azimuth (degrees)	0, 90,	180
Main Gun Elevation (positioned)	Low, Medium,	High
All Weapons	Variable rate of fire in accordance with realistic battle scenario (individually and/or simultaneously)	

Notes: 1. Engines should be tuned both in accordance with specifications and settings representative of extensive use.

2. Weapon tests should include firing the guns both before and after cleaning.

3. Firing tests should include all types of ammunition which are planned to be used with the weapons.

4. Test matrix should encompass repeat tests at/near measured critical exposure levels to provide measurement confidence.

Test Instrumentation and Measurements

Time dependent measurements of CO levels at specific locations within the vehicle are required. It is desirable that the instruments used to measure CO concentration levels for transient conditions have a response lag no greater than 5-10 seconds. This requirement is based upon a study of CO exposure records from weapons firing tests (see reference 17 and Figure 1(b) for examples) and the respiration frequency of adults (1). The 5-10-second instrument response lag requirement is governed primarily by the likely respiratory frequency of the crew member [11-30 breaths per minute (1) depending on work level] and the necessity of obtaining an accurate average value of CO concentration in that time period. It therefore follows that the selected instrument (for CO measurement) need not have a time-response characteristic which is more rapid than the time for an exposed individual to take several breaths; furthermore, it should be able to provide an average reading over that time period. The instrument sensitivity should be approximately one percent of its design range. Infrared analyzers such as the LIRA instruments in current use at Aberdeen Proving Ground (26) are adequate for making transient measurements. These instruments, however, are somewhat limited in their use, in that they are not portable and must be positioned outside the test vehicle; consequently, they cannot be used for tests with the test vehicle in motion should this be a requirement. A portable instrument capable of accurate transient measurements is needed for tests in moving vehicles with simultaneous weapons fire.

In selecting an instrument for transient measurement, the range of the sensor assembly is an important consideration. The accuracy of the instrument is usually specified in terms of percent of full range. If, for example, one selects an instrument for test which is specified by the manufacturer to have an accuracy of $\pm 2\%$ of full range and one anticipates making measurements of only 10% of full range, then it follows that the measurement accuracy will be on the order of $\pm 20\%$ and one has made a poor selection. Usually, instrument manufacturers provide a series of instruments covering several ranges to circumvent the above difficulty and to optimize measurement accuracy. The sensor-tube inlet should be placed in the immediate vicinity of each subject's head within the vehicle to provide a realistic simulation of the CO exposure.

When approximate measurements of steady state (Figure 1 - Type (a)) CO exposures are necessary, safety monitors such as the Monitaire or MSA Colorimetric Tester can be used. Such instruments, however, lack precision ($\pm 20\%$ accuracy) because of a sensitivity to atmospheric changes and other factors; consequently, IR type portable instruments are generally required. It is therefore recommended that, when CO concentrations reflecting the measurement of background levels in an enclosed vehicle are required, the IR type instrument be used.

Additional Measurements

Another measurement/estimate is required to be used in the evaluation of data results. The requirement involves the determination of work-stress level for each crew member for each specific task he performs during any applicable mission in accordance with the five element listing in Appendix A. The difficulty of actually measuring minute respiratory volume is recognized; however, if the minute respiratory rate is known, the work-stress level can be estimated and the minute respiratory volume can be approximated. Therefore, either the minute respiratory rate for each crew member for each task must be measured, or the work-stress level must be estimated.

Additional required measurements during each test phase consist of obtaining meteorological data as follows: barometric pressure, ambient temperature, humidity, wind velocity and wind direction. Standard instruments may be used or the information furnished by a local meteorological station.

Vehicle Test Procedure

The following is intended as a brief, general outline for the measurement of vehicle CO concentrations; it is recognized, however, that specific tests may require some alteration in the procedure.

Most test conditions can be characterized to relate to either type (a) or type (b) exposures as graphically shown in Figure 1. Each exposure type requires a distinct test methodology, and these methods are described separately.

Preparatory Data

Measure ambient CO levels both outside the vehicle and at each crew position: record documentary information such as meteorological data noted in the Additional Measurements section above, vehicle identification, date, time, test area and any other required documentary information pertinent to the test and the test vehicle.

Type (a) Exposures

Set the specific test conditions (engine settings, heaters, ventilators, hatches, vehicle speed, and any other applicable test variables); crew will be at their stations and will be performing their normal function as prescribed by the test condition; initiate data collection when the CO instrument readings are reasonably stable.

About five or six distinct readings (time duration of reading governed by instrumentation used) are required over at least a 20-25-minute period to confirm the stability of the data. If the measured CO concentration varies by more than ± 20 percent, the test condition should be extended. This is necessary to maintain the accuracy of COHb values as predicted by the empirical equation presented in Appendix A. If applicable, the data pertaining to crew respiration is also obtained during these tests. This test procedure is applicable to the mission segment exposure data for periods 1, 2, 8, 9, 15 and 16 presented in Table 1B.

Type (b) Exposures

There is considerable variation associated with CO measurements made for test conditions involving weapon firing. It is necessary, therefore, that these conditions include sufficient replication to obtain accurate average values. Each succeeding test should not commence until the ambient CO level approximates the level existing prior to the previous test for the same condition. This can be accomplished by purging the vehicle with the ventilation system, if existing.

Gun elevation and azimuth, firing rate and type of ammunition should be varied within the test design as necessary for each type of weapon being tested. Again, as in the section Type (a) Exposures, crew respiration data should be obtained if applicable. This procedure would provide data for mission segments similar to periods 3 thru 7, 10 thru 14, and 17 thru 21 of Table 1B.

The rate of fire, in particular, should be varied within the test matrix to provide CO emission data for low and intermediate rates as well as the maximum of which the weapon is capable. This rate of fire range is needed to model CO absorption (by crew members) for various battle scenarios. As has been stated earlier (Test Variables and Conditions) the test matrix should represent real situations and not be based solely on the maximum operational capability of each weapon.

Information Needed to Evaluate Toxic Hazard

Detailed information is required in order to evaluate the test results and determine whether the vehicle system is operationally safe with respect to CO contamination in accordance with the proposed method and the limits specified. The required information is separated into the following sections for convenience:

- Vehicle Mission Profile
- Configuration Details
- Test Apparatus and Instrumentation
- Test Conditions, Variables and Log
- Test results including respiratory rate¹

These sections are individually addressed:

Vehicle Mission Profile². This is necessary to assess the adequacy of the test program both in terms of realistic situations and specific test variables. The mission profile should be divided into sequential mission segments and should contain estimates of the physical work effort level (see scale in Appendix A) associated with each crew member for each mission segment. The necessity

¹Test results should include respiratory rate if mission profile does not include estimates of work effort level.

²Ordinarily, this information will not be furnished by the tester. Several possible sources for the mission profile include the combat developer, materiel developer, TRADOC, and AMSAA.

for division into segments results from a variety of vehicle operations which can potentially cause changes in the CO inspired by any particular crew member. These estimates can be based upon the actual respiratory rates or expert opinion if measurement is not made.

Configuration Details. A line assembly sketch of the vehicle internal and external arrangement showing locations of major toxic gas emitting components and ventilating controls and hatches/vents is required. The sketch should also show crew location stations. A cutaway pictorial view of the vehicle can be substituted for the line drawing if available.

Test Apparatus and Instrumentation. A listing of all instrumentation and recording apparatus used for the tests is required. The list should include manufacturer and model number of each item; the design range(s), sensitivity and accuracy of each CO sensor; and the method of data recording (tape, strip chart, visual or observed record, etc.). A line sketch showing placement of the CO instruments entrance tubes/ports within the vehicle is also required.

Test Conditions, Variables and Log. A tabulation of the test program is required. The tabulation should contain: test conditions, duration of each test sequence, and identification of the mission segment to which it is related. Additionally, it should encompass the basic meteorological data with which it is associated for each test day. A further requirement is that the test program listing include the test log which is the information related to test-peculiar events which occurred during the investigations.

Test Results. The test data should be presented in a form convenient for substitution in the equation of Appendix A: CO exposure in ppm, the duration of the exposure in minutes and work effort of the exposed crewmember based on the 5 level scale in Appendix A. These data can then be used to predict the resulting COHb blood content for each crew member represented by the data. For each test condition, a graph (ppm CO versus time) of a typical measurement period should be made. These plots should be identified so that they can be related to a specific test period/mission segment. In addition to these time dependent graphs, the data are required in a reduced form in terms of an average ppm CO value for each test condition and sensor. The averaging is applicable for time periods up to 30 minutes provided the respiratory parameter, B, (crewmember work effort) remains constant over that time period. This averaging is feasible since the equation is reasonably linear for periods no longer than 30 minutes, total. The TWA value is represented mathematically by the following expression:

$$(CO)_{TWA} = \int_{t_0}^{t_1 = 30 \text{ min. max.}} (CO_e) t \, dt$$

where (CO_e) is the CO exposure (in ppm) at any instantaneous time t , during the exposure interval. The solution of this integral may be simplified by trapezoidal rule if desired, or any other means appropriate. If the trace data are obtained on magnetic tape, it is amenable to computer solution. In general, if the CO exposure does not vary by more than 20% and the work level is constant, the averaging period may be extended indefinitely, as shown by the hypothetical 3-hour segments in the example in Appendix B. However, if the CO exposure or work level are significantly variable, as would be the case when weapons are fired, the time increments for averaging should be appropriate to the specific period of weapon firing so as to not obscure the data. This exemplified with the shorter time periods for the mission segments in Appendix Table

1B. Organizing the data results by mission segment permits its use in a computer model which can evaluate the effects of CO exposure on vehicle crewmembers as a function of battle scenario. By rearranging the segments one can determine toxic hazard differences for varied military tactics.

RECOMMENDATIONS FOR FUTURE RESEARCH

Additional research is required to validate more completely the threshold limit COHb value and to obtain a clear definition of work performance degradation which might exist at various COHb levels. In addition, Goldbaum *et al*, (12) strongly suggest that COHb may not be the medium of CO toxicity; it is indicated that "the probable toxic action of CO is on cellular respiration" and not on interference "with the O₂ carrying capacity of the blood." This line of research could potentially restructure an understanding of the effects of CO. Human engineering research efforts related to control, curtailment and elimination of the hazards of exposure to toxic elements should also be pursued. Some suggested general research requirements reflecting the above issues are enumerated as follows:

1. Determine the mechanism underlying CO toxicity and thereby potentially provide greater accuracy in defining CO safety standards.
2. Determine the degree of difference, if any, of CO toxicity effects on humans who differ in age, weight, frame size, physical condition, work-stress level and mental/ emotional stress level.
3. Determine if the human body can be physically conditioned to CO exposure. This document has previously noted that the published results of researchers have been different and contradictory in some instances. Further research should resolve the issue of possible physical conditioning to CO exposure.
4. Investigate the effects of toxic gas mixtures and their interaction on humans. In this regard, the question of whether the effects of these mixtures are proportionately additive, as currently assumed in the regulations (19) must be resolved. In particular, the influence of CO₂ on CO toxicity effects should be assessed. The importance of this research involves the probability of encountering relatively high CO₂ background levels in enclosed vehicles due to the number of occupants in a relatively small volume. This, in combination with other toxic element emissions resulting from weapon firing, could conceivably produce safety hazards for vehicle occupants which are not apparent when applying regulations which are basically formulated for the industrial community.
5. Determine the effects, if any, of repeated exposure to high-level concentrations of CO for brief periods. Although application of the evaluation method proposed in this document involves the use of an equation which calculates COHb present in an individual's blood at any given time, it is necessary to verify experimentally these levels for subjects who are repeatedly exposed. The limit value of 10% COHb proposed herein was based on infrequent exposures; what is required is the determination of the effects of repeated exposure so as to extend the method of evaluation.

6. Additional allied research effort, categorized as human engineering oriented, is related to design improvement. Some potential areas of interest are as follows:

- a. Weapons design concepts to reduce threat of toxic gas contamination.
- b. Systems design concepts such as pressurized compartments.
- c. Protective devices for vehicle occupants.
- d. Efficient diffusion of contaminant emissions.
- e. Reduction of toxicity of weapon firing byproducts.
- f. Design trade studies to ascertain compatibility of CO minimization concepts with CBR survivability concepts.

The possibility of environmental influence (i.e., heat, humidity, smog/smoke contamination, CO background level, or other condition representative of a battle scene) upon the results should be considered, if appropriate, when planning any investigations for a. through f. above.

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APPENDIX A

EQUATION FOR DETERMINING PERCENT COHB IN BLOOD

The following equation, derived from reference 7, is recommended as a means of predicting COHb levels on the basis of measurements of CO concentrations and estimates of work effort. Several variables in the original equation have been replaced by constant values, following the example of reference 18. For ease of application, work effort has been simplified to five categories which are then related to D_L and V_A , the respiratory factors in this formula which influence inspired CO.

$$(a) \%COHb_t = \%COHb_0 [e^{-(t/2398B)}] + 218 [1 - e^{-(t/2398B)}] [.007B + (\text{ppmCO}/1316)]$$

$\%COHb_0$ = percentage of COHb in the blood at time 0

$\%COHb_t$ = percentage of COHb at time t (t in minutes)

$B = 1/D_L + (P_B - 47)/V_A$ where D_L = rate of diffusion of CO in the lungs

P_B = barometric pressure in mm Hg

V_A = minute respiratory volume in ml

Work Effort	D_L	V_A	B (with $P_B = 760$)
1 sedentary	30	6000	.1522
2	35	12000	.0880
3 light work	40	18000	.0646
4	50	24000	.0497
5 heavy work	60	30000	.0404

The form of this equation presented by Coburn et al. (7) is as follows:

$$(1) \frac{\frac{[COHb] P_{CO_2}}{[O_2Hb] M} - V_{CO} \left[\frac{1}{D_L} + \frac{P_B - P_{H_2O}}{V_A} \right] - P_{I_{CO}}}{\frac{[COHb_0] P_{CO_2}}{[O_2Hb] M} - V_{CO} \left[\frac{1}{D_L} + \frac{P_B - P_{H_2O}}{V_A} \right] - P_{I_{CO}}} = e \exp - \left[\frac{(P_{CO_2}) t}{MV_b O_2 Hb \left[\frac{1}{D_L} + \frac{P_B - P_{H_2O}}{V_A} \right]} \right]$$

The following substitutions were made after reference 18.

$$M = 218, O_2 Hb = 0.2, V_{CO} = .007, P_B = 760, P_{H_2O} = 47$$

$$P_{CO} = \frac{\text{ppmCO}}{1316}, P_{CO_2} = 100, V_b = 5500$$

$$\%COHb = COHb \times 500 \quad B = \left[\frac{1}{D_L} + \frac{713}{V_A} \right]$$

$$(2) \quad \frac{\frac{\%COHb \times 100}{0.2 \times 218 \times 500} - .007B - \frac{\text{ppmCO}}{1316}}{\frac{\%COHb_0 \times 100}{0.2 \times 218 \times 500} - .007B - \frac{\text{ppmCO}}{1316}} = e \exp \left[\frac{-100t}{218 \times 5500 \times 0.2B} \right]$$

$$(3) \quad \%COHb/218 = \frac{COHb_0 e \exp [-t/2398B]}{218} + \left[1 - e \exp [-t/2398B] \right] \times \left[.007B + \frac{\text{ppmCO}}{1316} \right]$$

$$(4) \quad \%COHb = \%COHb_0 e \exp [-t/2398B] + 218 \left[1 - e \exp [-t/2398B] \right] \left[.007B + \frac{\text{ppmCO}}{1316} \right]$$

Equation (4) is the form used here. From inspection of the equation, it can be seen that $COHb_t$ will stabilize for constant B and ppmCO when t is sufficiently large. In addition, the elimination of CO by the body is represented by multiplying $COHb_0$ by e to the minus t. If the barometric pressure is much different from sea level (760 mmHg), its effect can be included by substituting the actual value into P_B and recalculating the values for the B term. At higher altitudes (i.e. lower pressures), the intake of CO is more rapid than at sea level.

There are three quantities which must be known or estimated in order to apply this equation--CO concentration in parts per million, the duration of exposure to that concentration, and a measure of the physical labor (i.e., respiration) being performed during the exposure period. It is anticipated that physical effort will simply be estimated for most military applications. The formula itself is inductive; the resulting COHb level is not affected by the particular time periods into which exposure is divided as long as the exposure elements are not changed. For example, a 100 min. exposure to 70 ppm CO for someone doing light work is identical to two consecutive periods of 50 minutes each, or 10 consecutive periods of 10 minutes each; any one of these would provide the same final level of COHb in the blood.

APPENDIX B

EXAMPLE OF APPLICATION

The data presented in Table 1B represent hypothetical exposure conditions experienced by a tank main gun loader during a mission lasting about 10 hours. The third, tenth and seventeenth periods are initiated by a firing of the main gun. This 10-hour mission has been divided into 21 segments so that exposure conditions within each period are not varying more than $\pm 20\%$. Since periods three through six share the same physical stress level (work effort equal to 4), and since the total time for these periods is less than 30 minutes, they could be represented by a single period of 3 minutes with 758 ppm CO. The exposure conditions of periods 8 through 14 and of 15 through 21 are identical to those of periods 1 through 7.

TABLE 1B

Mission Summary

t(min)	Work Effort	ppm CO	Percent COHb Periods		
			1-7	8-14	15-21
180	3	20	2.66	4.15	4.52
10	5	20	2.73	4.08	4.41
1	4	1500	4.78	6.12	6.45
1	4	700	5.71	7.04	7.37
.5	4	100	5.76	7.08	7.40
.5	4	50	5.77	7.08	7.41
10	5	35	5.78	6.96	7.26

COHb₀ = 1%

In order to apply the model, an initial level of COHb must be chosen. A typical level for a non-smoking healthy adult would be 1% or slightly less. Starting at 1% COHb, the conditions of the first period (180 minutes, B = .0646, CO = 20 ppm) are substituted into the formula of Appendix A, yielding a COHb of 2.66% at the end of the first 3 hours. This level then becomes the initial COHb for the second iteration, which yields a final COHb level of 2.73%. This process is repeated for the remaining 20 periods. If it is desirable to show the accumulation of COHb during the longer periods more accurately, the periods may be subdivided to the required degree of detail.

As can be seen from this example, brief exposure to high concentrations of CO can play an important role in overall exposure severity. In addition, if a smoker were used as the main gun loader, the initial level of COHb would probably be between 3 to 7%. Assuming 5% initially, with no smoking during the mission, results in a COHb of 6.77% after the first seven periods. This merely emphasizes that cigarette smoking by crew members may have to be restricted if predicted COHb levels approach the maximum.

The durations of the exposure periods in this example are not meant to imply any correlation with required sampling intervals; adequate testing must adjust CO sampling rate to the particular exposure conditions. A realistic sampling rate will depend upon the relative stability of the CO contamination. If the changes in concentrations are rapid, as with weapon firing, test sampling must correspond accordingly.

While the above example may provide an understanding for applying this method to varying exposure conditions, it is also helpful to analyze several specific extreme conditions. Table 2B was prepared in order to demonstrate the importance of the human variable in this equation. By varying the rate at which the exposed individual is working, it is possible to alter greatly the severity of the exposure to CO. The effect of physical effort on CO excretion is also highlighted. Both of these effects, ignored by industrial standards which assume minimal variations in CO concentration and work level, could be crucial in evaluating military CO exposure.

The method outlined in Appendix A is easily applied by using a programmable calculator or electronic computer. It would also be possible to model the performance decrements resulting from CO exposure, if the necessary research data to establish the relationship between COHb and performance were available. For example, the increase in tank gunner lay error as a result of CO exposure during a simulated firefight could then be predicted.

TABLE 2B
Influence of Work Level on Percent COHb

Exposure Duration (Minutes)	Work Level	CO (ppm)	COHb %	
			Initial	Final
1	Sedentary	6000	1.00	3.72
1	Heavy Work	6000	1.00	11.20
30	Sedentary	200	1.00	3.55
30	Heavy Work	200	1.00	9.57
60	Sedentary	5	10.00	8.64
60	Heavy Work	5	10.00	5.79