U.S. Army Public Health Center

Inhalation Rates for Military Exposure Guidelines and Other Applications

Public Health Information Paper No. 39-09-1118

Approved for public release; distribution unlimited.

March 2019

This report has been updated in alignment with Executive Orders and to ensure consistency with DOD policies in public health reporting.

APHC

Environmental Health Science and Engineering Directorate

Prepared by:

Mr. Kevin Ulmes **Environmental Health Risk Assessment Division**
Risk Assessment Capabilities Branch

Acknowledgements

Technical review and contributions were provided by Mr. Steve Comaty, Dr. Gabriel Intano, Dr. Laurie Roszell, Mr. Matthew McAtee, Dr. Adolph Januszkiewicz, Mr. Geoffrey Braybrooke, Ms. Susan Holt, Dr. Gerald Falo, Mr. Lee Crouse and Ms. Sherri Hutchens.

Questions and comments can be forwarded to—

U.S. Army Public Health Center
Risk Assessment Capabilities Branch
Environmental Health Risk Assessment Division
8252 Blackhawk Road, Bldg E5158 (Attn: MCHB-PH-HRA)
Aberdeen Proving Ground, Maryland 21010-5403
DSN 584-2953 or Commercial 410-436-2953
usarmy.apg.medcom-aphc.list.racb@mail.mil

Contents

Appendices

Tables

Figures

Inhalation Rates for Military Exposure Guidelines and Other Applications
March 2019

1. SUMMARY

1.1 Purpose

This paper is intended to present a standard set of inhalation rates linked to exposure timeframes that can be used when developing military exposure guidelines (MEGs). Previous MEG development used a single inhalation rate without regard to exposure duration (e.g., U.S. Army Public Health Command (USAPHC) 2013). The new methodology presented here provides for the consideration of a variable inhalation rate when developing exposure guidelines where the actual exposure rate is unknown. It recommends higher inhalation rates for shorter durations be used by default, but provides instructions for adjusting inhalation rates for specific assessments where more information about activity level or inhalation rate is known.

1.2 Abstract

The risk from inhalation of toxic materials is a function of how much contaminated air is inhaled, which in turn is related to the level of physical activity at the time of exposure. The inhalation rate of deployed military personnel is expected to be higher, on average, than the general population because of a greater physical activity level. There are many sources for different inhalation rates for different activity levels; however, current exposure guidelines are not tabulated by activity level, but rather by exposure duration. Heavy intensity tasks resulting in high inhalation rates are not expected to be sustainable over long durations; therefore, exposure guidelines for longer durations should not be based on heavy intensity tasks. However, if exposure guidelines for short durations do not consider relevant inhalation rates, then health risks may be underestimated. A relationship between activity level and endurance is presented to provide an estimated cap on inhalation rates for various durations. Inhalation rate recommendations are provided for short-duration exposures based on averages of measured inhalation rates in military personnel performing operationally relevant military tasks. Inhalation rate recommendations are provided for longer-duration exposures based on a mix of inhalation rates for operationally relevant tasks and other lower intensity activities.

1.3 Recommendations

When developing MEGs to address inhalation exposures, the inhalation rates from Table 2 should be used. These recommended inhalation rates can also be used for other risk assessment purposes when appropriate. Additionally, when specific exposure scenarios differ substantially from those used to derive the recommended inhalation rates, then time- and activity-level adjustments should be made using the method provided in this paper.

2. REFERENCES AND TERMS

Appendix A provides the references cited and the Glossary provides a list of acronyms and terms.

2.1 Inhalation Rate Terminology

Different organizations use slightly different terms to refer to the volume of air that flows in and out of the lungs of a human per unit time. Many toxicological studies (especially short term) use the terminology “minute volume” to refer to the volume of air breathed over a minute. “Minute ventilation” is also a term used for the same type of quantity. This is typically given in units of liters of air per minute (L/min), but has a fixed time basis of 1 minute, and so is not usually used in longer-term exposure assessments where exposure durations of years are common. The U.S. Environmental Protection Agency (USEPA) uses the terminology "inhalation rate" as a more general term to cover any time period and expresses these values in units of cubic meters of air per day (m^3/day) (USEPA 1989, 2011). Other terminology that is similar in the medical field is "breathing rate" or "respiratory rate," which describe the frequency of breathing (e.g., breaths per minute). The term inhalation rate has been in common use in the exposure assessment and environmental risk assessment community for some time, and is a more generic term than minute volume (i.e., a minute volume is a specific form of an inhalation rate with the time units fixed as 1 minute). Inhalation rate is used throughout this document to describe the volume inhaled per unit time during the act of breathing.

2.2 Units for Inhalation Rate

Inhalation rate is measured as a volume per unit time. Unfortunately, multiple units are commonly used to measure volume and time when discussing inhalation rate. This can cause confusion when different but similar units are used within a document. To alleviate this confusion, this document uses two rules to ensure comparison of inhalation rates from different sources is understood by the reader and provides the conversation between the units in Table 1.

1. All sources of inhalation data are reported in the original units provided by the source as well as the units of m^3/day for comparison purposes.

2. The final Inhalation rates recommended by this document are reported in units of both m^3/day and L/min to facilitate their use in both short-term and long-term guideline derivation.

Table 1. Inhalation Rate Unit Conversion

To Convert:	To:	Multiply by:
L/min	m^3/day	1.44
	m^3/hr	0.06
m^3/day	L/min	0.694
	m^3/hr	0.0417
m^3/hr	m^3/day	24
	L/min	16.7

3. OVERVIEW

The risk from inhalation of toxic materials and other hazards is a function of how much contaminated air is inhaled, which in turn is related to the level of physical activity at the time of exposure. Exposure guidelines (and health risks) can vary greatly depending upon the inhalation rate of the population at the time of exposure. This document provides an analysis of different sources of inhalation rates, and methods for calculating and selecting an inhalation rate for different exposure durations for use in establishing exposure guidelines. The inhalation rates provided in this document are based on an analysis of different activity levels and patterns, and do not account for varying inhalation rates based on exposure to chemicals that cause respiratory depression.

On average, the Inhalation rate of deployed military personnel is expected to be higher than the general population because of a greater physical activity level. The U.S. Environmental Protection Agency (USEPA) reports an average daily adult "inhalation rate" (IR_a) of 20 m^3/day (USEPA 1989). The *Exposure Factors Handbook* (EPA 2011) provides somewhat lower inhalation rates of 11.3 m^3/day and

15.2 m^3/day for females and males, respectively, for long-term exposures. These values assume moderate to light activity levels; whereas, deployed Soldiers are assumed to have higher activity levels. Based on this assumption, custom inhalation rates for each MEG exposure duration timeframe were developed for derivation of MEGs. These custom rates are summarized in Table 2 and explained in detail in this paper.

Table 2. Proposed Inhalation Rates for MEG Development

MEG Timeframe*	Inhalation Rate		Activity Level	Analysis
	L/min	m^3/day		
2-min	55.4	79.8	Average of heavy intensity tasks	Section 4.4
10-min	55.4	79.8	Average of heavy intensity tasks	
1-hr	30.5	43.9	Average of moderate intensity tasks	
8-hr	30.5	43.9	Average of moderate intensity tasks	
24-hr	19.6	28.2	Average of light intensity tasks	
14-day	19.6	28.2	Based on daily activity pattern	Section 4.3
1-year	17.6	25.4	Based on daily activity pattern	

Note:
* The MEG timeframe is equivalent to the duration of continuous exposure. Additional timeframes may be considered for future MEG development.

4. METHODS

4.1 Summary

Inhalation rates vary depending on the activity level of individuals. The activity level is very dependent on the type of task being performed and the physical fitness of the individual. Inhalation rates for MEGs should be specific to the deployed military population (i.e., generally physically fit) and the tasks they are expected to perform. The MEGs are derived for exposure timeframes, and so the inhalation rates used to derive the MEGs should also be reasonable for the timeframe in question. The methods described below use the idea that human endurance places limits on the amount of time that a certain level of physical activity can be maintained, and thus the inhalation rate that can be maintained during that time period. The default inhalation rates chosen for the MEGs in Table 2 represent average inhalation rates for Soldiers working near their limit of endurance for the duration of the MEG. These inhalation rate estimates can be adjusted by the methods given below for specific scenarios where activity patterns are better known. However, the decision to recommend inhalation rates on the higher end of the spectrum as the default was made to avoid default MEGs from underestimating the risk when screening exposures to hazards.

4.2 USARIEM Study

A U.S. Army Research Institute of Environmental Medicine (USARIEM) study provides useful information on inhalation rates based on Soldier-specific activities (USARIEM 1995). The authors evaluated the metabolic rate of Soldiers by measuring their oxygen uptake. Subjects were attired in mission-oriented protective posture (MOPP) and asked to perform tasks of various intensity while their heart rate and oxygen uptake were monitored. Two different classes of MOPP were used: MOPP-0 consisting of the battle dress uniform and MOPP-4 consisting of the battle dress oversuit with gloves, boots, and an M-17 protective mask. Since deployed military personnel are most likely to be in a battle dress uniform, only data from this experimental group (i.e., MOPP-0) were used in the analysis reported here.

To evaluate energy expenditure, Soldiers were asked to perform tasks with three different levels of intensity: light (<325 watts), moderate (325-500 watts), and heavy (>500 watts). In addition, each intensity level was broken down into different tasks. For example, task L-1 involved maintaining an M-16 rifle, and task L-2 referred to standing in a foxhole and performing guard duty. A higher numerical designation does not necessarily correspond with a higher work rate (more watts). Table 3 summarizes the USARIEM results.

Table 3. USARIEM Data on Inhalation Rates for Various Military Tasks

Task		Inhalation Rate				Work Rate (male) (Watts)	Task Description
		L/min		m³/day			
		Men	Women	Men	Women		
Light	L-1	26.7	20	38.4	28.8	304	Maintain M16 Rifle
	L-2	13.7	11.6	19.7	16.7	135	Standing in foxhole/guard duty
	L-3	15.3	15	22	21.6	170	Lift and carry, 25kg, 15m, 1x/2min
	L-4	18.1	15.1	26.1	21.7	201	Lift 22.7kg, 1.32m, 1x/min
	L-5	18.3	19.7	26.4	28.4	242	Lift and carry, 25kg, 15m, 1x/min
	L-6	24.4		35.1		298	Lift and carry, 36kg, 6.1m, 1x/min
	L-7	16.1	13.4	23.2	19.3	187	Lift and lower, 25kg, 1.32m, 1x/4min
	L-8	20.4	20	29.4	28.8	246	Lift and lower, 25kg, 1.32m, 2x/min
	L-9	20.5	18.1	29.5	26.1	247	Lift and carry, 18kg, 6.1m, 1x/min
	L-10	20.9	20.8	30.1	30	256	Lift 22.7kg, 1.32m, 2x/min
	L-11	23	22.7	33.1	32.7	270	Lift and carry, 27.3kg, 4m, 1x/min
	L-12	19.3	16	27.8	23	208	Lift and carry, 6.8kg, 15m, 1x/2min
	L-13	22.7		32.7		284	Lift and carry, 45kg, 5m, 2x/min
Moderate	M-1	26.2	23.7	37.7	34.1	325	Load carriage, 1.1m/s, LBE only
	M-2	27	27.1	38.9	39	330	Load carriage, 1.1m/s, 20kg load
	M-3	28.8	27.8	41.5	40	339	Two-person litter carry, 68.2kg, 250m
	M-4	37.1		53.4		446	Lift and carry, 45kg, 5m, 4x/min
	M-5	31.3		45.1		370	Lift and carry, 45kg, 5m, 3x/min
	M-6	30.3	28.1	43.6	40.5	388	Load carriage, 1.4m/s, LBE only
	M-7	31	30.6	44.6	44.1	370	Load carriage, 1.1m/s, 30kg load
	M-8	32	33.6	46.1	48.4	391	Load carriage, 1.1m/s, 40kg load
	M-9	27.5	28.4	39.6	40.9	349	Lift and carry 25kg, 15m, 2x/min
	M-10	29	26.2	41.8	37.7	384	Lift and carry, 18.2kg, 9m, 1x/min
	M-11	29.6	29.3	42.6	42.2	394	Lift 22.7kg, 1.32m, 4x/min
	M-12	33.9	32.1	48.8	46.2	460	Lift and lower, 22.7kg, 1.32m, 6x/min
	M-13	36.6	28.2	52.7	40.6	460	Dig defensive position
Heavy	H-1	42.1	27	60.6	38.9	557	Employ hand grenades
	H-2	37.8	37.5	54.4	54	505	Load carriage, 1.48m/s, 20kg load
	H-3	61.3	52.1	88.3	75	830	Move under direct fire (rush/crawl)
	H-4	37.1	38.4	53.4	55.3	509	Load carriage, 1.0m/s, 20kg load, sand
	H-5	41.3	44.1	59.5	63.5	592	Load carriage, 0.9m/s, 24.5kg load, 10% grade
	H-6	42.6	48	61.3	69.1	550	Load carriage, 1.48m/s, 30kg load
	H-7	54.7	57.9	78.8	83.4	727	Load carriage, 1.48m/s, 40kg load
	H-8	57.2	62.2	82.4	89.6	796	Load carriage, 1.31m/s, 20kg load, sand
	H-9	104.8	71.3	150.9	102.7	1162	Lift and carry, two 13.6kg, 30m, 4x/min
	H-10	46.4	40.2	66.8	57.9	609	Lift and carry, 25kg, 15m, 4x/min
	H-11	54.2	51.5	78	74.2	633	Four-person litter carry, 68.2kg, 1000m
	H-12	47.3		68.1		626	Two-person litter carry, 68.2kg, 100m
	H-13	86.8		125		1038	Load carriage, 0.9m/s, 54lb, 20% grade
	H-14	66.6	62.5	95.9	90	945	Load carriage, 2.24m/s, LBE only
	H-15	56.2	61.2	80.9	88.1	723	Two-person litter carry, 68.2kg, 27.5m
	H-16	64.7	54.5	93.2	78.5	796	Obstacle course

Source: USARIEM 1995

4.3 14-Day and 1-Year Inhalation Rates

The USARIEM study and data presented in the *Exposure Factors Handbook* (USEPA 2011) regarding activity intensity and the associated inhalation rate show reasonable similarity. Data from the USARIEM study were used to obtain a Soldier-specific inhalation rate because the degree of ventilation can be easily related to a specific activity. Table 4 summarizes the activity categories with the lowest and highest work rate for each intensity level. This information was only available for males from the USARIEM data set (USARIEM 1995).

Table 4. Work Rate Limits for Activity Level Descriptors

Task	Description	Work Rate in Watts
Light Intensity		
L-2	Standing in foxhole/guard duty	135
L-1	Maintain M-16 rifle	304
Moderate Intensity		
M-1	Load carriage, march 1.11 m/s, combat equipment with no rucksack	325
M-13	Dig defensive position	460
Heavy Intensity		
H-2	Load carriage, march 1.48 m/s, 20 kg load	505
H-9	Lift and carry, two 13.6 kg, 30 m, 4x/min	1162

Source: USARIEM 1995

4.3.1 Daily Activity Patterns

To estimate a daily inhalation rate for use in developing long-term MEGs (i.e., 14 days and longer), it is necessary to determine the probable daily activities of a deployed person. Since the type of activity is mission-dependent, it is not possible to pinpoint the exact number of hours a deployed person would spend on a task. Infantry personnel, however, would be expected to spend more hours performing higher intensity tasks than other personnel. Table 5 presents the number of hours spent per day on some common activities.

When developing some of the earliest methods for deriving MEG values, the U.S. Army Center for Health Promotion and Preventive Medicine (USACHPPM) considered and subjectively validated this information through interviews (USACHPPM 2002). Although only a limited number of military personnel were interviewed, their activity profile was deemed more realistic for deployed populations than assumptions used by the USEPA to derive inhalation rates for the general population. It should be noted that those who dug foxholes considered it to be a heavy activity, but USARIEM (1995) and the USEPA (2011) regard it as a moderate activity. Results from the USARIEM report suggest that digging foxholes is a more strenuous activity than other moderate intensity tasks. Activities such as night patrol and waiting-in-ambush were categorized as light as opposed to moderate (USARIEM 1995).

Table 5. Hours Spent On Various Activities by Deployed Military Personnel

Activity	Hours Spent Per Day
Sleep	4-8
Work such as digging foxholes	8
Meals	3
Evening patrol/ambush	2-4
Other light duties	1

Source: USACHPPM 2002

To estimate an inhalation rate for daily military activities, deployed military personnel were assumed to spend: 6 hours per day for sleeping, 4 hours per day for sedentary activities (activities conducted while awake but that require little to no physical exertion; e.g., eating, reading), 6 hours per day for light duties (e.g., ambush), and 8 hours per day for moderate duties (e.g., digging foxholes). Even though military personnel may engage in higher intensity work or obtain less sleep, the assumption that a Soldier would be performing moderate activities 8 hours a day for 365 days would balance out these conditions. Some of the intense to very heavy activities, as described by the USEPA, include competitive cycling and long-distance running. It is unlikely that deployed military personnel would be engaged in tasks at such intensity levels for prolonged periods of time.

4.3.2 Adjustment of USARIEM Inhalation Rate for Military Sex Ratio

Data from the Defense Medical Epidemiology Database (DMED) (DMED 2018) indicates that in 2016 the sex breakdown of U.S. Forces was approximately 84.2% male and 15.8% female. The average military population inhalation rate must take this sex ratio into account in order to estimate an average inhalation rate for the entire military population. Therefore, the inhalation rates presented in USARIEM (1995) were weighted by the percentage of male and female military members for the representative tasks outlined above. These sex-weighted averages are presented in Table 6.

Table 6. Sex-Weighted Inhalation Rates

Activity	Inhalation Rate					
	Male		Female		Sex-weighted average	
	L/min	m^3/day	L/min	m^3/day	L/min	m^3/day
Light activities	20.0	28.8	17.5	25.2	19.6	28.2
Moderate Activities	30.8	44.4	28.6	41.2	30.5	43.9
Digging Foxholes	36.6	52.7	28.2	40.6	35.3	50.8
Heavy Activities	56.3	81.1	50.6	72.9	55.4	79.8

Since the USARIEM study does not include inhalation rates for periods of sleep and rest, data from the USEPA were used to fill this data gap. The *Exposure Factors Handbook* provides inhalation rate data for various age ranges (USEPA 2011). The inhalation rate data is presented as a set of inhalation rate distributions (mean and upper 95% level in table 6-2 of USEPA 2011). The recommended values of 0.3 cubic meter per hour (m^3/hour) and 0.5 m^3/hour for sleep and sedentary activities, respectively, were chosen as the highest mean inhalation rate within the age range of 17-65 years. For light activities, the arithmetic mean of all light intensity tasks from the USARIEM report was used as the representative value (19.6 L/min, 1.2 m^3/hr). The arithmetic mean of moderate activities was computed to be 30.5 L/min (1.8 m^3/hr). However, this value was not used in the calculation of the 14-day inhalation rate because, as indicated above, work such as digging foxholes requires the most energy output of this intensity level.

For the 14-day exposure period, it is reasonable to believe that deployed individuals might be engaged at higher intensity work for a 14-day duration. However, for the 1-year inhalation rate, the average inhalation rate of all moderate activities (30.5 L/min, 1.8 m^3/hour) was used as it was considered more representative of a wider variety of moderate intensity tasks that might be performed throughout the year. These inhalation rates and the associated activity patterns are summarized in Table 7.

Table 7. Inhalation Rates for Daily Military Activities

Activity	Inhalation Rate		Source	Daily Activity Hours	
	m^3/day	m^3/hr		14-day MEG (hours)	1-year MEG (hours)
Sleep	7.2	0.3	USEPA 2011	6	6
Sedentary activities	12	0.5	USEPA 2011	4	4
Light activities	28.8	1.2	USARIEM 1995	6	6
Moderate activities	43.2	1.8	USARIEM 1995	N/A	8
Digging foxholes	50.4	2.1	USARIEM 1995	8	N/A

Legend:
N/A = not applicable

The final (weighted) inhalation rate recommended for use to develop MEGs was derived as shown in Equations 1 and 2.

Weighted Inhalation Rate (14-day):

$$IR_{14d} = \underbrace{\left(0.3\frac{m^3}{hr}\cdot 6\frac{hr}{day}\right)}_{Sleep} + \underbrace{\left(0.5\frac{m^3}{hr}\cdot 4\frac{hr}{day}\right)}_{Sedentary} + \underbrace{\left(1.2\frac{m^3}{hr}\cdot 6\frac{hr}{day}\right)}_{Light} + \underbrace{\left(2.1\frac{m^3}{hr}\cdot 8\frac{hr}{day}\right)}_{Dig\ Foxhole} = 27.8\frac{m^3}{day} \quad \text{(Equation 1)}$$

Weighted Inhalation Rate (1-year):

$$IR_{1yr} = \underbrace{\left(0.3\frac{m^3}{hr}\cdot 6\frac{hr}{day}\right)}_{Sleep} + \underbrace{\left(0.5\frac{m^3}{hr}\cdot 4\frac{hr}{day}\right)}_{Sedentary} + \underbrace{\left(1.2\frac{m^3}{hr}\cdot 6\frac{hr}{day}\right)}_{Light} + \underbrace{\left(1.8\frac{m^3}{hr}\cdot 8\frac{hr}{day}\right)}_{Moderate} = 25.4\frac{m^3}{day} \quad \text{(Equation 2)}$$

Where:
IR_{14d} = Weighted Inhalation Rate for 14-day exposure to air
IR_{1yr} = Weighted Inhalation Rate for 1-year exposure to air

These calculations results in a daily inhalation rate of 27.8 m^3/day or 19.3 L/min for 14-day exposures. The value of 19.3 L/min is very close to the 24-hr continuous light duty inhalation rate calculated for the short-term MEGs (see Section 4.4). Due to the similarity between the two values calculated in different manners, it was decided to use 19.6 L/min for both 24-hr and 14-day MEGs for simplicity.

The 1-year exposure timeframe inhalation rate resulted in a weighted inhalation rate of 25.4 m^3/day or 17.6 L/min. These values should be used for developing 1-year air MEGs. This value is higher than the EPA *Exposure Factors Handbook* recommended value of 16.3 m^3/day for long-term exposures for males and females aged 16-21 (EPA 2011).

4.4 Inhalation Rates for Exposure Durations of 24 Hours or Less

Inhalation rates can vary by large amounts over the short term as demonstrated in the USARIEM study. Additionally, there is an upper limit to the time very high inhalation rates can be sustained, yielding a decreasing average inhalation rate as the exposure time increases. This general inverse relationship between inhalation rate and exposure time leads to multiple different inhalation rates that are recommended for MEG development.

USARIEM measured inhalation rates for tasks that were grouped into light, medium, and heavy exertion categories depending on the energy that was expended while performing the task. All of these measurements were for durations not exceeding 30 minutes. Using the idea that performing heavy work can only be sustained for a short timeframe, while lighter work can be sustained for a longer timeframe, the average inhalation rate for the three different exertion levels from the USARIEM study were assigned to the MEG timeframes and resulted in the inhalation rates shown below in Table 8.

Table 8. Inhalation Rates Selected for Short-Term Exposure Periods

MEG Timeframe	Work Intensity	Inhalation Rate	
		L/min	m^3/day
2-min	Heavy	55.4	79.8
10-min	Heavy	55.4	79.8
1-hr	Moderate	30.5	43.9
8-hr	Moderate	30.5	43.9
24-hr	Light	19.6	28.2

4.5 Adjustment of MEGs for Scenario-Specific Inhalation Rates

The MEGs assume a constant inhalation rate for the exposure duration. This results in a linear relationship between the MEG concentration and the inhalation rate chosen for the exposure duration. Published MEGs can be adjusted for different inhalation rates if a particular scenario is being evaluated where the MEGs default inhalation rate assumptions do not apply. Equation 3 may be used to adjust the default MEGs to a different inhalation rate.

Adjustment of MEGs for different Inhalation Rates:

$$MEG_{adj} = MEG \cdot \left(\frac{IR_D}{IR_S}\right) \qquad \text{(Equation 3)}$$

Where: (units)

MEG	=	Default published MEG value	mg/m^3
MEG_{adj}	=	MEG adjusted for scenario-specific inhalation rate	mg/m^3
IR_D	=	MEG inhalation rate (see Table 8)	m^3/day
IR_S	=	Scenario-specific inhalation rate	m^3/day

4.6 Limits on Inhalation Rate Adjustment

Adjustment of exposure guidelines to scenario-specific inhalation rates will help to increase confidence in the overall risk assessment for which the MEGs are being used. However, the scenario-specific

inhalation rates chosen should fall within the limits outlined below. These limits represent the highest and lowest inhalation rates expected to be encountered by military personnel during deployment activities. The USEPA *Exposure Factors Handbook* provides a range of inhalation rates for adults (males and females combined) of different ages for long-term exposures (USEPA 2011). The population mean rates range from 15.7 m^3/day to 16.3 m^3/day (95th percentile rates are also provided). These values are for U.S. civilians, and represent inhalation rate estimates for typical everyday activity; deployed Soldiers are assumed to have higher activity levels. Indeed, one of the studies USEPA cites in their analysis includes a separate derivation for daily (24-hr) inhalation rates for active and very active people between the ages of 18-50 years that range from 12.8 m^3/day to 21.5 m^3/day depending on sex and energy expenditure (USEPA 2011). These differences in inhalation rate tend to be more important for short exposure periods (2 min to 24 hr), because high levels of physical activity are expected to be common for military tasks; however, they are not expected to be sustained for long durations (i.e., 1 year). For durations less than 24 hours, the *Exposure Factors Handbook* also includes recommended population mean inhalation rate values in the general civilian population of between
26 L/min to 29 L/min for moderate activity levels and 49 L/min to 53 L/min for heavy activity levels (USEPA 2011). USEPA, however, does not specifically address the military population or inhalation rates associated with military-specific tasks. To address this, data from the 1995 USARIEM study was used to estimate inhalation rates specific for military personnel for short durations. This same study was used, along with estimates about typical daily tasks, for establishing a long-term inhalation rate that is used to adjust long-term values in Section 4.3.

Inhalation rate adjustment should only be used for guidelines based on health effects via the inhalation route of exposure. Guidelines based on effects via other routes of exposure (ocular, percutaneous, etc.) to vapors or aerosols should not be adjusted for inhalation rate due to these exposure routes not being affected by inhalation rate.

4.6.1 Methodology for Setting Upper Limits on Inhalation Rates

Inhalation rates for short durations can greatly exceed the typical resting inhalation rate, and will vary based on the work rate of the task being performed. There are endurance limits related to how long an individual can maintain a particular work rate (i.e., light duty work might be able to be sustained for hours, whereas extremely heavy duty work might only be able to be sustained for minutes). Studies by the National Aeronautics and Space Administration (NASA 1973) have determined the maximum work rate healthy adults can maintain for a particular duration. Additionally, USARIEM (1995) has determined the inhalation rate of Soldiers performing a range of military-specific tasks and the work rate associated with them.

The results from these studies are combined to determine the maximum sustained inhalation rate for short-duration exposures, and this inhalation rate can be used to adjust inhalation exposure guidelines or to derive new guidelines for exposure to military personnel. This methodology does provide an upper dose estimate for an inhalation exposure, and it was considered to be applicable for the purposes of MEG development for multiple reasons. It uses military-specific tasks that are representative of tasks expected to be performed on a battlefield during deployment, and measurements from service members performing those tasks. While not all deployment exposure scenarios would take place on a battlefield, conceptually many would, and would also involve service members performing strenuous tasks causing their inhalation rate to increase above a typical resting rate. Additionally, the data used to estimate the maximum physical exertion for a specified duration were generated for healthy adults. Thus, the data should be representative of the deployed military population.

4.6.2 Inhalation Rates vs Energy Costs

The USARIEM study looked at 42 military tasks gathered from the Soldier’s Manual of Common Tasks, and the Military Occupational Specialty (MOS) Physical Task List (USARIEM 1995). The tasks were categorized into Light, Moderate, and Heavy work rates based on the energy cost of each task. Measurements of oxygen uptake, inhalation rate, heart rate, and Soldier perception of physical exertion and respiratory distress were recorded while groups of Soldiers performed each of the selected tasks. A calculation of the energy costs (in watts) was made based on the oxygen uptake for each task and reported along with the total ventilation for that task.

This data can be used to estimate total ventilation based on the total energy an individual is expending to perform a particular task. Inhalation rate and energy cost data from USARIEM (1995) were plotted and a curve fit to the data in order to estimate energy cost based on inhalation rate (Figure 1). As can be seen from the chart, inhalation rate increases almost linearly for light and moderate duty costs and then begins to climb for high energy cost tasks. This is most likely due to high inhalation rates requiring shorter-duration breaths, and decreased oxygen extraction efficiency for shorter-breath durations. The almost perfect fit can be attributed to the work rate being calculated directly from oxygen uptake measurements, and oxygen uptake being closely linked to inhalation rate (via ambient oxygen concentration, and lung oxygen extraction efficiency).

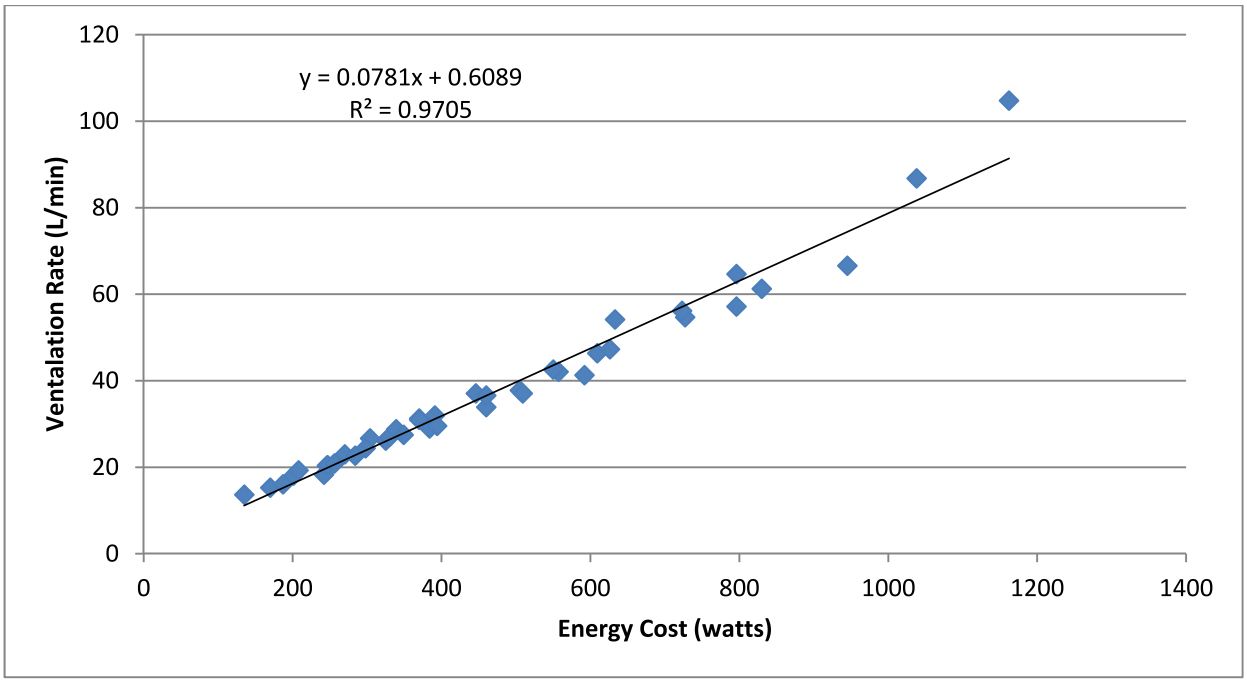

Figure 1. Inhalation Rates of Male Soldiers Performing Military Tasks in MOPP0 vs the Task Energy Cost

4.6.3 Human Thermal Efficiency

It is important to note that the energy cost in Figure 1 is the energy used or burned by the Service member to perform a task. However, humans are not perfectly efficient machines, and therefore much of the energy burned to perform a task goes into generating heat and not useable work. The maximum mechanical work measured by NASA is a measure of the useable work an individual can perform for a certain duration, and not the total amount of energy required by a human to perform that work. This is analogous to a car where much of the energy in the gasoline goes into heating the exhaust gas, or the engine block, and only a fraction actually is converted into motion. Therefore, an estimate of human thermal efficiency is required to link this data set to the information from NASA.

Multiple sources that estimate human thermal efficiency place the value between 5 and 40%. The actual efficiency will vary between individuals and the level of effort exerted to perform the work. Whitt and Wilson (1976) cite a thermal efficiency of 25% measured for bicyclists, whereas NASA cites values between 10 and 30% for most tasks in the second edition of the *Bioastronautics Data Book* (NASA 1973). In that reference, NASA uses a value of 20% when developing a chart used to calculate between work rate, heat production, and oxygen ventilation. NASA also states the following related to variations in thermal efficiency between individuals and between specific tasks:

> *"The efficiency with which external work is accomplished also varies widely. It is lowest in the work of respiration (less than 5 percent), is 10 to 20 percent for common tasks, and highest in bicycling and walking on the inclined treadmill (up to 35 percent and occasionally 40 percent in trained men)."*

For these calculations, a value of 20% is used as it falls within the normal range of efficiencies for typical activities cited by NASA. Using 20% rather than 25%, as cited in Whitt and Wilson (1976), is considered appropriate because it results in a slightly higher inhalation rate, and therefore tends to result in a lower guideline concentration. In addition, the data for bicyclists who are performing a constant aerobic task at a fairly steady pace may result in higher thermal efficiencies than the many different tasks performed by Soldiers that vary both in intensity and duration.

4.6.4 Human Endurance

The maximum work rate for a human is a function of how long that work is performed, and decreases with increased work duration. The NASA compiled data on different durations and the maximum work rate that could be sustained for durations up to 60 minutes. Two performance curves were provided for first-class athletes and healthy men. While Soldiers have to maintain a certain level of physical fitness, the performance curve for healthy men was chosen to better represent Soldier performance. This was due to the assumption that Soldiers had a large variety of duties, including physical training, and that increasing their physical performance was not their sole focus. It is important to note that this curve was derived for men and may not be representative of the maximum physical work rate for women. While this is an uncertainty in the data, it is minimized by the fact that at this point women make up a smaller percentage of the deployed military population, and it is assumed on average that men are able to maintain a higher work output (in watts) over time than women.

For durations beyond 1 hour, data from the *NASA Bioastronautics Data Book: Second Edition* (NASA, 1976) and the book *Bicycling Science* (Whitt, 1976) extends this performance curve out to approximately 1 day. This data along with other similar performance data from different individuals or selected populations (e.g., champion athletes) are plotted in Figure 2 below.

Selecting time points corresponding to short-term MEG durations from this plot yields the following table of maximum sustainable work rates for the given MEG durations (Table 9).

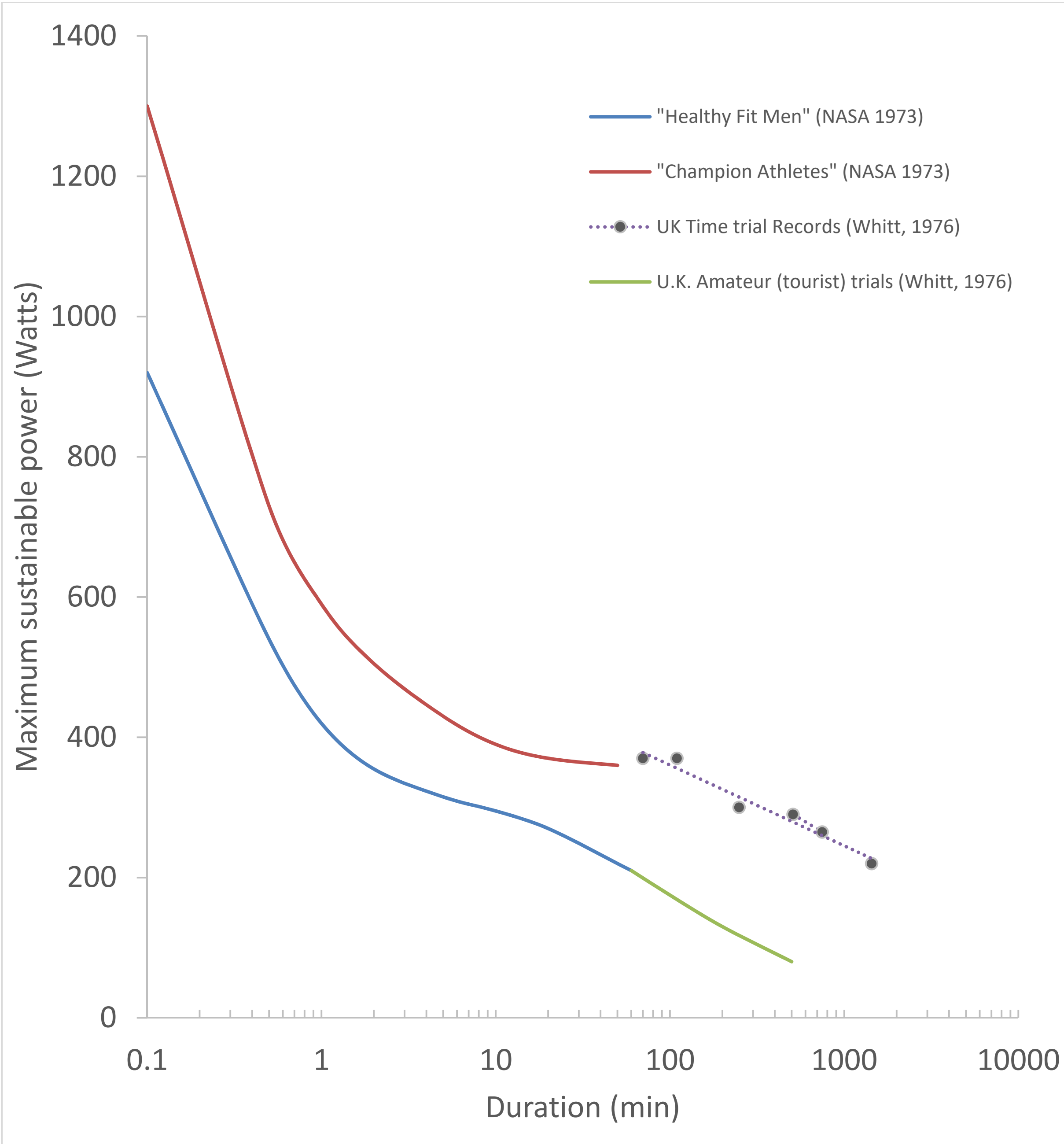

Figure 2. Human Work Endurance Curves (NASA, 1964 and Whitt, 1976)

(Figure best viewed in color)

Table 9. Maximum Sustainable Work Rates for Short-Term MEG Durations

Duration	Max Sustainable Power (watts)
2-min	340
10-min	280
1-hr	200
8-hr	85
24-hr	60

4.6.5 Maximum Inhalation Rate for a Given Duration

From the data described in Sections 4.6.2 through 4.6.4, the maximum inhalation rate sustainable for a selected MEG duration can be estimated for healthy men. The maximum work rate for a given duration from Section 4.6.4 can be converted into the maximum thermal energy production using the human thermal efficiency of 20% in Section 4.6.3. This thermal work rate can then be used in the model fit of the USARIEM data presented in Section 4.6.2 to estimate maximum inhalation rates for the selected duration. Table 10 contains the results of these calculations, which are the recommended upper limit for adjustment of MEGs for inhalation rate differences in exposure scenarios.

Table 10. Maximum Inhalation Rates for Short-Term Exposure Periods

MEG Timeframe	Max Sustainable Power (watts, work)	Energy Cost (watts, thermal)	Inhalation Rate	
			L/min	m^3/day
2-min	340	1700	121.0	174.3
10-min	280	1400	101.3	145.9
1-hr	200	1000	74.5	107.28
8-hr	85	425	34.1	49.1
24-hr	60	300	24.8	35.7

4.6.6 Minimum Inhalation Rate

The recommended lower limit on adjustment of MEGs for inhalation rate differences in exposure scenario is **4.2 L/min.** The minimum inhalation rate does not have the same dependency on the task being performed. Typical inhalation rates for different levels of activities are available in the *Exposure Factors Handbook* for males and females combined, grouped by age group (in Table 6-2 of USEPA 2011). The minimum inhalation rate for individuals aged 21 and older was 4.2 L/min and is described by the EPA as a “Sedentary/passive” activity level. While these numbers are tabulated for the general population and not the military-specific population, this number is expected to be a good estimate of the lower limit for the range of inhalation rates the MEGs may be adjusted for.

5. SUMMARY OF OTHER PUBLISHED SHORT-TERM INHALATION RATES

Other organizations have published inhalation rate numbers for different activity levels or tasks that are useful for comparison purposes to the numbers recommended in this document. These values are based on some measure of activity level and are not tied to a specific timeframe. Both civilian and military sources are included below.

5.1 NATO AMedP-7.5 Casualty Estimation Values

The North Atlantic Treaty Organization (NATO) uses increased inhalation rates for short-term exposures to perform casualty estimation. These inhalation rates are provided in Allied Medical Publication-7.5 (AMedP-7.5) (NATO, 2016) for four activity levels but are not tied to timeframes. Specifically, AMedP-7.5 recommends 7.5 L/min for at rest, 15 L/min for light activity, 30 L/min for moderate activity, and 75 L/min for heavy activity (Table 11). These numbers are comparable to the recommended inhalation rates suggested for use with the MEGs with the exception of the heavy work rate. The NATO recommendation of 75 L/min falls within the range of the USARIEM heavy tasks, but is above the average of all USARIEM tested heavy tasks that is being considered for use for the 2-min and 10-min MEGs. A rate of 75 L/min is also feasible for exposure durations less than 1 hour based on the human endurance and work rate information presented previously.

Table 11. Inhalation Rates for Different Activity Levels from NATO AMedP-7.5

Activity Level	Inhalation Rate (L/min)
Heavy	75
Moderate	30
Light	15
At Rest	7.5

5.2 USEPA Exposure Factor Handbook Values

The USEPA provides a wide range of inhalation rates for various activity levels in their *Exposure Factors Handbook* (EPA 2011). These inhalation rates are tabulated for different age ranges, genders, overweight status, activity levels at both population averages, and various distribution percentiles. Selected mean population inhalation rates for 21- to 31-year-old males and females for short durations across various activity categories are presented in Table 12.

Table 12. Short-Duration Inhalation Rates from USEPA Exposure Factors Handbook (2011)

Activity Level	Inhalation Rate (L/min)*
Sleep/Nap	4.3
Sedentary/Passive	4.2
Light	12
Moderate	26

Activity Level	Inhalation Rate (L/min)*
High	50

Note:
* Values are provided in units of m^3/min by USEPA and converted for this table.

5.3 USAMRDC Ventilatory Requirements of M1 Tank Crew Members

The U.S. Army Medical Research & Development Command (USAMRDC) issued a report looking at the ventilation requirements for the M1 tank crew during simulated battlefield scenarios (Parmer, et al., 1989). These ventilation rates are complementary to the USARIEM rates mentioned above as they are primarily for mounted Soldiers, whereas the USARIEM study was focused on tasks performed by dismounted Soldiers. The crew positions and the associated ventilation requirements from this report are summarized in Table 13. The report has additional details on what tasks each position is required to perform, and recommends updating the ventilation rate used in assessing exposure of the crew to combustion gas inside the M1 to 61 L/min from the standard at the time of 24 L/min.

Table 13. Ventilation Requirements for M1 Abrams Tank Crew During Live-Fire Scenarios (Parmer, et al., 1989)

Tank Crew Position	Mean Ventilation Requirement (L/min)	Maximum Ventilation Requirement (L/min)
Loader	47.0	60.9
Commander	25.7	44.5
Driver	12.1	13.7
Gunner	12.9	16.3

5.4 RIVM MPPD Activity Breathing Parameters

The Netherlands National Institute for Public Health and the Environment (*Rijksinstituut voor Volksgezondheid en Milieu*) (RIVM) published a report on the Multiple Path Particle Dosimetry (MPPD) model for calculation of particulate matter deposition in tissue-specific areas of the rat and human respiratory system (RIVM 2002). The report includes a list of minute volumes and exertion levels for various civilian tasks ranging from sleep to marathon running. While these tasks are not military specific, the large range of exertion levels and task descriptions are very useful as a comparison to the inhalation rates recommended by this document. These minute volumes along with their assigned exertion levels and activity descriptions are shown in Table 14.

Table 14. Levels of Physical Exertion for Adult, Corresponding Representative Activities and Breathing Parameters (RIVM 2002)

Minute Volume (L/min)	Exertion Level	Representative Activity
5	Rest	Sleep
7.5	Rest	Awake
13	Light	Walk (4 km/hr); washing clothes
19	Light	Walk (5 km/hr); bowling; scrubbing floors
25	Light	Dance; push a 15 kg wheelbarrow; building activities; piling firewood; walk (7 km/hr)
30	Modest	Quiet cycling; pushing a 75 kg wheelbarrow; using a sledgehammer
35	Modest	Climb 3 stairs; play tennis; digging soil
40	Modest	Cycle (23 km/hr); walk in snow; digging a trench; jogging
59 (55-63)	Heavy	Skiing cross-country; mountaineering; climbing stairs with weight
72	Very Heavy	Squash and handball; chopping wood
85	Very Heavy	Running (18 km/hr); cycle racing
100 (>100)	Extremely Heavy	Marathon; triathlon; cross-country ski race

6. CONCLUSIONS AND RECOMMENDATIONS SUMMARY

The risk from inhalation of toxic materials is a function of how much contaminated air is inhaled, which in turn is related to the level of physical activity at the time of exposure. The inhalation rate of deployed military personnel is expected to be higher, on average, than the general population because of a greater physical activity level. However, the previous MEG development methodology used a single inhalation rate without regard to exposure duration.

This paper documents the development of a standard set of inhalation rates linked to exposure timeframes that can be used when developing MEGs and for other applications when assessing inhalation health risks. The proposed methodology provides for the consideration of a variable inhalation rate when developing exposure guidelines and for when the actual exposure rate is unknown. It recommends higher inhalation rates for shorter durations be used by default, but provides instructions for adjusting inhalation rates for specific assessments where more information about activity level or inhalation rate are known.

Heavy intensity tasks resulting in high inhalation rates are not expected to be sustainable over long durations, and therefore exposure guidelines for longer durations should not be based on heavy intensity tasks. However, if exposure guidelines for short durations do not consider relevant inhalation rates, then health risks may be underestimated. A relationship between activity level and endurance is presented to provide an estimated cap on inhalation rates for various durations. Inhalation rate recommendations are provided for short-duration exposures based on averages of measured inhalation rates in military personnel performing operationally relevant military tasks. Inhalation rate recommendations are provided for longer-duration exposures based on a mix of inhalation rates for operationally relevant tasks and other lower intensity activities.

When developing MEGs to address inhalation exposures, the inhalation rates from Table 2 should be used. These recommended inhalation rates can also be used for other risk assessment purposes when appropriate. Additionally, when specific exposure scenarios differ substantially from those used to derive the recommended inhalation rates, then a method for making time- and activity-level adjustments is provided (see Section 4.5).

APPENDIX A

REFERENCES

DMED. 2018. Defense Medical Epidemiology Database query. Available at: http://www.afhsc.mil/dmed/. Accessed on 21 February 2018.

Finney, D.J. 1971. Probit Analysis. The University Press: Cambridge, Great Britain.

NASA. 1973. *Bioastronautics Data Book: Second Edition.* NASA SP-3006, Washington, D.C.

NATO. 2016. Allied Medial Publication 7.5. NATO Planning Guide for the Estimation of CBRN Casualties, Edition A Version 1, Final Draft, October 2016.

Parmer, D.L., Smart, D.A., Torrington, K.G., Mundie, T.G., Ripple, G.R., and R.H. Svihlik. 1989. Ventilatory requirements of M1 tank crew members during simulated battlefield conditions. Technical Report 8909, AD-A217 595, 15 May 1989.

RIVM. 2002. From concentration to dose: factors influencing airborne particulate matter deposition in humans and rats. Authors: R. de Winter-Sorkina and F.R. Cassee. *Rijksinstituut voor Volksgezondheid en Milieu* (RIVM) rapport 650010031.

USACHPPM. 2002. Reference Document 230, A Companion Document to Technical Guide 230 Chemical Exposure Guidelines for deployed Military Personnel. Aberdeen Proving Ground, Maryland.

USAPHC. 2013. Technical Guide 230, Environmental Health Risk Assessment and Chemical Exposure Guidelines for Deployed Personnel. Aberdeen Proving Ground, Maryland.

USARIEM. 1995. Metabolic Cost of Military Physical Tasks in MOPP 0 and MOPP 4. Natick, Massachusetts.

USEPA. 1989. Risk Assessment Guidance for Superfund (RAGS) Vol 1: Human Health Evaluation Manual, Part A, Interim Final, Office of Emergency and Remedial Response. EPA/540/1-89-002. U.S. Environmental Protection Agency. Washington D.C. Available at: http://www.epa.gov/oswer/riskassessment/superfund_hh_exposure.htm

USEPA. 2011. Exposure Factors Handbook. 2011 Edition. EPA/600/R-09/052F. U.S. Environmental Protection Agency. Washington D.C. September 2011.

Whitt, F.R. and D.G. Wilson. 1976. *Bicycling Science.* MIT Press: Cambridge, Great Britain.

GLOSSARY

APHC
Army Public Health Center

DMED
Defense Medical Epidemiology Database

IR
Inhalation rate

L/min
Liters per minute

m^3/day
cubic meters per day

MEG
Military Exposure Guideline

MOPP
Mission-Oriented Protective Posture

NASA
National Aeronautics and Space Administration

NATO
North Atlantic Treaty Organization

USAPHC
U.S. Army Public Health Command

USACHPPM
U.S. Army Center for Health Promotion and Preventive Medicine

USAMRDC
U.S. Army Medical Research & Development Command

USARIEM
U.S. Army Research Institute of Environmental Medicine

USEPA
U.S. Environmental Protection Agency