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An Investigation of Combat Vehicle Ventilation Requirements

by Otto H. Heuckeroth, Ph.D., and Sam E. Middlebrooks, Ph.D.

ARL-SR-231 **September 2011**

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Human Research and Engineering Directorate, ARL

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14. ABSTRACT

There is a concern that some armored vehicles currently in use by the U.S. Army do not meet the requirements for ground vehicles found in MIL-STD-1472F. This report attempts to highlight the requirements for ventilation in closed vehicle systems, such as military tactical vehicles. In this process, numerous quantitative metrics are provided to indicate how those requirements should be addressed by evaluating the current military and commercial standards, as applicable. We present a review of selected system evaluations performed in the past and evaluate appropriate test procedures and modeling methodologies to determine future requirements for ventilation in tactical military vehicles. In order to understand the ventilation requirement in MIL-STD-1472F and to determine if additional or substitute requirements would better identify ventilation safety in armored vehicles, the following questions will be addressed: (1) How was this requirement developed? (2) What is the impact of not meeting this requirement in terms of human performance and impact on mission performance? (3) Are there better measures for acceptable vehicle ventilation?

15. SUBJECT TERMS

vehicle, combat vehicle, vehicle ventilation, armored, MANPRINT

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Executive Summary

The aim of this report is to address the current requirements for combat vehicle ventilation.

The base finding of this study is that the vehicle ventilation requirements found in MIL-STD-1472F[1] are consistent with standards and provisions found in other regulations and standards in the open literature. The provisions of MIL-STD-1472F should be followed in the design of vehicle ventilation systems for all military vehicle designs, especially those where the crew compartment is sealed due to the requirements of armored configurations. Unfortunately, many previous vehicle designs that have already been fielded, as noted in this study, have not adhered to the requirements of MIL-STD-1472F.

The intent of this study is to provide a document that can be used by system development managers to familiarize themselves with heating, air-conditioning, and ventilation needs of combat vehicles before interacting with professional engineers. While a few "open" literature documents were reviewed, the major review centered around use of the MIL-STD-1472F and the American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE) 2009 handbook[2] and several of its associated standards (notably 62.1[3]). Review of those documents did not reveal any major discrepancies in methodology, but a few changes were noted among the parameters of potential contaminants. However, consistent with many military documents, the standard was primarily a presentation of key findings; at the other end of the spectrum, the ASHRAE handbook and its assorted publications were presented much like a compendium of refereed journal articles with a near-complete presentation of supported research.

This report provides a large sampling of hazards (contaminants) that may exist in combat vehicles—biological hazards (bioaerosols), chemical hazards (gaseous and particularities), and physical hazards (thermal comfort). Some discussion covers the general techniques for control of each hazard and the domains where the professional engineer must have some knowledge—epidemiology and biostatistics, industrial hygiene, microbiology, mycology, aerobiology, and toxicology. Major parameters of most of those contaminants are presented to permit documenting assessment needs.

[1]U.S. Department of Defense. *Human Engineering* (Military Standard – Department of Defense Design Criteria Standard); MIL-STD-1472F; U.S. Army Aviation and Missile Command: Redstone Arsenal, AL, 23 August 1999.

[2]American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE). *2009 Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL _DISPLAY_bookid =2554&VerticalID=0 (accessed February 2011).

[3]American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE). *Ventilation for Acceptable Indoor Air Quality*; ASHRAE Standard 62.1-2010 (supersedes ANSI/ASHRAE Standard 62.1-2007); Atlanta, GA, 2010.

The impacts on physical and cognitive abilities of occupants who are exposed to various contaminants are discussed through MANPRINT and human factors engineering assessments for several U.S. Army combat vehicles where ventilation requirements have been incompletely addressed.

Finally, major tools used to assess vehicle ventilation requirements include mathematical modeling and specific test procedures that have been used to establish indoor air quality.

Two points need to be emphasized when using this report:

- This report is designed to serve as a familiarization document to permit meaningful dialogue between professional engineers, who must address the identified ventilation needs, and the systems' development managers (as from the U.S. Army Evaluation Center). This is analogous to U.S. Army Research Laboratory, Survivability/Lethality Analysis Directorate, engineers who provide design specifications to provide relative impermeability ("hardening") of system software to attempted enemy electrical disruptions.

- Reduction of concentrations of all contaminants to the lowest level is not economically feasible. The ASHRAE standard 62.1[3] defines acceptable indoor air quality as "air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."

1. Introduction

This report attempts to quantify the requirements for ventilation in closed vehicle systems, such as military tactical vehicles, by evaluating the current military and commercial standards as applicable. We present a review of selected system evaluations performed in the past and evaluate appropriate test procedures and modeling methodologies to determine future requirements for ventilation in tactical military vehicles, such as the Mine-Resistant Ambush-Protected series of vehicles (Augustus, 2007; U.S. Army Test and Evaluation Command, 2001, 2002).

The assumption is that the vehicle operator and passenger compartments are completely enclosed, and that there is no difference in ventilation requirements for the following conditions:

- Tracked vs. wheeled vehicles
- Armored vs. unarmored vehicles
- Moving vs. stationary vehicles

The following sections describe the current standards for vehicle ventilation for adequacy and look at test procedures recommended to ensure that the standards are met.

2. Current Requirements for Combat Vehicle Ventilation

This section addresses the question of whether the current requirements for vehicle ventilation as defined in MIL-STD-1472F (U.S. Department of Defense, 1999) and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) handbook (ASHRAE, 2009a) are adequate to meet human physiological needs for effective performance. As seems characteristic of many documents created by the U.S. Army (at least), there appears to be a concerted effort to minimize the size of the document by either ignoring details upon which the "facts" presented are based and/or providing general references that lack specific detail. A review of Manpower and Personnel Integration (MANPRINT) reports (several examples are cited in appendix A) supports this perception. Generally, those documents present only the apparent deficiencies noted when the system was undergoing developmental/operational assessment. They contain an abbreviated method section noted in most scientific research reports and focus almost entirely on system description, results, and discussion.

Within the test and evaluation (T&E) community, findings are presented largely for the user target audience, for they are expected to use the system and make adaptations necessary to complete their assigned missions. Their reports generally are not written with attention to the nuances of test design and procedures (as in reports in the research community). For those in the T&E user community, procedures are generally viewed as transparent; nevertheless, those who develop T&E assessment instruments must often go through procedures similar to those in the research community for creation of data collection tools. This perceived deficit led to the creation of a MANPRINT tutorial document based on ~20 years of supporting MANPRINT data collection and assessment for several U.S. Army systems (Heuckeroth, 2008). The purpose of that document is to guide the T&E analyst who is called upon to provide those "transparent" procedural data collection documents.

2.1 The ASHRAE Handbook

In contrast to MIL-STD-1472F (U.S. Department of Defense, 1999), the ASHRAE handbook is written more like a research document. More attention is paid to research that cites studies that contain facts which address how the detailed heating, ventilation, and air conditioning needs were identified by heating and air-conditioning engineers. A review of several chapters of ASHRAE suggests that there were probably different authors, hence information is repeated. We will focus on chapters 9–11, which contain material most appropriate to vehicles.

This report is intended to be used as a guide to T&E managers who must assure that the ventilation needs of combat vehicles are met. It is not intended to make those managers experts in heating and air-conditioning methodology, but rather to give them an exposure that will facilitate their interaction with heating and air-conditioning engineers during system assessment (in assessment planning and/or validation) to eliminate health hazards, and system safety and human factors concerns. As the major goals are to provide T&E managers with an overview of ventilation needs and to facilitate communication with heat and air-conditioning engineers, chapters that focused on the mechanics of implementing ventilation equipment were not addressed. Thus, the material extracted from the ASHRAE handbook that addresses the topics of heating, ventilation, and air conditioning in combat vehicles were selected to satisfy at least three major requirements:

1. To keep the occupants comfortable while they are exercising their mission tasks—to facilitate elimination of irrelevant factors that can interfere with their cognitive processing.

2. To prevent injury to the occupants (health hazards control) and to prevent damage to the system within which they must operate (system safety control) from physical characteristics (temperature) and contaminants within that environment.

3. To more closely optimize the human factors task performance.

According to ASHRAE, there are three broad classes of hazards that are amenable to control (including ventilation):

- Chemical

- Biological
- Physical

2.1.1 Chemical Hazards

ASHRAE (2009a) identifies two categories of chemical hazards: gaseous (vapors/gases) and particulate (dusts, fumes, mists, aerosols, fibers).

2.1.1.1 Chemical Hazards: Gaseous. ASHRAE (2009a) lists four categories of gaseous hazards with measurements in parts per million (ppm) by volume and milligrams per cubic meter (mg/m^3):

- *True gases* are identified as having boiling points less than room temperature.
- *Vapors of liquids* have boiling points above normal indoor temperatures.
- *Volatile organic compounds* (VOCs) include 4–16 carbon alkanes, chlorinated hydrocarbons, alcohols, aldehydes, ketones, esters, hydrocarbons, esterterpenes, ethers, aromatic hydrocarbons (such as benzene and toluene), and heterocyclic hydrocarbons (see table 1). For future systems, chlorofluorocarbons and hydrochlorofluorocarbons will not be used as refrigerants because of environmental protection concerns (Calm and Domanski, 2004). ASHRAE Standard 34 classifies refrigerants by safety level, with standard 15 specifying that maintenance be by certified technicians for parts during use, transport, and storage. It is further specified that repairs of heating, ventilation, and air conditioning (HVAC) leaks should use adequate dilution ventilation.

Table 1. Volatile organic compounds (VOCs) commonly found in buildings.

Benzene	Styrene
m-, p-xylene	p-dichlorobenzene
1,2,4-trimethylbenzene	n-undecane
n-octane	n-nonane
n-decane	Ethyl acetate
n-dodecane	Dichloromethane
Butyl acetate	1,1-trichloroethane
Chloroform	Tetrachloroethylene
Trichloroethylene	Carbon disulfide
Trichlorofluoromethane	Acetone
Dimethyl disulfide	2-butanone
Methyl isobutyl ketone	Methyl tertiary butyl ether
Limonene	Naphthalene
α-,β-pinene	4-phenyl cyclohexene
Propane	Butane
2-butoxyethanol	Ethanol
Isopropanol	Phenol
Formaldehyde	Siloxanes
Toluene	

Source: ASHRAE. Chapter 11, Air Contaminants. In *Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009d; http://knovel.com/web/portal/browse/display?_EXT _KNOVEL _DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

- *Inorganic gaseous air contaminants* include ammonia, nitrogen oxides, ozone, sulfur dioxide, carbon monoxide, and carbon dioxide (by convention, even though the latter two have carbon atoms, they are included as inorganic gaseous air contaminants). See table 2 for a listing of the limits of these kinds of contaminants.

Table 2. Comparison of indoor environment standards and guidelines.

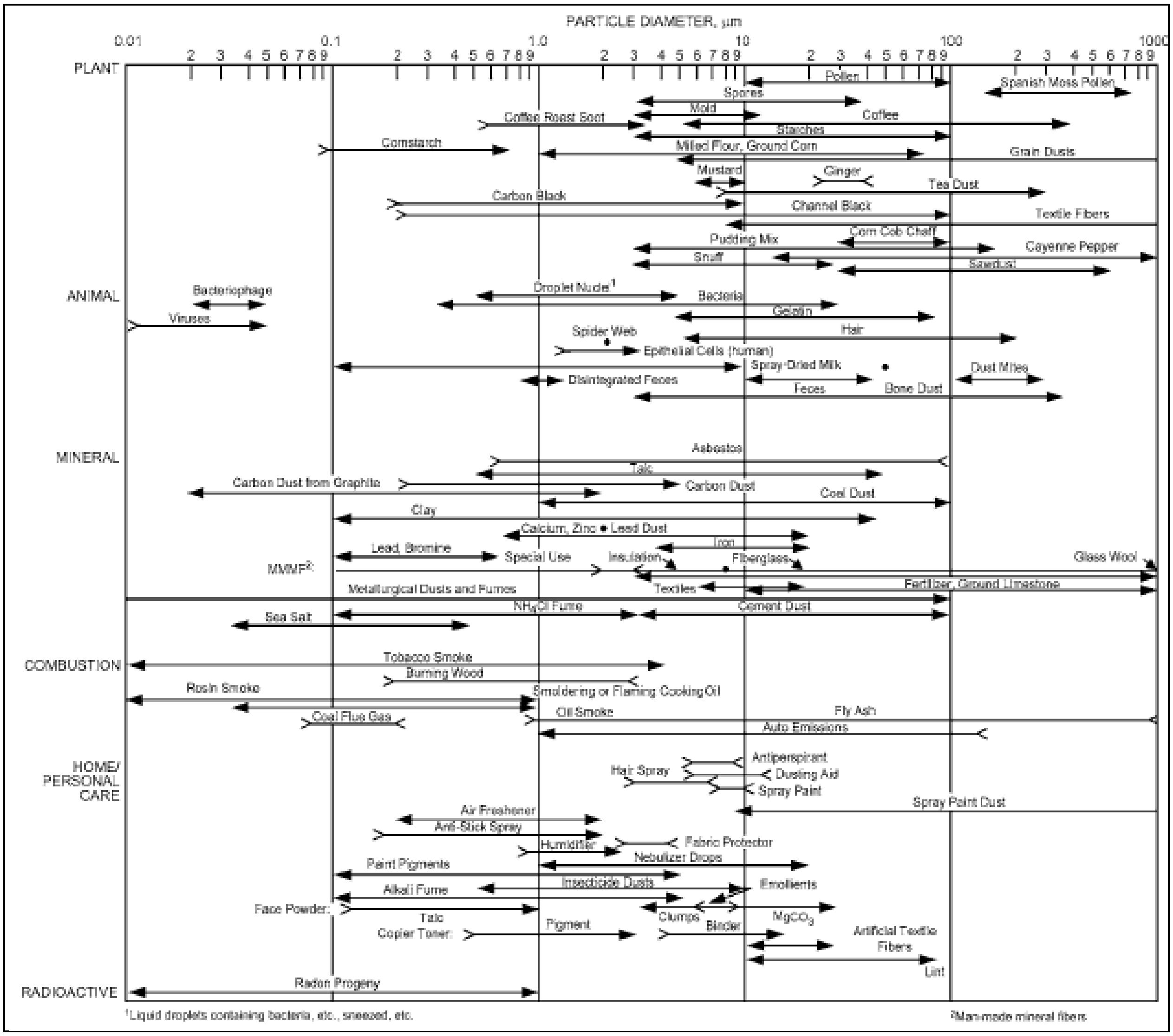
	Canadian[c]	WHO/Europe	NAAQS/EPA[f]	NIOSH REL (TWA)[h]	OSHA (TWA)[h]	ACGIH (TWA)[h]	MAK[g] (TWA)[h]
Acrolein	0.02 ppm[a]			0.1 ppm 0.3 ppm (15 min)	0.1 ppm	C 0.1 ppm, A4	
Acetaldehyde	5.0 ppm			Ca: ALARA[b]	200 ppm	C 25 ppm	50 ppm 100 ppm (5 min)
Formaldehyde	0.1 ppm (1 h) 0.04 ppm (8 h)	0.081 ppm (30 min)		0.016 ppm 0.1 ppm (15 min) Ca	0.75 ppm 2 ppm (15 min) Ca	C 0.3 ppm, A2	0.3 ppm 1.0 ppm (5 min)
Carbon dioxide	3500 ppm			5000 ppm 30,000 ppm (15 min)	5000 ppm	5000 ppm 30,000 ppm (15 min)	5000 ppm 10,000 ppm (60 min)
Carbon monoxide	11 ppm (8 h) 25 ppm (1 h)	8.6 ppm (8 h) 25 ppm (1 h) 51 ppm (30 min) 86 ppm (15 min)	9 ppm (8 h) 35 ppm (1 h)	35 ppm C 200 ppm	50 ppm	25 ppm	30 ppm 60 ppm (30 min)
Nitrogen dioxide	0.05 ppm 0.25 ppm (1 h)	0.02 ppm (1 yr) 0.1 ppm (1 h)	0.053 ppm (1 yr)	1 ppm (15 min)	C 5 ppm	3 ppm 5 ppm (15 min), A4	5 ppm 10 ppm (5 min)
Ozone	0.12 ppm (1 h); Insufficient data for long-term level	0.06 ppm (8 h)	0.12 ppm (1 h) 0.085 ppm (8 h)	C 0.1 ppm	0.1 ppm	0.05 ppm, A4 (for heavy work) 0.2 ppm (2 h) (light, moderate, or heavy work)	
Particles <2.5 MMAD[d]	40 μg/m³ (8 h) 100 μg/m³ (1 h)		15 μg/m³ (1 yr) 35 μg/m³ (24 h)		5 mg/m³ (respirable fraction)	3 mg/m³ (8 h) (no asbestos, <1% crystalline silica, with median cut point of 4.0 μm)	1.5 mg/m³ (for less than 4 μm)
Sulfur dioxide	0.019 ppm 0.38 ppm (5 min)	0.047 ppm (24 h) 0.019 ppm (1 yr)	0.03 ppm (1 yr) 0.14 ppm (24 h)	2 ppm (8 h) 5 ppm (15 min)	5 ppm	2 ppm 5 ppm (15 min)	0.5 ppm 1.0 ppm (5 min)
Radon	800 Bq/m³[e]		4 pCi/l				

( ) Numbers in parentheses represent averaging periods
C = ceiling limit
Ca = carcinogen
A4 = not classifiable as human carcinogen per ACGIH
[a]Parts per million (10^6)
[b]As low as reasonably achievable
[c]Health Canada *Exposure Guidelines for Residential Indoor Air Quality*
[d]Mass median aerodynamic diameter
[e]Mean in normal living areas
[f]U.S. EPA National Ambient Air Quality Standards
[g]German Maximale Arbeitsplatz Konzentrationen
[h]Value for 8-h TWA, unless otherwise noted
[i]WHO Air Quality Guidelines for Europe

Source: ASHRAE. Chapter 10, Indoor Environmental Health. In *Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009c; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

2.1.1.2 Chemical Hazards: Particulates. ASHRAE lists four types of particles that can potentially cause harm to vehicle occupants. Particles are usually measured so that 1 mg/m^3 = 1000 $\mu m/m^3$. Safety/health professionals are primarily concerned with particles smaller than 2 μm; particles larger than 8–10 μm in aerodynamic diameter are primarily separated and retained by the upper respiratory tract and swallowed or coughed out.

Figure 1 contains many of the most important larger particulates that need to be removed from the internal invironment—specifically:



Source: ASHRAE. Chapter 11, Air Contaminants. In *Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009d; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

Figure 1. Sizes of indoor particulates.

- Nonbiological (synthetic vitreous fibers, asbestos, environmental tobacco smoke, combustion nuclei, nuisance dust).
- Dust (0.1–100 µm)—any industrial process that produces dust (about 10 µm) that remains in the air long enough to be inhaled or ingested should be regarded as potentially hazardous, e.g., asbestosis and silica dust.
- Smoke (0.25 µm).
- Fumes (<0.1 µm).

2.1.2 Biological Hazards (Bioaerosols)

According to ASHRAE (2009a), these hazards refer to any airborne biological particulate matter including bacteria, viruses, fungi, and other living or nonliving organisms that can cause acute or chronic illnesses to occupants by inhalation, skin contact, and ingestion. The degree of risk depends on hazard potency, magnitude, and duration of exposure of a susceptible person.

2.1.3 Physical Hazards (Thermal Comfort)

Hardy et al. (1952) reported that skin temperature >113 °F or <64.5 °F causes pain. With sedentary activities, ambient temperatures between 91.5 and 93 °F are associated with discomfort that decreases with increasing activity (Fanger, 1967). An internal temperature <82 °F can lead to serious cardiac arrhythmia and death, and a temperature >115 °F can cause irreversible brain damage. Hensel (1981) noted that the hypothalamus (in the brain) is the central control organ for body temperature. In extreme heat, vasodilation of skin blood vessels results in transfer of internal heat to the skin surface for transfer to the environment. When the body temperature falls too low, the skin surface blood vessels vasoconstrict to narrow and reduce heat transfer from the internal body.

"[In exploring the] role of thermoregulatory effort in comfort, Chatonnet et al. (1965) compared the sensation of placing a subject's hand in relatively hot or cold water (86–100 °F) for 30 s with the subject at different thermal states. When the person was overheated (hyperthermic), the cold water was pleasant and the hot water was very unpleasant, but when the subject was cold (hypothermic), the hand felt pleasant in hot water and unpleasant in cold water" (ASHRAE, 2009b, p 9.2).

"Seven psychometric parameters used to describe the thermal environment are

(1) air temperature t_a,

(2) wet-bulb temperature t_{wb},

(3) dew-point temperature t_{dp},

(4) water vapor pressure p_a,

(5) total atmospheric pressure p_t,

(6) relative humidity (r_h), and

(7) humidity ratio W_a" (ASHRAE, 2009b, p 9.10).

"Two other important parameters include air velocity, V, and mean radiant temperature, T_r" (ASHRAE, 2009b, p 9.10). The radiant temperature is the temperature of individual surfaces in the environment.

"Studies by Rohles (1973) and Rohles and Nevins (1971) on 1600 college-age students revealed correlations between comfort level, temperature, humidity, sex, and length of exposure. . . . The thermal sensation scale developed for these studies is called the ASHRAE thermal sensation scale: +3 hot; +2 warm; +1 slightly warm; 0 neutral; –1 slightly cool; –2 cool; –3 cold" (ASHRAE, 2009b, p 9.11).

ASHRAE (2009b) states: "Equations in Table 9 [table 3 in this report] indicate that women were more sensitive to temperature and less sensitive to humidity than the men, but in general about a 5.4 °F change in temperature or a 0.44 psi change in water vapor pressure is necessary to change a thermal sensation vote by one unit or temperature category*. . . . Because people wear different levels of clothing depending on the situation and seasonal weather, ASHRAE Standard 55-2004 (2004) defines comfort zones for 0.5 and 1.0 clo (0.44 and 0.88 $ft^2 \cdot h \cdot °F/Btu$) clothing levels. . . . The amount of airspeed increase is affected by the mean radiant temperature ($\dot{t}_r$) in °F. Figure 6 [figure 2 in this report] indicates the air speed needed to [attenuate] temperatures above the warm temperature boundaries shown in Figure 5 [figure 3 in this report]. The curves of figure 6 are for different levels of ($\dot{t}_r - t_a$). That is, when the mean radiant temperature is low and the air temperature is high, elevated air speed is less effective at increasing heat loss and a higher air speed is needed for a given temperature increase. Conversely, elevated air speed is more effective when the mean radiant temperature is high and air temperature is low; then, less of an air speed increase is needed. Figure 6 applies to lightly clothed individuals) clothing insulation between 0.5 and 0.7 "clo" who are engaged in near-sedentary physical activity. The elevated air speed may be used to offset an increase in temperature by up to 5.4 °F above the warm-temperature boundary of Figure 5 [figure 3]."

These "studies revealed that the thermal environments preferred by older people do not differ from those preferred by younger people. The lower metabolism of older people is compensated for by a lower evaporative loss" (ASHRAE, 2009b).

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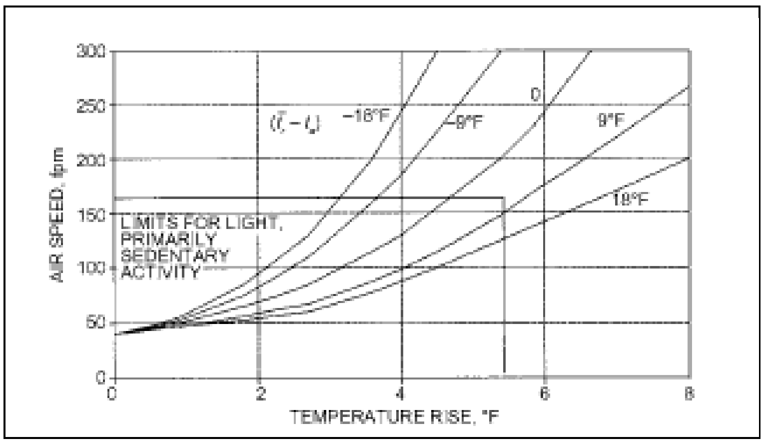
*Defining thermal sensation rating as Y, and two main effect variables, t = dry bulb temperature (F°) and p = vapor pressure (psi), data collected are summarized by the simple linear model Y = at + bp + c. Coefficients for "t" for each exposure condition "h" are larger for women in each exposure condition, and coefficients for vapor pressure (humidity) (p) are smaller for women in the two largest exposure periods (h). Inserting values of "t" and "t + 5.4" and computing Y (thermal sensation)—for each of the equations while holding "p" constant—should show an average difference of about "1" in "Y"; inserting values of "p" and "p + .44" while holding "t" constant should produce a comparable average difference in thermal sensation.

Table 3. Equations for predicting thermal sensation Y of men, women, and men and women combined.

Exposure Period, h	Subjects	Regression Equations[a, b] t = dry-bulb temperature, °F p = vapor pressure, psi
1.0	Men	$Y = 0.122t + 1.61p - 9.584$
	Women	$Y = 0.151t + 1.71p - 12.080$
	Both	$Y = 0.136t + 1.71p - 10.880$
2.0	Men	$Y = 0.123t + 1.86p - 9.953$
	Women	$Y = 0.157t + 1.45p - 12.725$
	Both	$Y = 0.140t + 1.65p - 11.339$
3.0	Men	$Y = 0.118t + 2.02p - 9.718$
	Women	$Y = 0.153t + 1.76p - 13.511$
	Both	$Y = 0.135t + 1.92p - 11.122$

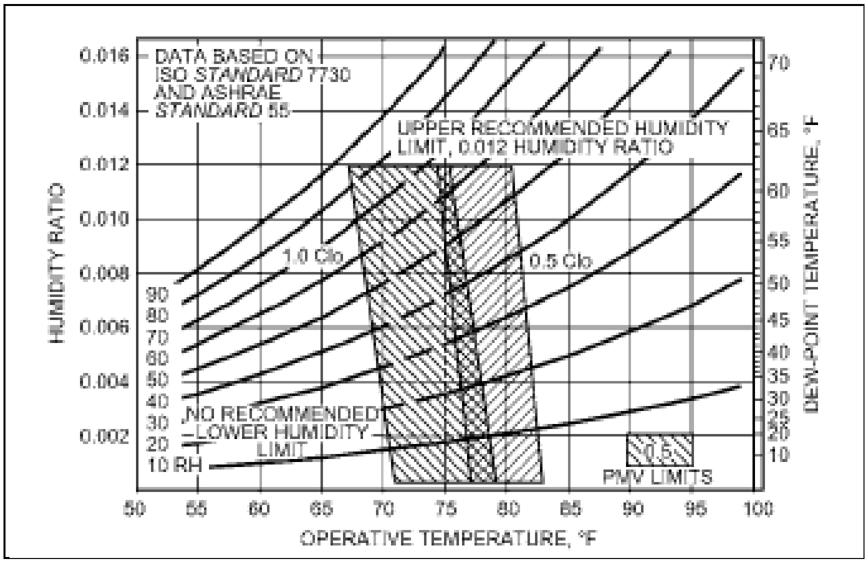
[a] Y values refer to the ASHRAE thermal sensation scale.
[b] For young adult subjects with sedentary activity and wearing clothing with a thermal resistance of approximately 0.5 clo, $\bar{t}_r < \bar{t}_a$ and air velocities < 40 fpm.

Source: ASHRAE. Chapter 9, Thermal Comfort. In *Handbook – Fundamentals* (I-P Edition), Atlanta, GA, 2009b; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).



Source: ASHRAE. Chapter 9, Thermal Comfort. In *2009 Handbook – Fundamentals,* (I-P Edition); Atlanta, GA, 2009b; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

Figure 2. Air speed to offset temperatures above warm-temperature boundaries of figure 3.



Source: ASHRAE. Chapter 9, Thermal Comfort. In *2009 Handbook – Fundamentals,* (I-P Edition); Atlanta, GA, 2009b; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

Note: "Acceptable ranges of operative temperature and humidity with air speed ≤ 40 fpm for people wearing 1.0 and 0.5 clo clothing during primarily sedentary activity (≤1.1 met)" (ASHRAE, 2009b).

Figure 3. ASHRAE summer and winter comfort zones.

2.1.4 Hazard Control: Methodology

The following health sciences disciplines are used to identify conditions affecting occupant comfort:

1. *Epidemiology and biostatistics*. [This] "studies the cause, distribution and control of disease in human and animal populations. [Epidemiology] represents the application of quantitative methods to evaluate health-related events and effects. [As a discipline, it] is traditionally subdivided into two components. [The observational component is] generally performed with a defined group [of interest] because of a specific exposure or risk factor [and] a control group selected with common criteria, but without the risk factor. [The analytical component] attempts to identify causal relationships. Those relationships [include] consistency, temporality, plausibility, specificity, strength of association, and dose/response" (ASHRAE, 2009c, p 10.2).

2. *Industrial hygiene*. This is the "science of anticipating, recognizing, evaluating, and controlling workplace conditions that may cause worker illnesses or injury" (ASHRAE 2009c, p 10.3).

3. *Microbiology, mycology, and aerobiology*. These are concerned with the "effective, practical, and safe disinfection practices usually developed and validated by microbiologist and mycologists" (ASHRAE 2009c, p 10.3). "Microbiology studies microorganisms,

including bacteria, viruses, fungi, and parasites; mycology is a sub-specialty that focuses on fungi" and "aerobiology is the study of airborne microorganisms or other biologically produced particles" (ASHRAE, 2009c, p 10.3).

4. *Toxicology*. "[This] studies the influence of chemicals on health" (ASHRAE, 2009c, p 10.3) with a focus on the component of the structure and its dosage that has the harmful effect.

ASHRAE (2009c) goes on to explain, "Quantitative hazard analysis and control processes are practical and cost-effective. Preventing disease from hazards requires facility managers and owners to answer three simple site-specific questions:

- What is the hazard?
- How can it be prevented from harming people?
- How can it be verified that the hazard has been prevented from harming people?

[There are] seven principles that comprise effective hazard analysis and control:

1. Use process flow diagrams to perform systematic hazard analysis
2. Identify critical control points (process steps at which the hazard can be eliminated or prevented from harming people
3. Establish hazard control critical limits at each critical control point
4. Establish a hazard control monitoring plan for critical limits at critical control points
5. Establish hazard control corrective actions for each critical limit
6. Establish procedures to document all activities and results
7. Establish procedures to confirm that the plan: (a) actually works under operating conditions (validation); (b) is being implemented properly (verification); and (c) is periodically reassessed" (ASHRAE, 2009c, p 10.4).

2.1.5 Hazard Control: General Techniques

The following sections explain techniques used to control different types of hazards.

2.1.5.1 Physical Hazard. This consists of controlling temperature as previously discussed in section 2.1.3.

2.1.5.2 Gaseous Hazards. Gaseous hazards are generally controlled by one of five control strategies (listed in order of preference):

1. Substitution (removal of the hazardous substance)
2. Isolation

3. Disinfection

4. Ventilation

5. Air cleaning (filtration)

While "engineering controls such as ventilation and air cleaning may be effective for a range of hazards, local exhaust ventilation is more effective for controlling point source contaminants than is general dilution ventilation such as would be used with a building HVAC system" (ASHRAE, 2009c, p 10.3). No single type of media is effective for the broad range of indoor gaseous contaminants. Granular-activated charcoal is generally an agent of choice for nonpolar compounds and is suitable for O_3 and NO_2, but not for SO_x (sulfur oxides) and NO; for these latter gaseous contaminants, permanganate-impregnated alumina is more appropriate. "Local exhaust ventilation is an appropriate and effective control in most occupational cases for CO exposure. Dilution ventilation is much less effective than local exhaust for reducing contamination from point-source emissions. Reduction of concentrations of all contaminants to the lowest level is not economically feasible" (ASHRAE, 2009d, p 11.16).

While control of VOC hazards "in most cases leads to the recommended hierarchy for control (generally), this process requires careful planning: specifications, and selection, modification, and treatment of products, as well as special installation procedures and proper ventilation system operation" (ASHRAE, 2009d, p 11.13).

2.1.5.3. Particulate and Dust Hazards. Consistent with gaseous hazards, source elimination is the best control method to use by maintaining negative pressure inside the entire enclosure by exhaust ventilation (Alpaugh and Hogan, 1988). Local exhaust is a hazard-control strategy used most frequently where particles are generated either in large volumes or with high velocities. High-velocity air movement captures the particles and removes them from the work environment. General dilution ventilation is used to reduce particulate exposure when particulate sources are numerous and widely distributed over a large area; however, this is not a cost-effective strategy of control if conditioned (warm or cold) air is exhausted and unconditioned air is introduced without the benefit of airside energy recovery. Filtration can be more cost-effective than general ventilation, "although the increased pressure drop across a filter adds to fan horse-power requirements and increased maintenance adds to system operating cost" (ASHRAE, 2009c, p 10.5).

2.1.5.4. Bioaerosols. While the "physical and biological properties of bioaerosols need to be understood, at present, numerical guidelines for bioaerosol exposure in indoor environments are not available for several reasons:

- Incomplete data on background concentrations and types of microorganisms indoors, especially as affected by geographical, season, and building parameters.

- Incomplete understanding of and ability to measure routes of exposure, internal dose, and intermediate and ultimate clinical effects.
- Absence of epidemiological data relating bioaerosol exposure indoors to illness.
- Enormous variability in types of microbial particles, including viable cells, dead spores, toxins, antigens, MVOCs, and viruses.
- Large variation in human susceptibility to microbial particles, making estimates of health risk difficult" (ASHRAE, 2009c, p 10.8).

2.2 MIL-STD-1472F

Sections 2.2.1–2.2.3 outline the guidance provided in MIL-STD-1472F (U.S. Department of Defense, 1999).

2.2.1 Guidance for Heating

1. "The crew compartment shall be provided with a heating system capable of maintaining temperatures above 20 °C (68 °F) during occupancy when personnel are not wearing Arctic clothing and exposure exceeds 3 hours.
2. When Arctic clothing is worn, cab heaters shall be capable of maintaining a reference temperature of not less than 5 °C (41 °F) at the minimum ambient design temperature with the vehicle moving at two-thirds maximum speed and the defrosters operating at maximum capacity.
3. The reference temperature is measured 61 cm (24") above the seat reference point of each operator/passenger position.
4. Air temperatures around any part of the operator/passenger's body shall not vary more than ±5 °C (±9 °F).
5. The heater shall achieve these requirements within one hour after it is turned on" (p 165, para 5.12.6.1).

2.2.2 Guidance for Ventilation

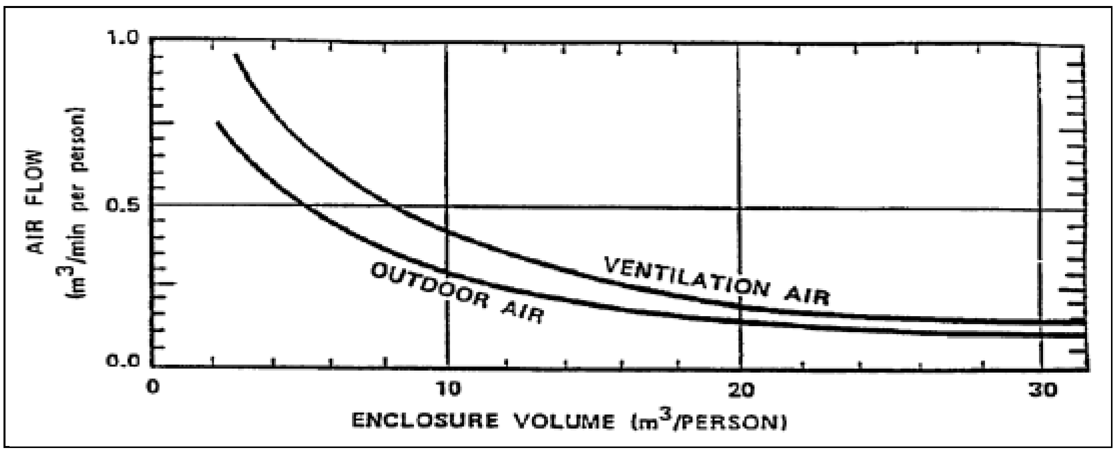
1. "Outside fresh air shall be supplied at minimum rate of 0.57 m^3 (20 ft^3)/ min/person.
2. Air flow rates for hot-climate operation (temperatures above 32 °C (90 °F)) shall be maintained between 4.2 and 5.7 m^3 (150 and 200 ft^3)/min./person, unless air conditioning or individual (microclimate) cooling is provided.
3. Air velocity at each person's head location shall be adjustable either continuously or with not less than three settings (OFF, LOW and HIGH) from near zero to at least 120 m (400 ft)/minute" (p 165, para 5.12.6.2).

4. “The heating-ventilating system shall be designed to minimize degradation of visibility due to frosting or misting of the windshield” (p 165, para 5.12.6.3).

5. “Adequate ventilation shall be assured by introducing fresh air into any personnel enclosure.

6. If the enclosure volume is 4.25 m^3 (150 ft^3) or less per person, a minimum of 0.85 m^3 (30 ft^3) of ventilation air per minute shall be introduced into the enclosure—approximately two-thirds should be outdoor air.

7. For larger enclosures, the air supply per person may be in accordance with the curves in Figure 35 [figure 4 in this report].



Source: U.S. Department of Defense. *Human Engineering* (Military Standard - Department of Defense Design Criteria); MIL-STD-1472F; U.S. Army Aviation and Missile Command: Redstone Arsenal, AL, 23 August 1999.

Figure 4. Ventilation requirements.

8. Air shall be moved past personnel at a velocity no more than 60 m (200 ft) per minute.

9. Where manuals or loose papers are used, airspeed past these items shall be not more than 30 m (100 ft) per min—20 m (65 ft) per min if possible.

10. Under NBC conditions, ventilation requirements shall be modified as required.

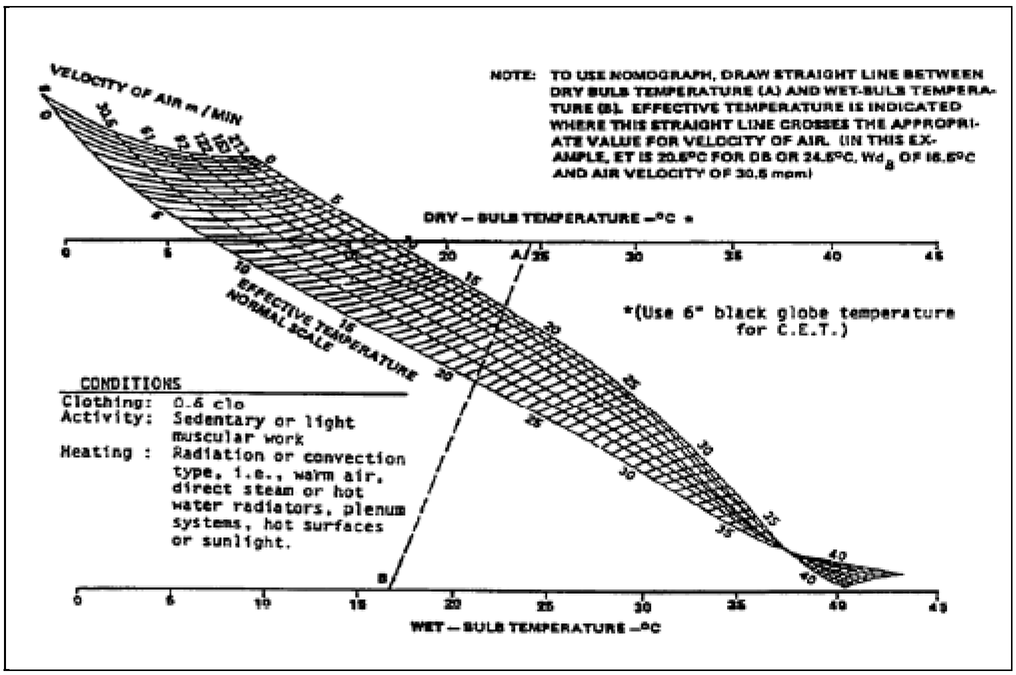
11. Ventilation or other protective measures shall be provided to keep gases, vapors, dust, and fumes within the Permissible Exposure Limits specified by 29 CFR 1910 and the limits specified in the American Conference of Governmental Industrial Hygienists Threshold Limit Values.

12. Intakes for ventilation systems shall be located to minimize the introduction of contaminated air from such sources as exhaust pipes” (p 121, para 5.8.1.2).

2.2.3 Guidance for Air Conditioning

1. "If vehicle mission profile requires personnel to occupy a vehicle cabin for a period exceeding 30 minutes in climatic (ambient) conditions greater than +24 °C (75 °F), then the provisions of 5.8.1.3 through 5.8.1.8 shall apply" (p 165, para 5.12.6.4).

2. "The effective temperature or CET within personnel enclosures used for detail work during extended periods shall be no greater than 29.5 °C (85 °F) (see Figure 34 [figure 5 in this report]) and cold-air shall not be directly discharged on personnel" (p 121, para 5.8.1.3).

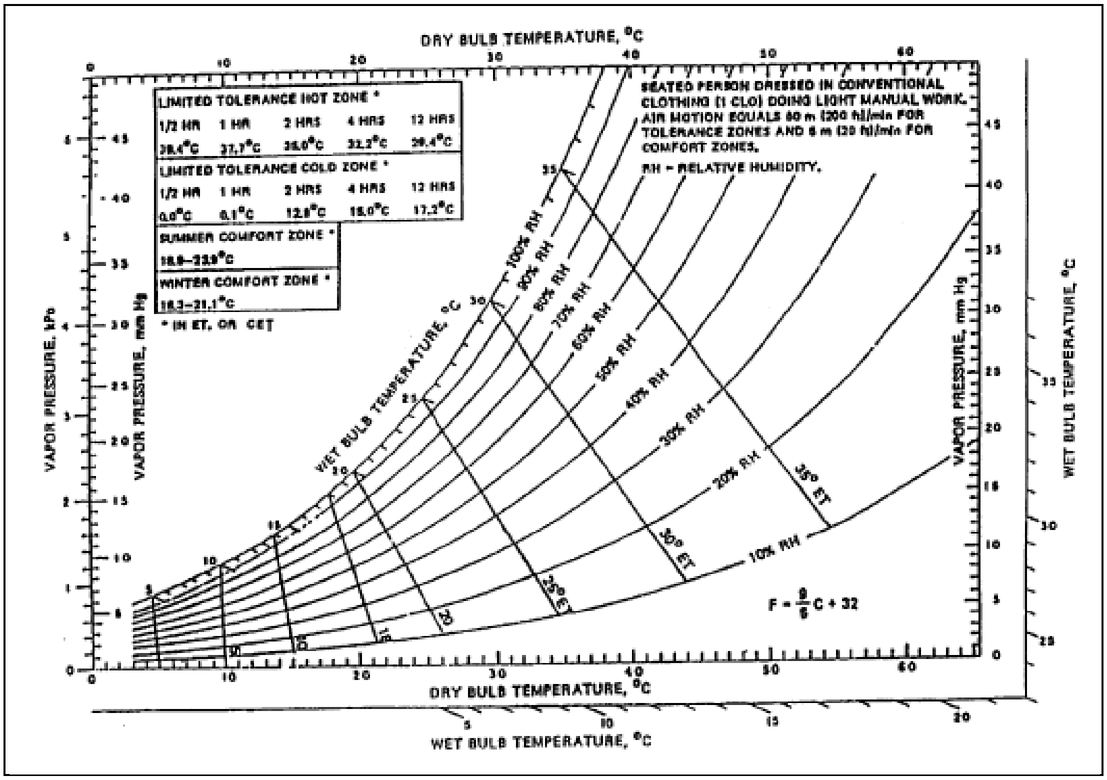


Source: U.S. Department of Defense. *Human Engineering* (Military Standard - Department of Defense Design Criteria); MIL-STD-1472F; U.S. Army Aviation and Missile Command: Redstone Arsenal, AL, 23 August 1999.

Figure 5. Effective temperature (ET) or corrected effective temperature (CET).

3. "Approximately 45% relative humidity should be provided at 21 °C (70 °F) and this value should decrease with rising temperatures (but should remain above 15 percent to prevent irritation and drying of body tissues, e.g., eyes, skin, and respiratory tract (see Figure 36 [figure 6 in this report])" (p 121, para 5.8.1.4).

4. "When special protective clothing or personal equipment (including full and partial pressure suits, fuel handler suits, body armor, arctic clothing, and temperature regulated clothing) are required and worn, a comfort micro-climate between 20 °C (68 °F), 14 mm Hg ambient water vapor pressure and 35 °C (95 °F), 3 mm Hg ambient water vapor pressure is desirable and, where possible, shall be maintained by heat transfer systems" (p 121, para 5.8.1.6).



Source: U.S. Department of Defense. *Human Engineering* (Military Standard - Department of Defense Design Criteria); MIL-STD-1472F; U.S. Army Aviation and Missile Command: Redstone Arsenal, AL, 23 August 1999.

Figure 6. Summer and winter comfort zones and thermal tolerance for inhabited compartments.

5. "Temperature and humidity exposure should not exceed the effective temperature limits given in Figure 36 [figure 6] when corrected for air velocity" (p 121, para 5.8.1.7).

6. "Where hard physical work is to be required for more than two hours, an environment not exceeding a wet bulb globe temperature or wet-dry index of 25 °C (77 °F) shall be provided.

7. Where wearing protective clothing systems (which reduce evaporation of sweat from the skin) is required, this index shall be decreased 5 °C (9 °F) for complete chemical protective uniforms, 4 °C (7 °F) for intermediate clothing systems, and 3 °C (5 °F) for body armor" (p 121, para 5.8.1.8).

3. Adequacy of the Current Standards for Combat Vehicle Ventilation

This section addresses the question of whether the ventilation standards in 1472 and ASHRAE are adequate for this application. If so, why? If not, what should be added or deleted?

Based upon the review of the ventilation literature to date, including the MANPRINT reported findings for combat vehicles in the next section, "adequacy" can imply several things. If one uses "completeness" as a synonym, the answer is always no. An incomplete body of knowledge—or even key references—does not make it inadequate. What is important regarding the completeness of references is their appropriateness to correction of the problem described and their ease of use. MIL-STD-1472F provides only the facts; it is a well-indexed document but contains no comprehensive references section. This can leave the reader with a sense of doubt that the author is providing accurate information. Like many military documents, the procedures used to obtain those facts are assumed to be "transparent," when to a nonanalyst, they are not.

The first section of this report indicated that this "defect" occurs in many MANPRINT and human factors engineering reports that motivated the primary author to prepare a MANPRINT tutorial (Heuckeroth, 2008). The tutorial seemed a useful contribution to the MANPRINT /human factors engineering community in providing guidelines and many specific examples of how data within those domains could be validly collected. If there is any question of the validity of the guidelines provided in MIL-STD-1472F, a review of the various ASHRAE handbooks should allay those fears.

As stated in the first section of this report, the intent is to provide nonventilation experts with a talking knowledge of potential ventilation needs when they are communicating with ventilation experts. Consistent with this perception, chapter 16 of the ASHRAE handbook (2009e) indicates that changing ventilation and infiltration rates to solve thermal comfort problems and reduce energy consumption can affect indoor air quality (IAQ) and may be against code. Any changes should be approached with care and be under the direction of a registered professional engineer with expertise in HVAC analysis and design.

According to our understanding, whenever ASHRAE publishes a new handbook, they no longer release previous issues; however, selective review by the primary author where ASHRAE documentation for earlier years was available through library referencing did not reveal differences in the methodology employed that would affect the familiarization process. Changes in criteria used did occasionally change as updated measurements were employed with culturally induced changes. For example, one change that did occur in 1989 was the minimum outdoor airflow rate changed from 5 to 15 cfm (cubic feet per minute) per person. While the specific benchmarks used in assessments have undergone some change over the years (driven in part by cultural changes, like actions to reduce and control the smoking habit), it appears that the basic methodology has continued to reflect the existing scientific methodology with improved measurement techniques.

If there is any serious criticism of the ASHRAE handbook, it is that many chapters contain the same information, and there did not seem to be any a priori basis for knowing how to make sense of this vast compendium of information. Section 2 of this report reflects the difficulty of reviewing many of the chapters in the handbook to create a sort of mosaic of the fields of ventilation, air-conditioning, and heating expertise. As research was being addressed for one section of this report, information germane to other parts was found. This observation tends to support the perception that professional engineers organize information according to their discipline; system developers and evaluators prefer material organized differently. As indicated in section 2, the main purpose of this document is to bridge the gap so that engineers and systems application (development and evaluation) personnel can more easily communicate.

Repeated documentation of failures to correct ventilation, AC, and/or heating standards in combat vehicles—in MANPRINT and/or human factors engineering assessments (Akens, 1993; Dickinson and Brown, 1962; Krohn and Spiegel, 1990; McMahon, 1996; Singapore, 1994, 1998, 1999, 2001, 2004a, 2004b, 2004c, 2007, 2008)—does exist. While differences in the organization of information by professionals in different fields vary, the number of documented instances makes it unlikely that adequacy of standards or the organization of information is significantly at fault. Saving money for expensive mechanical "fixes" is conjectured as the primary reason.

4. Impact on Human Performance of Poor Vehicle Ventilation

This section addresses the impact on human performance and resulting mission performance if the required ventilation requirements are not met.

There are two types of support/nonsupport for this concern: anecdotal and MANPRINT/human factors engineering reports. Anecdotal support for the importance of meeting ventilation requirements comes from the number of presumed authorities and those with command support who must "sign off" on published documents that validate the consequences of failing to meet ventilation requirements. MANPRINT/human factors engineering reports serve as explicit documentation of the consequences of not providing adequate ventilation requirements in combat vehicles.

4.1 Anecdotal

Data that specifically addresses this topic would require an assessment of successful and unsuccessful mission performances when ventilation conditions are and are not met or degradations in human performance when the relative efficacy of ventilation capabilities are known. No studies that presented such control were reviewed. The 1999 MIL-STD-1472F presents only requirements without providing background studies leading to those findings. The other major sources reviewed to address ventilation requirements were the ASHRAE handbook (2009a) and standards such as ASHRAE Standard 62.1 (2010a, 2010b) and earlier standards by ASHRAE (2004). The MIL-STD-1472F explicitly names thermal problems (usually excess heat) associated with ventilation needs but provides only generic reference to gases, vapors, dust, and fumes, and cites limits in 29 CFR 1910 (U.S. Department of Labor, 2010). The ASHRAE handbook provides detailed listings by name and numerous characteristics of dust, gases, vapors, and fumes. ASHRAE Standard 62.1 (2007) states, "Establishing the contaminants of concern for specific application is a somewhat subjective task, since hundreds of contaminants are known to be harmful to human occupants and/or to affect perceived acceptability."

Sometime after military standards were, in fact, treated as standards, it was decided that they should be more appropriately considered "guidelines." The reason(s) for these changes were not communicated. Contractors may have diminished the standards' importance because meeting those "standards" would require higher costs, and it could be expected that those on military oversight committees didn't want to spend the extra money on meeting guidelines. Those in the military have suffered because of these changes. Records that document the effects of heat and/or contaminant exposure on the Soldier and the diverse symptoms that could have been prevented reported by retired military are not available. It is suspected that training units mitigated intense training periods during the hottest time of day because they knew that their troops would suffer from thermal stress if they continued. For example, Soldiers who drove the Heavy Equipment Transport Systems (HETS) scheduled their training sessions no later than 0600 and after 1800 to avoid the heat stress that would exist in the HETS M1070 cab (Akens, 1993). For training, that is a workable expedient to keep Soldiers from heat prostration, but in a battle environment like Iraq, the enemy would eventually recognize such mission scheduling.

4.2 MANPRINT/Human Factors Investigations

The consequences of failing to meet the ventilation requirements in various combat vehicles have been documented since at least the early 1980s. Appendix A summarizes several of those sources and highlights the nature of the problems and resulting consequences when ventilation requirements have not been met. Most of the summaries presented in appendix A are either MANPRINT or human factors engineering reports prepared and submitted to the Human Research and Engineering Directorate (HRED) and reviewed and signed off by the director. Other examples from past studies can be identified from the three-volume bibliography of MANPRINT studies and evaluations published in 2010 (Middlebrooks, 2010a, 2010b, 2010c).

The HRED documents cite the expected consequences of failing to meet the ventilation requirements in various combat vehicles. In some cases those findings represent judgments Soldiers made on survey instruments. In the HETS IOTE, MANPRINT data-collecting assistants were given a design matrix where they recorded physical temperature measurements under various conditions expected to vary the heat stress Soldiers were expected to endure. Other reported findings in appendix A show that ambient temperatures and heat with the combat vehicles during operation were recorded.

5. Tools for Evaluating Vehicle Ventilation

This section addresses the tools used to evaluate vehicle ventilation, mathematical models, and test procedures. The question is whether these tools are adequate for ventilation assessment requirements for new vehicles in development. If they are not, how should they be modified and/or expanded?

5.1 Multidisciplinary Approaches

When establishing adequate IAQ, professional engineers apply approaches that are multidisciplinary in nature. Substantively, knowledge of physical measurements/relationships and conversion is needed with a basic understanding of chemistry. To understand hazard control and what constitutes a hazard, knowledge of the relationship of cause and effect requires a rudimentary understanding of medicine and the relationship between different chemical structures and the potential health consequences of exposure. In formulating these understandings, professional engineers must be familiar with the value of epidemiology and biostatistics to discern cause and effect, industrial hygiene, microbiology, mycology, aerobiology, and toxicology. Along with that knowledge, engineers employ mathematical/structural modeling and procedures to identify specific hazards to be removed (hazards that can cause harm to occupants or create conditions that diminish occupant effectiveness [physical and cognitive processing]). The professional engineer must be a bit of a generalist.

5.2 The Role of Mathematical Modeling in Establishing Adequate Indoor Air Quality Environments

Modeling is used to estimate energy consumption for two purposes: “Modeling for building and HVAC system design and associated design optimization (forward modeling) and modeling energy use of existing buildings for establishing baselines and calculating retrofit savings (data-driven modeling)” (ASHRAE, 2009f, p 19.1).

“A mathematical model describes the behavior of a system and is made up of three components:

1. **Input variables** (statisticians call these regressor variables, whereas physicists call them forcing variables), which act on the system. One type is controllable by the experimenter and another type are uncontrollable (e.g., climate—heat, contaminants, gases, dust).
2. **System structure and parameters/properties**, which provide the necessary physical description of the system (e.g., thermal mass or mechanical properties of the elements).
3. **Output** (response, or dependent) variables, which describe the reaction of the system to the input variables. Energy use is often a response variable" (ASHRAE, 2009f, p 19.1).

Rabl (1988) believes that there are two broad, yet distinct, approaches to modeling. One approach is dictated by the objective and the other by the purpose of the investigation.

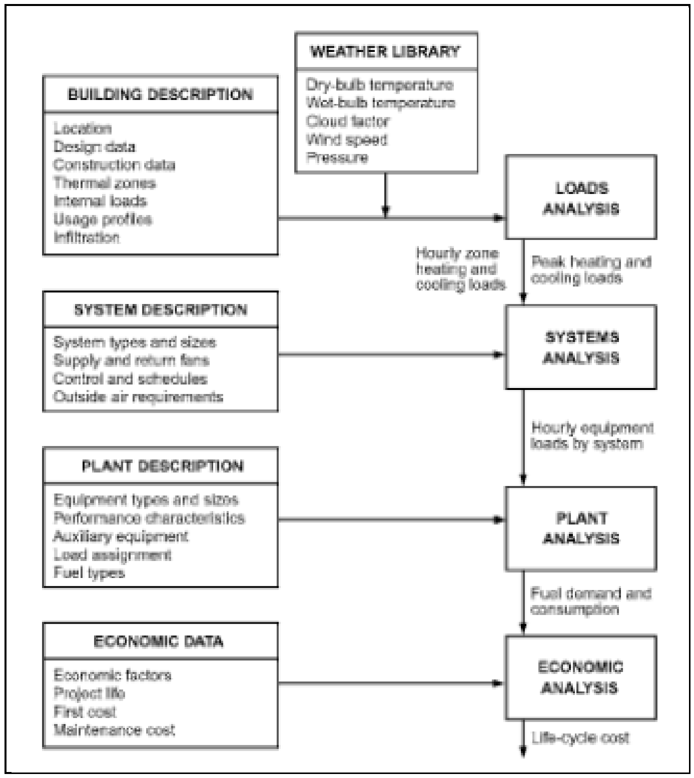
5.2.1 Forward (Classical) Approach

The objective of the forward approach is to predict the output variables of a specified model with known structure and known parameters when subject to specified input variables. "The main advantage of this approach is that the system need not be physically built to predict its behavior. Major government-developed simulation codes, such as BLAST, DOE-2 and Energy Plus, are based on forward simulation models" (ASHRAE, 2009f, p 19.1).

Figure 7 illustrates the ordering of the analysis typically performed by a building energy simulation program. The figure shows the level of complexity involved in using one (or more) of the four basic ventilation techniques to indicate control of the indoor environment of combat vehicles. A major reason that this type of model was not conceived is that "tuning the forward-simulation model is often awkward and labor intensive" (ASHRAE, 2009f, p 19.2).

In his discussion of this approach to modeling, Chang et al. (2007) indicate that in developing advanced armor, there is a need to deal with the influence of cabin ventilation and temperature as well as operating on nuclear, biological, and chemical (NBC) battlefields. These factors complicate the design of air conditioning and ventilation systems for modern armored vehicles and can be realized through consideration of complex heat flow dynamics and distribution aspects. In practice, each modeled environment tends to have its own unique geometry characteristics and boundary conditions, hence if meaningful results are to be obtained, the researcher should have considerable experience.

Chang began by developing a contour mesh vehicle model and conducting a numerical simulation of the ventilation system. The numerical simulation is based on various theoretical mathematical models derived from fluid dynamics principles and is expressed in terms of partial derivatives of a host of fluid dynamics variables. The fact that this approach to modeling ventilation systems exists and is covered in some detail in the ASHRAE handbook indicates the validity of the approach.



Source: ASHRAE. Chapter 19, Energy Estimating and Modeling Methods. In *Handbook - Fundamentals* (I-P Edition); Atlanta, GA, 2009f; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

Figure 7. Flow chart for building energy simulation program.

While the senior author of this report does have some experience with modeling, it is not from the perspective of professional engineers in the ventilation, air-conditioning, and heating disciplines. Among the criteria mathematical modelers strive for in their modeling efforts is parsimony. While the classical modeling approach has a higher fidelity (is more representative of how the real world ventilation system operates), “tuning the forward-simulation model is often awkward and labor intensive” (and with a much higher cost) (ASHRAE, 2009f, p 19.2). In terms of meeting the ventilation needs for “relatively simple” systems, the data-driven modeling approach, discussed in the next section, is considered more cost effective, and Standard 62.1 procedures seem to apply more readily. These concerns reinforce the desirability of planning and developing a viable ventilation system with the aid and counsel of a professional engineer. As already stated, this report was written to familiarize system planners, such as U.S. Army Evaluation Center (AEC) personnel, with the terminology and concepts used by ASHRAE-type professional engineers and to facilitate that interaction.

5.2.2 Data-Driven (Inverse) Approach

ASHRAE (2009f) states, "In this case, input and output variables are known and measured, and the objective is to determine a mathematical description of the system and to estimate system parameters. In contrast to the forward approach, the data-driven approach is relevant when the system has already been built and actual performance data are available" (or could be relatively easily collected in a series of mini-simulations). Based on figure 7, the forward (classical) approach is more akin to modeling an entire system (from "square one") rather than considering the combat vehicle as a system already conceived to meet a U.S. Army need, and specific adaptations are needed to address ventilation, AC, and heating environmental factors.

Our preference for this type of modeling approach is based on several factors:

- Having worked as a MANPRINT data collector for the Heavy Equipment Transport System and noting the thermal stress to which drivers and assistant drivers could be periodically exposed.
- Having reviewed several MANPRINT and human factors engineering reports for several other combat vehicle systems where Soldiers' performance is still impeded by heat and other contaminants after these conditions were assessed and recommended for remediation.
- Other combat vehicle systems still seemed to be relatively new in their life-cycle development processes.
- The continuation of our national empire-building objectives in environments where the application of ventilation procedures would be consistent with pursuing those goals.

"The data-driven model has to meet requirements very different from the forward model. The data-driven model can only contain a relatively small number of parameters because of the limited and often repetitive information contained (or will be exhibited) in performance data during operations" (ASHRAE, 2009f, p 19.2). In general, data-driven models are less flexible than forward models in evaluating energy implications of different design and operational alternatives.

ASHRAE (2009f) goes on to explain, "To better understand the uses of data-driven models, consider some of the questions that a building professional may ask about an existing building (vehicle) with known energy consumption (Rabl, 1988):

- How does consumption compare with design predictions?
- How would consumption change if thermostat settings, ventilation rates, or indoor lighting levels were changed?
- How much energy could be saved by retrofits to the building shell, changes to air handler operation from CV to VAV, or changes in the various control settings?

- If retrofits are implemented, can one verify that the savings are due to the retrofit and not to other causes?
- How can one detect faults in HVAC equipment and optimize control and operation?"

The data-driven model would also address assessment (measurement of changes in heat stress and exposure to gaseous and particulate with the implementation of different forms of ventilation control). The ASHRAE handbook (2009e) indicates that changing ventilation and infiltration rates to solve thermal comfort problems and reduce energy consumption can affect IAQ and may be against code, so any changes should be approached with care and be under the direction of a registered professional engineer with expertise in HVAC analysis and design. With this level of professional oversight, one should sit down with an experienced engineer to assess the operational atmosphere within the different combat vehicles that still need some form of ventilation and measure the extent of thermal stress and the level of different contaminants (gases, dust, and fumes) that would be expected in the intended operational environment. With those measurements, the engineer should be able to make retrofit recommendations to improve Soldier comfort and cognitive functioning. Using existing combat vehicles as data-driven models in this manner should reduce the amount of "tuning [of] the forward-simulation model [and avoid what] is often awkward and labor intensive [iterations]" (ASHRAE, 2009f, p 19.2). Table 4 provides a sampling of analysis methods for tuning different combat vehicles.

A simple criterion to determine whether a model is steady state or dynamic is to look for the presence of time-lagged variables, either in the response or regressor variables. Steady-state models do not contain time-lagged variables.

For those who might be interested in exploring the application of different modeling techniques to address ventilation requirements of combat vehicles, table 4 provides a sampling. Because of my preference for data-driven models and my fairly extensive background with FORTRAN programming, I might be inclined to use the ASHRAE Inverse Modeling Toolkit (Haberl et al., 2003; Kissock et al., 2003). This toolkit contains FORTRAN 90 and executable code for performing linear and change-point linear regressions, variable-base degree days, multilinear regression, and combined regressions.

Table 4. Classification of analysis methods for building energy use.

Method	Forward	Data-Driven: Empirical or Black-Box	Data-Driven: Calibrated Simulation	Data-Driven: Physical or Gray-Box	Comments
Steady-State Methods					
Simple linear regression (Kissock et al. 1998; Ruch and Claridge 1991)	—	X	—	—	One dependent parameter, one independent parameter. May have slope and *y*-intercept.
Multiple linear regression (Dhar 1995; Dhar et al. 1998, 1999a, 1999b; Katipamula et al. 1998; Sonderegger 1998)	—	X	—	—	One dependent parameter, multiple independent parameters.
Modified degree-day method	X	—	—	—	Based on fixed reference temperature of 65°F.
Variable-base degree-day method, or 3-P change point models (Fels 1986; Reddy et al. 1997; Sonderegger 1998)	X	X	—	X	Variable base reference temperatures.
Change-point models: 4-P, 5-P (Fels 1986; Kissock et al. 1998)	—	X	—	X	Uses daily or monthly utility billing data and average period temperatures.
ASHRAE bin method and data-driven bin method (Thamilseran and Haberl 1995)	X	X	—	—	Hours in temperature bin times load for that bin.
ASHRAE TC 4.7 modified bin method (Knebel 1983)	X	—	—	—	Modified bin method with cooling load factors.
Multistep parameter identification (Reddy et al. 1999)	—	—	—	X	Uses daily data to determine overall heat loss and ventilation of large buildings.
Dynamic Methods					
Thermal network (Rabl 1988; Reddy 1989; Sonderegger 1977)	X	—	—	X	Uses equivalent thermal parameters (data-driven mode).
Response factors (Kusuda 1969; Mitalas 1968; Mitalas and Stephenson 1967; Stephenson and Mitalas 1967)	X	—	—	—	Tabulated or as used in simulation programs.
Fourier analysis (Shurcliff 1984; Subbarao 1988)	X	—	X	X	Frequency domain analysis convertible to time domain.
ARMA model (Rabl 1988; Reddy 1989; Subbarao 1986)	—	—	—	X	Autoregressive moving average (ARMA) model.
PSTAR (Subbarao 1988)	X	—	X	X	Combination of ARMA and Fourier series; includes loads in time domain.
Modal analysis (Bacot et al. 1984; Rabl 1988)	X	—	—	X	Building described by diagonalized differential equation using nodes.
Differential equation (Rabl 1988)	—	—	—	X	Analytical linear differential equation.
Computer simulation: DOE-2, BLAST, EnergyPlus (Crawley et al. 2001; Haberl and Bou-Saada 1998; Manke et al. 1996; Norford et al. 1994)	X	—	X	—	Hourly and subhourly simulation programs with system models.
Computer emulation (HVACSIM+, TRNSYS) (Clark 1985; Klein et al. 1994)	X	—	—	—	Subhourly simulation programs.
Artificial neural networks (Kreider and Haberl 1994; Kreider and Wang 1991)	—	X	—	—	Connectionist models.

Source: ASHRAE. Chapter 19, Energy Estimating and Modeling Methods. In *Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009f; http://knovel.com /web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid =2554&VerticalID=0 (accessed February 2011).

5.3 Test Procedures Used to Establish Indoor Air Quality

As earlier sections were reviewed, the focus was on identifying procedures for identifying vehicle ventilation. In this context, modeling techniques for designing the system to an "ideal" internal structure did not seem cost effective. It seems more likely that a vehicle meeting mission design requirements would exist, and contaminant sources would be identified. Among the measurement techniques, a form of ventilation would be considered to eliminate them. Work with military vehicles led to the systems, and that "good enough" design optimization could be acquired with modeling approaches described in section 5.2.2. Those procedures would be used to establish baselines and calculate retrofit savings consistent with cost-effective procedures presented in ASHRAE Standard 62 (2007).

ASHRAE (2010b, p 6-43) states, “The Indoor Air Quality Procedure (IAQP) may be used as an alternative to the Ventilation Rate Procedure (VRP). The performance of the HVAC system in maintaining good air quality is based upon two requirements: (1) maintaining concentrations of specific contaminants below target concentration limits, and (2) achieving a design target level of perceived indoor air quality acceptability. Sometime meeting the target concentrations will result in perceived acceptability and sometimes not.” The IAQ procedures require the building and its ventilation system to be designed to achieve both objective and subjective criteria. The IAQP may allow for a more cost-effective solution to providing good air quality since the following design strategies may be considered and compared:

- Dilution ventilation.
- Controlling contaminants at the source.
- Air cleaning.
- Evaluation of occupant satisfaction based on perceived air quality in similar buildings or through postoccupancy evaluation.

“Many of these strategies involve added construction and maintenance costs, but the IAQP may also be used to achieve better air quality than the VRP (lower contaminant levels and/or higher perceived acceptability) with or without increasing first cost or maintenance cost” (ASHRAE, 2010b, p 6-43).

5.3.1 Contaminant Requirement

Indoor and outdoor ventilation standards and guidelines are outlined in table 2.

ASHRAE (2010b, p 6-43) outlines that designing for compliance using IAQP requires the following four steps:

1. “Determining contaminants of concern (COC).
2. Determining acceptable concentrations of these contaminants.
3. Specifying the perceived indoor air quality criteria.
4. Applying an acceptable design approach to achieve the performance criteria.”

5.3.2 Contaminant Sources

“Establishing the COC for a specific application is a somewhat subjective task, since hundreds of contaminants are known to be harmful to human occupants and/or to affect perceived acceptability. For instance, does one choose those contaminants present in the highest concentration—even though they represent a very low odor or irritation risk?” (ASHRAE, 2010b). Identification of the COC produced by indoor sources may come from previous experience with a particular building type or occupancy pattern. “Choosing the indoor COC may require collaboration among the HVAC system designer, building owner/operator, and the authority having jurisdiction.   Identification and selection of the COC may also be influenced by whether the application involves new construction, renovation, or simple retrofit" (ASHRAE, 2010b).

While the focus of this research effort is on the application of ventilation procedures to new combat vehicles, the review in section 3 clearly indicates that numerous combat vehicles currently in the U.S. Army inventory are being actively used without the needed ventilation. For those vehicles, COC selection may be determined by direct and/or indirect contaminant-monitoring techniques and may be combined with assessment of occupant-perceived acceptability.

5.3.3 Contaminant Concentration

ASHRAE Standard 62-1 (2010b) requires that, for each COC, a target concentration limit be specified along with the corresponding exposure period. An appropriate reference to a cognizant authority must be specified for each contaminant concentration. "A cognizant authority is defined as either:

- An agency or organization in possession of both the expertise and jurisdiction to establish and regulate concentration limits of airborne contaminants.
- An organization that is recognized as authoritative and whose scope includes the establishment of guidelines, limit values, or concentrations levels for airborne contaminants."

5.3.4 Perceived Indoor Air Quality

The definition of acceptable IAQ found in ASHRAE Standard 62-1 (2010b) reads, "Air in which there are no known contaminants at harmful concentrations as determined by cognizant authorities and with which a substantial majority (80% or more) of the people exposed do not express dissatisfaction."

5.3.5 Design Approaches

"The fourth step in the IAQP is to apply the data collected in the previous steps by using one of four design approaches. The four methods are:

- Mass balance analysis;
- Those having proved successful in similar buildings;
- Those validated by contaminant monitoring and subjective occupant evaluations;
- Application of one of these three approaches to specific contaminants and the use of the VRP to address the general aspects of indoor air quality" (ASHRAE, 2010b, p 6-46).

5.3.6 Mass Balance Analysis

Mass balance analysis is the most commonly used method. For example, this technique was used (Allen et al., 1992) to evaluate the ventilation inside the M1, M1A1, M60, and M2A2-M3A2. The results indicated that the M1A1 ventilation system is only capable of meeting the ventilator requirements of MIL-STD-1472C specified for ambient temperatures of <90 °F with the 200 CFM NBC dump employed or when in motion with the hatches open. The M1A1 ventilation system could not operate to satisfy the MIL-STD-1472C specifications for temperatures ≥90 °F in any system configuration. The M1 met both of the ventilator requirements specified in MIL-STD-1472C when the 1500 CFM intake fan was operating as well as in the M60 and the Bradley Fighting Vehicle (M2A2-M3A2). The ASHRAE 2007 publication provides the following equations for performing a steady-state mass balance analysis on single zone systems:

Units of Measurement (Chapter 11, page 10):

ppm = parts of contaminant by volume per million parts of air by volume
ppb = parts of contaminant by volume per billion parts of air by volume
1000 ppb = 1 ppm
mg /m^3 = milligrams of contaminant per cubic metre of air
µg /m^3 = micrograms of contaminant per cubic metre of air
1 mg/m^3 = 1000 µg /m^3 (Chapter 11, page 4)
Conversions Between ppm and mg/m^3
$ppm = [0.6699*(459.7 + t)*M*p]*(mg/m^3)$
$mg/m^3 = [1.493*(M*p)/(459.7 + t]*(ppm)$
where M = relative molecular weights of contaminant
p = mixture pressure, psia
t = mixture temperature, °F
Concentration data are often reduced to standard temperature and pressure (i.e., 77 °F and 14.7 psia) in which case
$ppm = (24.46/M)*(mg/m^3)$

Selected values of M from this equation (molecular weight) are shown in table 5:

Table 5. Characteristics of selected gaseous air contaminants.

	Chemical and Physical Properties				
Contaminant	Family[a]	CAS[b] number	BP,[c] °F	Sat. VP[d]	M[e]
Acetaldehyde	15	75-07-0	68	1.2	44
Acetone	16	67-64-1	133	0.3	58
Acrolein	15	107-02-8	124	3.6	56
Ammonia	5	7664-41-7	−28	9.9	17
Benzene	19	71-43-2	177	0.1	78
2-Butanone (MEK)	16	78-93-3	175	0.1	72
Carbon dioxide	4	124-38-9	Sub[f]	>40	44
Carbon monoxide	3	630-08-0	−312	>60	28
Carbon disulfide	25	75-15-0	116	0.5	76
Carbon tetrachloride	11	56-23-5	170	0.15	154
Chlorine	1	7782-50-5	−30	7.7	71
Chloroform	11	67-66-3	142	0.2	119
Dichlorodifluoromethane	10	75-71-8	−20	6.4	121
Dichloromethane	12	75-09-2	104	0.6	85
Ethylene glycol	13	107-21-1	387	0.0001	62
Ethylene oxide	21	75-21-8	56	1.7	44
Formaldehyde	15	50-00-0	−2	5.1	30
n-Heptane	7	142-82-5	209	0.06	100
Hydrogen chloride	4	7647-01-0	−121	46.4	37
Hydrogen cyanide	18	74-90-8	79	1.0	27
Hydrogen fluoride	4	7664-39-3	67	1.2	20
Hydrogen sulfide	4	7783-06-4	−77	20.2	34
Mercury	1	7439-97-6	674	<0.00002	201
Methane	7	74-82-8	−263	>100	16
Methanol	13	67-56-1	149	0.2	32
Nitric acid	4	7697-37-2	187	0.07	63
Nitrogen dioxide	2	10102-44-0	70	1.1	46
Ozone	2	10028-15-6	−170	>60	48
Phenol	13	108-95-2	360	0.0005	94
Phosgene	27	75-44-5	47	1.9	90
Propane	7	74-98-6	−44	9.3	44
Sulfur dioxide	4	7446-09-5	14	4.2	64
Sulfuric acid	4	7664-93-9	639		98
Tetrachloroethylene	11	127-18-4	250	0.02	166
Toluene	19	108-88-3	231	0.04	92
Toluene diisocyanate	18	584-84-9	484	0.00001	174
1,1,1-Trichloroethane	11	71-55-6	165	0.2	133
Trichloroethylene	11	79-01-6	188	0.1	131
Vinyl chloride monomer	24	75-01-4	8	3.5	63
Xylene	19	106-42-3	281	0.01	106

[a]Chemical family numbers are as given in Table 5.
[b]CAS = Chemical Abstracts Services.
[c]BP = boiling point at 14.7 psia (1 atm) pressure.
[d]Sat. VP = saturated vapor pressure at 77°F, atm.
[e]M = molecular weight.
[f]Sub = solid sublimes at −109°F.

Source: ASHRAE. Chapter 11, Air Contaminants. In *Handbook – Fundamentals* (I-P Edition); Atlanta, GA, 2009d; http://knovel.com/web/portal/browse/display?_EXT_KNOVEL_DISPLAY_bookid=2554&VerticalID=0 (accessed February 2011).

5.3.7 Design Approaches Proven Successful in Similar Building

The key here is "similar" and generally applies to multizone enclosures—a collection of occupied spaces of the same occupancy category, occupant density, and air distribution effectiveness.

5.3.8 Contaminant Monitoring and Occupant Surveys

Many building studies have discussed the time it takes for initial higher building emission rates to decrease; these data can aid in deciding when to begin monitoring and evaluations that address steady state conditions.

5.3.9 Combination of Methods With the VRP

In this situation, the VRP is used to determine the design ventilation rate of the space, and the IAQP is used to address the specific contaminants through source control, supplemental ventilation, exhaust at the source, air cleaning, or some other means.

5.4 Documentation

The ASHRAE Standard 62-1 (2010b) requires that the IAQP be documented with the following procedures:

- The design approach used.
- The COCs used in the design process.
- Source strengths of COC found indoors /outdoors.
- Target concentration limits and exposure periods for the COC.
- Basis for concluding that design approach in similar buildings successfully is of similar design—key features that may include occupancy category and/or occupant density and/or distribution effectiveness.

In order to implement the procedures that comprise the IAQP, appendix B contains detailed specifications of recommended limits for numerous COCs. The IAQ process flow procedure is illustrated in figure 8. A mathematical example of this process is provided in appendix C.

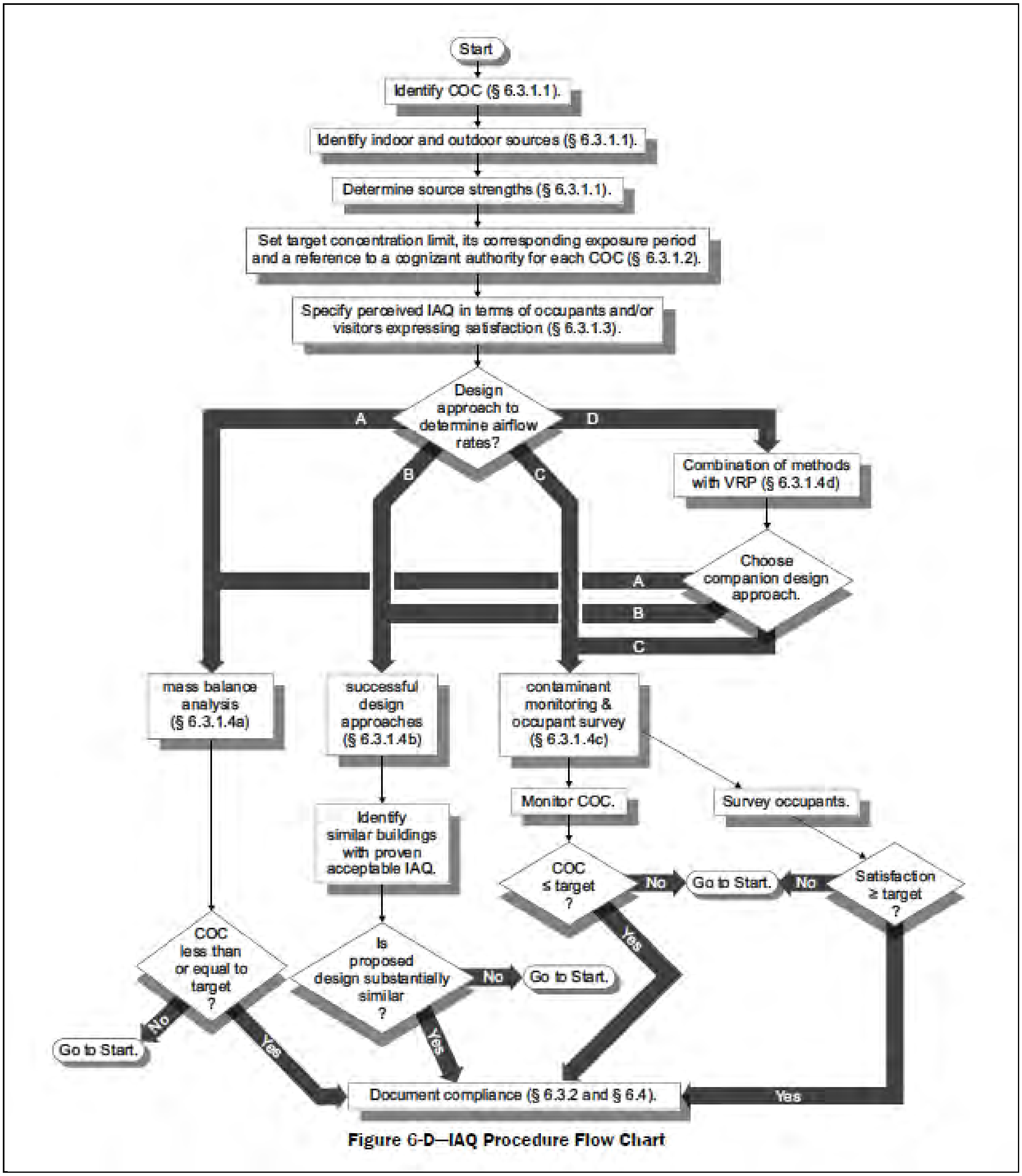


Figure 6-D—IAQ Procedure Flow Chart

Source: ASHRAE. *62.1 User's Manual, Ventilation for Acceptable Indoor Air Quality;* ANSI/ASHRAE Standard 62.1-2007; Atlanta, GA, 2007.

Figure 8. IAQ procedure flow chart.

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Appendix A. Consequences of Failure to Meet Ventilation Requirements in Combat Vehicles

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles.

Author	Date	Title	Reference Method	Procedure	Results
Allen et al., 1992	1992	*Evaluation of Ventilation Inside Armored Vehicles*	ASHRAE Standard 62-1989 Standard 62.1-2007 Standard 62-2010	Mass balance equation; airflow rate needed to maintain steady state (e.g., CO_2 , CO).	**M1A1**: ventilation system is only capable of meeting ventilator requirements of MIL-STD-1472 for ambient temperature of <90 ^{o}F with the 200 cubic feet per minute (CFM) bulk dump employed or when in motion with hatches open; over 90^{o}, M1A1 *cannot* operate under any ventilation configuration to meet increased ventilator requirements. **M1**: meets both ventilator requirements when 1500 CFM intake fan is operating. **M1A1 and M1**: adequate ventilation may be unachievable or may result from unacceptable overpressure if the leakage rate is reduced to 100 CFM at 1.5-in water gauge. **M60 and M2A2-M3A2**: capable of supplying 740 to 1480 CFM outside air to crew compartment as they have ventilation systems that easily meet the contaminant (CO)-based ventilator requirement below or above 90 ^{o}F.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Krohn and Spiegel, 1990	1990	*MANPRINT Evaluation of the High Mobility Multipurpose Wheeled Vehicle-Heavy Variant (HMMWV-HV)* Research Report 1546		Data collection included a total of 10 structured interview, checklist, and questionnaire forms.	(A)=MAXI-AMBULANCE (B)=MINI-AMBULANCE (C)=SHELTER CARRIER Problem Area (2) (AB) Accumulating dust conditions and poor door seals. Description: Large quantities of dust enter the rear of the ambulances through the ventilation system and numerous vehicle gaskets and seals (p. 6). Dust enters through ineffective seals at the rear door gaskets and the retractable stair gaskets. Dust comes in through the ventilation system when used to obtain outside fresh air. Probable Cause: The step latch hardware malfunctions when fouled with dust (p. 20). A large percentage of dust enters the vehicle through the front windows. These windows are usually kept open so operators can keep the cab temperature within acceptable comfort limits (p. 40). Problem Area (3) Description: (ABC) Heat from engine/ transmission cowling. Heat comes from the engine /transmission cowling between the driver and passenger and leads to high cab temperatures and burns crewmen's legs if the front seating position is used or cause their legs to hit the throttle control knob (p. 42).

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2004a	2004	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker- Infantry Carrier Vehicle (ICV) and Seven Configurations			d. Human factors engineering (HFE) (2) Major Problems: (a) Inadequate ventilation for operation in high ambient temperature: Data collected during the developmental test indicates that ventilation airflow is below the recommended guidelines of MIL-STD-1472F, Human Factors Engineering Design Guide for Military Systems Design Criteria Standard, while operating in ambient temperatures (outside) above 90^{o} F. Data indicates that the ventilation system will be able to provide ventilation air of 66 cam/person in the ICV instead of 200 person/person recommended by the MIL-STD-1472. Insufficient cooling and ventilation increases soldier fatigue and thus will lead to performance degradation. (All configurations except ATGM, CV, and FVS) (p. 3). (j) Breathing Toxic Fumes: With the vehicle moving, engine fumes are directed at commander, when standing in the cupola. Breathing toxic fumes could be potential health hazard which would result in cognitive decrement without having other health symptoms (p. 4). (r) Stowage of Hot Gun (for MC-B): Mortar tube gets very hot after completing a firing scenario. It is a burn hazard while preparing stowage of the tube. Also, the crew compartment gets very hot when hatches are closed, making working conditions difficult (p. 5). (v) Location of air-vent (for MEV): The air vent on the TC's side could strike the head of taller patients being elevated by the litter lift system. It may result in injury to patients (p. 6).

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2004a (continued)	2004	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker- Infantry Carrier Vehicle (ICV) and Seven Configurations			e. System Safety (2) Medium Risk Hazards: (b) High Temperature Inside the Vehicle (Heat Stress): High temperatures result from solar loads in hot climates and electronic equipment. The high temperatures cause adverse health and performance effects (e.g., performance decrement, heat cramps, heat exhaustion, and heat stroke) depending upon the level and duration of exposure. At temperatures exceeding 90 degrees Fahrenheit, the ventilation fans and recirculation fans will not be able to keep soldiers cool. The Technical Manuals contain warnings to follow the guidelines of FM 21-10 and FM 21-11 for proper precautions and preventive measures. For those variants with air conditioning (A/C) (CV and NBCRV), the probability could be lower but the severity would be the same in event of A/C failure. f. Health Hazards (1) Critical Health Hazard: Chemical substance exposures to engine/APU exhaust. Additional test data is required to assess engine/APU exhaust. An assessment of test data is currently being completed to resolve this issue. (Applies to all ICV configurations) (2) Major Health Hazards: (a) Chemical substance exposure resulting from TOW Missile motor propellant combustion products while firing from inside the MC-B, data has recently been collected at and requested form the Yuma Test Center to support an HHAR to resolve this issue. (b) Cold stress exposures during cold climate operation: A heating and air circulation system is provided but cold weather test data is requested for an updated assessment of test data to resolve this issue (applies to all ICV configurations).

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2004a (continued)	2004	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker- Infantry Carrier Vehicle (ICV) and Seven Configurations			g. Soldier Survivability (2) Major Soldier Survivability Issues: (d) Physical and Mental Fatigue: The most serious issue is the lack of cooling inside the crew compartment, which could in significant thermal stress (except for the CV). Other concerns include the potential cognitive overload (excessive duration of high intensity mental work) resulting from the use of FBCB2 on the vehicle (p. 11). 1. Inadequate ventilation for operation in high ambient temperature a. Major Problem b. Does not apply to ATGM, CV and FSV Configurations c. Operational Significance: MIL-STD-1472 guidelines require ventilation airflow of 200 CFM/person while operating in above 90^{o} F ambient. With 11 occupants, only 66cfm/person can be provided. Insufficient cooling and ventilation increases soldier fatigue and thus performance degradation. Keeping crew and squad hatches open to provide needed ventilation to prevent chronic high temperatures from causing heat stroke with hatches open will compromise crew survivability d. Recommendation: Increase amount of ventilation for the crew and squad by increasing ventilation fan capacity or better add air conditioning so performance can be maintained under high exterior temperatures as well as maintaining NBC protection. 10. Breathing Toxic Fumes a. Major Problem: With vehicle moving, engine fumes are directed at commander, when standing in the cupola. b. Operational Significance: Breathing toxic fumes could be potential health hazard which would result in cognitive decrement without having other health symptoms.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore 2004a (continued)	2004	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker- Infantry Carrier Vehicle (ICV) and Seven Configurations			c. Recommendations: The vehicle exhaust should be directed in such a manner that it will not affect open hatch operation Mortar Carrier—Version B 1. Stowage of Hot Gun a. Major Problem: Mortar tube gets very hot after completing a firing scenario and is a burn hazard and contributes to heat in the closed hatches in the crew compartment. b. Recommendation: Provide protective measures to reduce burn hazard and reduce heat transfer to the crew compartment.
Akens, 1993, 1994		Human Engineering Assessment (HEA) for the Heavy Equipment Transport System (HETS), (M1000 Semi- trailer and M1070 Truck Tractor)		For varying ambient Temperature conditions, temperatures at varying positions within HETS M1070 Cab were measured with windows open, half open, and closed.	Results indicate that when ambient temperatures exceed 90^{o} F, temperature inside HETS M1070 Cab exceeds 100^{o}F—markedly higher than recommended by MIL-STD-1472.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 1994	1994	Manpower and Personnel Integration (MANPRINT) Assessment for the M1A2 Abrams Tank		a. Purpose: Test performed at Ft. Hood, TX, to assess high temperature impact on crew positions and line replaceable units (LRU). 1) An M1A1 and M1A2 were each tested for a period of 12 h. 2) Test Conditions: Engine idle, NBC operating for the initial 5 h, LRUs operational, and ambient outside air temperature was ~96^o F.	c. Results: 1) Average temperature in M1A1 crew compartment was 102.4^o F -way above the effective temperature of 85^o F (96^o F ambient) -the maximum limit for reliable human performance 2) Average air temperature of the M1A2 crew compartment was approximately 5^o F higher than the M1A1 under similar operating conditions 3) Internal temperatures approaching 160^o F have been recorded (FM 90-3 Desert Operations) within the crew stations of a tank "buttoned up" and sitting in the sun 4) Use of microclimatic vest by an M1A2 crew during an EUTE helped with cooling but did not solve the heat problems 5) If condition is allowed to continue without providing increased cooling to the crew compartment, the crew will suffer from dehydration and performance decrements in tasks: a) Tasks which require attention to detail (map plotting, coding or decoding, target identification b) Tasks which require arm-hand steadiness (aiming, tracking, shooting) c) Tasks with sudden or sustained demands for physical or cognitive action d) Reference for 5a–5c: Environmental Medicine Support for Desert Operations, U.S. Army Research Institute of Environmental Medicine, J.D. Ramsey & S.J. Morrissey in "Isodecrement Curves for Task Performance in Hot Environments" (*Applied Ergonomics*, 1978, *9*, 66–72)

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 1994 (continued)	1994	Manpower and Personnel Integration (MANPRINT) Assessment for the M1A2 Abrams Tank			5) If condition is allowed to continue without providing increased cooling, following performance decrements are expected: (1) For cognitive tasks 60 minutes 88 degrees no performance decrement 90 minutes 88 degrees 30% performance decrement 140 minutes 88 degrees 50% performance decrement 175 minutes 88 degrees 100% performance decrement (2) For vigilance tasks 100+ degrees performance always affected 80+ degrees performance 50% of time affected. Soldiers expressed continued strong concern that no improvement had been done to resolve the heat problems identified during the EUTE and customer test. (SEE RESULTS OF THERMAL EXCURSION TEST) 1. Major concern among M1A2 crew that excessive heat in the crew stations would result in potential injuries from contact burns because of the high surface temperature of the LRUs. 2. HRED recommends that conditioned air be provided to the crew compartment to prevent human performance degradation during combat operation under high ambient temperature environment.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
McMahon, 1996	1996	MANPRINT Assessment for the Command and Control Vehicle (C2V)			System Safety (SS) and Health Hazards (HH) are rated AMBER for Emergency ventilation for Mission Module egress (fire emergency). In several instances during testing the MM quickly filled with smoke when an electronic device failed. Smoke quickly rose to the ceiling and engulfed the breathing zones of all the MM crew. The hazard is the amount of CO, CO2, and toxic byproducts from electrical installations.
Singapore, 1998	1998	Manpower and Personnel Integration (MANPRINT) Assessment for the Striker XM707 Fire Support Vehicle			It is recommended that the Striker proceed to low rate initial production, after plans are in place to resolve the critical concern for heat stress to the crew, and the major concern for the Operator's seat belt design.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 1999	1999	Manpower and Personnel Integration (MANPRINT) Assessment for the Armored Security Vehicle (ASV)			"1. Conclusions and Recommendations: Based on the individual domain assessment reports, the overall status of the ASV program with regard to MANPRINT is rated RED. It is recommended that the ASV program not proceed to the full rate production phase of the materiel acquisition cycle until plans are in place and resourced to resolve critical and high level risk hazards" that include: "(5) inadequate heating, ventilation and air-conditioning systems, (6) presence of toxic gases in the crew compartment from weapons firing and air intrusion from the engine compartment,... "2. Domain Status Reports. ... d. Health Hazards. AMBER. The Initial Health Hazard Assessment Report (IHHAR) prepared by the Center for Health Promotion and Preventive Medicine (CHPPM) has assessed ... potential (principal) health hazards. ... HAZARD RISK RAC (1) Presence of Diesel Engine Exhaust HIGH 2 and Weapon Ammo Combustion Products in the crew compartment (2) High crew compartment temperature HIGH 2 (In-efficient air conditioning System; Potential for heat stress) (3) Crew compartment temperature too low HIGH 2 (In-effective heater; potential for cold stress) (4) Insufficient ventilation air supply for crew HIGH 2 (Oxygen Deficiency) The IHHAR recommends hardware fixes for all above listed high level hazards of heating, cooling, and ventilation and leakage between crew compartment and the engine compartment."

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2001	2001	Manpower and Personnel Integration (MANPRINT) Assessment for the Bradley Fighting Vehicle Systems A3 (BFVS A3). 6 February 2001			"1. Conclusions and Recommendations. The overall status of the Bradley A3 with regard to MANPRINT is rated AMBER. Recommended that the BFVS program proceed to the full rate production phase of the materiel acquisition cycle after plans are established to resolve all MANPRINT concerns" including "heat stress and heat related performance degradation, ..." "2. Domain Status Reports. a. Human Factors Engineering (HFE) - AMBER. Heat Related Crew Performance Degradation is identified as a critical problem in the Human Factors Engineering Assessment. Data collected by ARL-HRED... indicates that at the ambient temperature of 100^o F. (Dry Bulb, operating with hull ventilation fan "On", temperatures at the driver's station, in the turret, and in the squad area would be 104.7^o (WBGT), 103.3^o (WBGT), and 98.4^o (WBGT), and with the hull fan "Off" 120.6^o (WBGT), 108^o (WBGT), and 104^o (WBGT), respectively. As ambient temperature increases, the interior temperature increases accordingly. Temperatures well above the recommended effective temperature of 85^o F. (WBGT) considered to be the maximum limit for reliable human performance while wearing standard combat clothing, and 75^o (WBGT) when the crew is in MOPP IV." b. Soldier Survivability (SSv) - AMBER. ... (4) Reduce crew mental and physical fatigue, implement heat reduction measures as soon as possible in the production program

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2001 (continued)	2001	Manpower and Personnel Integration (MANPRINT) Assessment for the Bradley Fighting Vehicle Systems A3 (BFVS A3). 6 February 2001			f. Health Hazard (HH) - AMBER. ...The HHA report identified chemical substance as a medium risk, which is controlled with a narrow margin of safety. The ventilation system on BFVS has a problem with removing combustion products from the crew spaces. The HHA also concludes that at the upper operational temperatures range the BFVS A3 will exceed the recommended threshold limits and heat casualties are likely. It is recommended that the ventilation system be improved to alleviate effect of combustion products, and to pursue a comprehensive integrated solution to the environmental control problem to reduce the potential for heat stress."
Singapore, 2007	2007	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker - Nuclear, Biological, and Chemical Reconnaissance Vehicle (NBCRV)			(2) HFE problems still unresolved: f. Health Hazards (1) Critical Health Hazard: (a) Chemical Substance: R-134a Refrigerant. The Climatic Control System (CCS) installed on the NBCRV uses R-134 refrigerant that, contrary to the Toxicity Clearance (TC) approved by the AMC Surgeon's Office can allow leaks in the crew compartment almost twice what is allowed. It is recommended that the CCS be redesigned to isolate R-134a from the crew compartment. (b) Exposure to Oxygen Deficiency (Ventilation Air). Test data indicates a total fresh air supply provided by the Over Pressure System (OPS) of approximately 60 CFM; the MIL-STD-1472 requires 20CFM/person (total of 80 CFM for a four person crew) of fresh air; especially important since the vehicle operates with all hatches closed.

Table A-1. MANPRINT/human factors reports documenting the consequences of failure to meet ventilation requirements in combat vehicles (continued).

Author	Date	Title	Reference Method	Procedure	Results
Singapore, 2008	2008	Manpower and Personnel Integration (MANPRINT) Assessment for the Stryker Mobile Gun System (MGS)			III. IDENTIFICATION--ASSESSMENT OF HFE PROBLEMS Issue 6: During the LUT crew members reported high interior vehicle temperature while operating in the buttoned-up condition. Operational Significance: There is no temperature data available for this vehicle, other similar armored vehicle evaluations had indicated that vehicle interior temperature could get approximately twenty degrees higher than the outside ambient temperature while operating buttoned-up. This rise in interior temperature will drastically reduce crew performance, in potential heat stress conditions. Recommendation: Provide environmental control system for the vehicle such that the vehicle temperature can be maintained at or below 85^{o} Wet-Bulb Globe Temperature (WBGT) in accordance with MIL-STD-1472, HFE design guidelines.
Webster et al., 2006	2006	System Assessment (SA) for the Joint Service Nuclear, Biological, and Chemical Reconnaissance System (JSLNBCRS) High Mobility Multipurpose Wheeled Vehicle (HMMWV) Variant			The JSLNBCRS HMMWV variant did not pass the High Temp requirement. The base vehicle had numerous issues, most specifically the APU and ECU failures that would make the vehicle inoperable. Recommended: Improve the APU so that it does not overheat during fording Improve the ECU reliability to operate in appropriate environmental conditions (such as high temperature, blowing sand, and rain)
Deluca et al., 2001	2001	System Evaluation Report (SER) for the Bradley Fighting Vehicle System (BFVS) - M2/M3A3			Driver's station temperatures, while still high, were reduced during IOT to approximately equal the Bradley A2 with the addition of a heat shield in the engine compartment (p. 2–5).

Appendix B. Limits for Air Contaminants

Source: The U.S. Department of Labor, Occupational Health and Safety Administration Web site. 29 CFR 1910.1000 Table Z-1 Limits for Air Contaminants. http://www.osha.gov/pls/oshaweb/owadisp.show_document?p_table=STANDARDS&p_id=9992 (accessed February 2011).

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Regulations (Standards - 29 CFR) - Table of Contents

• Part Number: 1910

• Part Title: Occupational Safety and Health Standards

• Subpart: Z

• Subpart Title: Toxic and Hazardous Substances

• Standard Number: 1910.1000 TABLE Z-1

• Title: TABLE Z-1 Limits for Air Contaminants.

TABLE Z-1 LIMITS FOR AIR CONTAMINANTS

NOTE: Because of the length of the table, explanatory Footnotes applicable to all substances are given below as well as at the end of the table. Footnotes specific only to a limited number of substances are also shown within the table.

Footnote(1) The PELs are 8-hour TWAs unless otherwise noted; a (C) designation denotes a ceiling limit. They are to be determined from breathing-zone air samples.

Footnote(a) Parts of vapor or gas per million parts of contaminated air by volume at 25 degrees C and 760 torr.

Footnote(b) Milligrams of substance per cubic meter of air. When entry is in this column only, the value is exact; when listed with a ppm entry, it is approximate.

Footnote(c) The CAS number is for information only. Enforcement is based on the substance name. For an entry covering more than one metal compound measured as the metal, the CAS number for the metal is given - not CAS numbers for the individual compounds.

Footnote(d) The final benzene standard in 1910.1028 applies to all occupational exposures to benzene except in some circumstances the distribution and sale of fuels, sealed containers and pipelines, coke production, oil and gas drilling and production, natural gas processing, and the percentage exclusion for liquid mixtures; for the excepted subsegments, the benzene limits in Table Z-2 apply. See 1910.1028 for specific circumstances.

Footnote(e) This 8-hour TWA applies to respirable dust as measured by a vertical elutriator cotton dust sampler or equivalent instrument. The time-weighted average applies to the cotton waste processing operations of waste recycling (sorting, blending, cleaning and willowing) and garnetting. See also 1910.1043 for cotton dust limits applicable to other sectors.

Footnote(f) All inert or nuisance dusts, whether mineral, inorganic, or organic, not listed specifically by substance name are covered by the Particulates Not Otherwise Regulated (PNOR) limit which is the same as the inert or nuisance dust limit of Table Z-3.

Footnote(2) See Table Z-2.

Footnote(3) See Table Z-3.

Footnote(4) Varies with compound.

Footnote(5) See Table Z-2 for the exposure limits for any operations or sectors where the exposure limits in 1910.1026 are stayed or are otherwise not in effect.

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Acetaldehyde...........	75-07-0	200	360	
Acetic acid............	64-19-7	10	25	
Acetic anhydride.......	108-24-7	5	20	
Acetone................	67-64-1	1000	2400	
Acetonitrile...........	75-05-8	40	70	
2-Acetylaminofluorene; see 1910.1014........	53-96-3			
Acetylene dichloride; see 1,2-Dichloroethylene.				
Acetylene tetrabromide.	79-27-6	1	14	
Acrolein...............	107-02-8	0.1	0.25	
Acrylamide.............	79-06-1	....	0.3	X
Acrylonitrile; see 1910.1045........	107-13-1			
Aldrin.................	309-00-2	....	0.25	X
Allyl alcohol..........	107-18-6	2	5	X
Allyl chloride.........	107-05-1	1	3	
Allyl glycidyl ether... (AGE)................	106-92-3	(C)10	(C)45	
Allyl propyl disulfide.	2179-59-1	2	12	
alpha-Alumina..........	1344-28-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Aluminum Metal (as Al).	7429-90-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
4-Aminodiphenyl; see 1910.1011........	92-67-1			
2-Aminoethanol; see Ethanolamine.....				
2-Aminopyridine........	504-29-0	0.5	2	
Ammonia................	7664-41-7	50	35	
Ammonium sulfamate.....	7773-06-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
n-Amyl acetate.........	628-63-7	100	525	
sec-Amyl acetate.......	626-38-0	125	650	
Aniline and homologs...	62-53-3	5	19	X
Anisidine (o-,p-isomers).......	29191-52-4	....	0.5	X
Antimony and compounds				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
(as Sb).............	7440-36-0	....	0.5	
ANTU (alpha Naphthylthiourea)....	86-88-4	....	0.3	
Arsenic, inorganic compounds (as As); see 1910.1018........	7440-38-2			
Arsenic, organic compounds (as As)....	7440-38-2	....	0.5	
Arsine.................	7784-42-1	0.05	0.2	
Asbestos; see 1910.1001........	(4)			
Azinphos-methyl........	86-50-0	....	0.2	X
Barium, soluble compounds (as Ba)....	7440-39-3	....	0.5	
Barium sulfate.........	7727-43-7			
Total dust...........		....	15	
Respirable fraction..		....	5	
Benomyl................	17804-35-2			
Total dust...........		....	15	
Respirable fraction..		....	5	
Benzene; See 1910.1028. See Table Z-2 for the limits applicable in the operations or sectors excluded in 1910.1028(d)	71-43-2			
Benzidine; See 1910.1010........	92-87-5			
p-Benzoquinone; see Quinone.				
Benzo(a)pyrene; see Coal tar pitch volatiles............				
Benzoyl peroxide.......	94-36-0	....	5	
Benzyl chloride........	100-44-7	1	5	
Beryllium and beryllium compounds (as Be).............	7440-41-7		(2)	
Biphenyl; see Diphenyl.				
Bismuth telluride, Undoped.............	1304-82-1			

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Total dust...........		....	15	
Respirable fraction..		....	5	
Boron oxide............	1303-86-2			
Total dust...........		....	15	
Boron trifluoride......	7637-07-2	(C)1	(C)3	
Bromine................	7726-95-6	0.1	0.7	
Bromoform..............	75-25-2	0.5	5	X
Butadiene (1,3-Butadiene); See 29 CFR 1910.1051; 29 CFR 1910.19(1)....	106-99-0	1 ppm/5 ppm STEL		
Butanethiol; see Butyl mercaptan.				
2-Butanone (Methyl ethyl ketone)	78-93-3	200	590	
2-Butoxyethanol........	111-76-2	50	240	X
n-Butyl-acetate........	123-86-4	150	710	
sec-Butyl acetate......	105-46-4	200	950	
tert-Butyl-acetate.....	540-88-5	200	950	
n-Butyl alcohol........	71-36-3	100	300	
sec-Butyl alcohol......	78-92-2	150	450	
tert-Butyl alcohol.....	75-65-0	100	300	
Butylamine.............	109-73-9	(C)5	(C)15	X
tert-Butyl chromate (as CrO(3)).......... see 1910.1026	1189-85-1			
n-Butyl glycidyl ether (BGE)................	2426-08-6	50	270	
Butyl mercaptan........	109-79-5	10	35	
p-tert-Butyltoluene....	98-51-1	10	60	
Cadmium (as Cd); see 1910.1027........	7440-43-9			
Calcium Carbonate......	1317-65-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Calcium hydroxide......	1305-62-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
Calcium oxide..........	1305-78-8	....	5	
Calcium silicate.......	1344-95-2			
Total dust...........		....	15	
Respirable fraction..		....	5	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Calcium sulfate........	7778-18-9			
Total dust...........		....	15	
Respirable fraction..		....	5	
Camphor, synthetic.....	76-22-2	....	2	
Carbaryl (Sevin).......	63-25-2	....	5	
Carbon black...........	1333-86-4	....	3.5	
Carbon dioxide.........	124-38-9	5000	9000	
Carbon disulfide.......	75-15-0		(2)	
Carbon monoxide........	630-08-0	50	55	
Carbon tetrachloride...	56-23-5		(2)	
Cellulose..............	9004-34-6			
Total dust...........		....	15	
Respirable fraction..		....	5	
Chlordane..............	57-74-9	....	0.5	X
Chlorinated camphene...	8001-35-2	....	0.5	X
Chlorinated diphenyl oxide................	55720-99-5	....	0.5	
Chlorine...............	7782-50-5	(C)1	(C)3	
Chlorine dioxide.......	10049-04-4	0.1	0.3	
Chlorine trifluoride...	7790-91-2	(C)0.1	(C)0.4	
Chloroacetaldehyde.....	107-20-0	(C)1	(C)3	
a-Chloroacetophenone (Phenacyl chloride)..	532-27-4	0.05	0.3	
Chlorobenzene..........	108-90-7	75	350	
o-Chlorobenzylidene malononitrile........	2698-41-1	0.05	0.4	
Chlorobromomethane.....	74-97-5	200	1050	
2-Chloro-1,3-butadiene; See beta-Chloroprene.				
Chlorodiphenyl (42% Chlorine)(PCB)..	53469-21-9	....	1	X
Chlorodiphenyl (54% Chlorine)(PCB)..	11097-69-1	....	0.5	X
1-Chloro-2, 3-epoxypropane; See Epichlorohydrin.				
2-Chloroethanol; See Ethylene chlorohydrin				
Chloroethylene; See Vinyl chloride.				
Chloroform (Trichloromethane)...	67-66-3	(C)50	(C)240	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
bis(Chloromethyl) ether; see 1910.1008.	542-88-1			
Chloromethyl methyl ether; see 1910.1006.	107-30-2			
1-Chloro-1-nitropropane	600-25-9	20	100	
Chloropicrin...........	76-06-2	0.1	0.7	
beta-Chloroprene.......	126-99-8	25	90	X
2-Chloro-6 (trichloromethyl) pyridine............	1929-82-4			
Total dust...........		....	15	
Respirable fraction..		....	5	
Chromic acid and chromates (as CrO(3))	(4)		(2)	
Chromium (II) compounds (as Cr).............	7440-47-3	....	0.5	
Chromium (III) compounds (as Cr)....	7440-47-3	....	0.5	
Chromium (VI) compounds See 1910.1026(5)				
Chromium metal and insol. salts (as Cr).	7440-47-3	....	1	
Chrysene; see Coal tar pitch volatiles......				
Clopidol..............	2971-90-6			
Total dust...........		....	15	
Respirable fraction..		....	5	
Coal dust (less than 5% SiO(2)), respirable fraction..			(3)	
Coal dust (greater than or equal to 5% SiO(2)), respirable fraction............			(3)	
Coal tar pitch volatiles (benzene soluble fraction), anthracene, BaP, phenanthrene, acridine, chrysene, pyrene..............	65966-93-2	....	0.2	
Cobalt metal, dust,				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
and fume (as Co).....	7440-48-4	....	0.1	
Coke oven emissions; see 1910.1029........				
Copper.................	7440-50-8			
Fume (as Cu).........		....	0.1	
Dusts and mists (as Cu)..............		....	1	
Cotton dust (e), see 1910.1043........		....	1	
Crag herbicide (Sesone)	136-78-7			
Total dust...........		....	15	
Respirable fraction..		....	5	
Cresol, all isomers....	1319-77-3	5	22	X
Crotonaldehyde.........	123-73-9 4170-30-3	2	6	
Cumene.................	98-82-8	50	245	X
Cyanides (as CN).....	(4)	....	5	X
Cyclohexane............	110-82-7	300	1050	
Cyclohexanol...........	108-93-0	50	200	
Cyclohexanone..........	108-94-1	50	200	
Cyclohexene............	110-83-8	300	1015	
Cyclopentadiene........	542-92-7	75	200	
2,4-D (Dichlorophen-oxyacetic acid)......	94-75-7	....	10	
Decaborane.............	17702-41-9	0.05	0.3	X
Demeton (Systox).......	8065-48-3	....	0.1	X
Diacetone alcohol (4-Hydroxy-4-methyl-2-pentanone).........	123-42-2	50	240	
1,2-Diaminoethane; see Ethylenediamine..				
Diazomethane...........	334-88-3	0.2	0.4	
Diborane...............	19287-45-7	0.1	0.1	
1,2-Dibromo-3-chloropropane (DBCP); see 1910.1044........	96-12-8			
1,2-Dibromoethane; see Ethylene dibromide...				
Dibutyl phosphate......	107-66-4	1	5	
Dibutyl phthalate......	84-74-2	....	5	
o-Dichlorobenzene......	95-50-1	(C)50	(C)300	
p-Dichlorobenzene......	106-46-7	75	450	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
3,3'-Dichlorobenzidine; see 1910.1007........	91-94-1			
Dichlorodifluoromethane	75-71-8	1000	4950	
1,3-Dichloro-5, 5-dimethyl hydantoin.	118-52-5	....	0.2	
Dichlorodiphenyltri- chloroethane (DDT)...	50-29-3	....	1	X
1,1-Dichloroethane.....	75-34-3	100	400	
1,2-Dichloroethane; see Ethylene dichloride..				
1,2-Dichloroethylene...	540-59-0	200	790	
Dichloroethyl ether....	111-44-4	(C)15	(C)90	X
Dichloromethane; see Methylene chloride...				
Dichloromonofluoro- methane.............	75-43-4	1000	4200	
1,1-Dichloro-1- nitroethane..........	594-72-9	(C)10	(C)60	
1,2-Dichloropropane; see Propylene dichloride.				
Dichlorotetrafluoro- ethane..............	76-14-2	1000	7000	
Dichlorvos (DDVP)......	62-73-7	....	1	X
Dicyclopentadienyl iron	102-54-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Dieldrin..............	60-57-1	....	0.25	X
Diethylamine..........	109-89-7	25	75	
2-Diethylaminoethanol..	100-37-8	10	50	X
Diethyl ether; see Ethyl ether......				
Difluorodibromomethane.	75-61-6	100	860	
Diglycidyl ether (DGE).	2238-07-5	(C)0.5	(C)2.8	
Dihydroxybenzene; see Hydroquinone.....				
Diisobutyl ketone......	108-83-8	50	290	
Diisopropylamine.......	108-18-9	5	20	X
4-Dimethylaminoazo- benzene; see 1910.1015........	60-11-7			
Dimethoxymethane;				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
see Methylal.........				
Dimethyl acetamide.....	127-19-5	10	35	X
Dimethylamine..........	124-40-3	10	18	
Dimethylaminobenzene; see Xylidine.........				
Dimethylaniline (N,N-Dimethylaniline)	121-69-7	5	25	X
Dimethylbenzene; see Xylene...........				
Dimethyl-1,2-dibromo-2, 2-dichloroethyl phosphate............	300-76-5	....	3	
Dimethylformamide......	68-12-2	10	30	X
2,6-Dimethyl-4-heptanone; see Diisobutyl ketone....				
1,1-Dimethylhydrazine..	57-14-7	0.5	1	X
Dimethylphthalate......	131-11-3	....	5	
Dimethyl sulfate.......	77-78-1	1	5	X
Dinitrobenzene (all isomers)........			1	X
(ortho).............	528-29-0			
(meta)..............	99-65-0			
(para)..............	100-25-4			
Dinitro-o-cresol.......	534-52-1	....	0.2	X
Dinitrotoluene.........	25321-14-6	....	1.5	X
Dioxane (Diethylene dioxide).	123-91-1	100	360	X
Diphenyl (Biphenyl)....	92-52-4	0.2	1	
Diphenylmethane diisocyanate; see Methylene bisphenyl isocyanate...........				
Dipropylene glycol methyl ether.........	34590-94-8	100	600	X
Di-sec octyl phthalate (Di-(2-ethylhexyl) phthalate)...........	117-81-7	....	5	
Emery..................	12415-34-8			
Total dust...........		....	15	
Respirable fraction..		....	5	
Endrin.................	72-20-8	....	0.1	X

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Epichlorohydrin........	106-89-8	5	19	X
EPN....................	2104-64-5	....	0.5	X
1,2-Epoxypropane; see Propylene oxide......				
2,3-Epoxy-1-propanol; see Glycidol.........				
Ethanethiol; see Ethyl mercaptan......				
Ethanolamine...........	141-43-5	3	6	
2-Ethoxyethanol (Cellosolve).........	110-80-5	200	740	X
2-Ethoxyethyl acetate (Cellosolve acetate).	111-15-9	100	540	X
Ethyl acetate..........	141-78-6	400	1400	
Ethyl acrylate.........	140-88-5	25	100	X
Ethyl alcohol (Ethanol)	64-17-5	1000	1900	
Ethylamine.............	75-04-7	10	18	
Ethyl amyl ketone (5-Methyl-3-heptanone)...........	541-85-5	25	130	
Ethyl benzene..........	100-41-4	100	435	
Ethyl bromide..........	74-96-4	200	890	
Ethyl butyl ketone (3-Heptanone)........	106-35-4	50	230	
Ethyl chloride.........	75-00-3	1000	2600	
Ethyl ether............	60-29-7	400	1200	
Ethyl formate..........	109-94-4	100	300	
Ethyl mercaptan........	75-08-1	(C)10	(C)25	
Ethyl silicate.........	78-10-4	100	850	
Ethylene chlorohydrin..	107-07-3	5	16	X
Ethylenediamine........	107-15-3	10	25	
Ethylene dibromide.....	106-93-4		(2)	
Ethylene dichloride (1,2-Dichloroethane).	107-06-2		(2)	
Ethylene glycol dinitrate............	628-96-6	(C)0.2	(C)1	X
Ethylene glycol methyl acetate; see Methyl cellosolve acetate...				
Ethyleneimine; see 1910.1012........	151-56-4			
Ethylene oxide;				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
see 1910.1047........	75-21-8			
Ethylidene chloride;				
see 1,1-Dichlorethane				
N-Ethylmorpholine......	100-74-3	20	94	X
Ferbam.................	14484-64-1			
Total dust...........		....	15	
Ferrovanadium dust.....	12604-58-9	....	1	
Fluorides (as F).......	(4)	....	2.5	
Fluorine...............	7782-41-4	0.1	0.2	
Fluorotrichloromethane				
(Trichloro-				
fluoromethane).......	75-69-4	1000	5600	
Formaldehyde;				
see 1910.1048........	50-00-0			
Formic acid............	64-18-6	5	9	
Furfural...............	98-01-1	5	20	X
Furfuryl alcohol.......	98-00-0	50	200	
Grain dust (oat, wheat				
barley)..............	....	....	10	
Glycerin (mist)........	56-81-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Glycidol...............	556-52-5	50	150	
Glycol monoethyl ether;				
see 2-Ethoxyethanol..				
Graphite, natural				
respirable dust......	7782-42-5		(3)	
Graphite, synthetic....				
Total dust...........		....	15	
Respirable Fraction..		....	5	
Guthion;				
see Azinphos methyl..				
Gypsum.................	13397-24-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Hafnium................	7440-58-6	....	0.5	
Heptachlor.............	76-44-8	....	0.5	X
Heptane (n-Heptane)....	142-82-5	500	2000	
Hexachloroethane.......	67-72-1	1	10	X
Hexachloronaphthalene..	1335-87-1	....	0.2	X
n-Hexane...............	110-54-3	500	1800	
2-Hexanone (Methyl				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
n-butyl ketone)......	591-78-6	100	410	
Hexone (Methyl isobutyl ketone).....	108-10-1	100	410	
sec-Hexyl acetate......	108-84-9	50	300	
Hydrazine.............	302-01-2	1	1.3	X
Hydrogen bromide.......	10035-10-6	3	10	
Hydrogen chloride......	7647-01-0	(C)5	(C)7	
Hydrogen cyanide.......	74-90-8	10	11	X
Hydrogen fluoride (as F)..............	7664-39-3		(2)	
Hydrogen peroxide......	7722-84-1	1	1.4	
Hydrogen selenide (as Se).............	7783-07-5	0.05	0.2	
Hydrogen sulfide.......	7783-06-4		(2)	
Hydroquinone...........	123-31-9	....	2	
Iodine.................	7553-56-2	(C)0.1	(C)1	
Iron oxide fume........	1309-37-1	....	10	
Isomyl acetate.........	123-92-2	100	525	
Isomyl alcohol (primary and secondary)...........	123-51-3	100	360	
Isobutyl acetate.......	110-19-0	150	700	
Isobutyl alcohol.......	78-83-1	100	300	
Isophorone.............	78-59-1	25	140	
Isopropyl acetate......	108-21-4	250	950	
Isopropyl alcohol......	67-63-0	400	980	
Isopropylamine.........	75-31-0	5	12	
Isopropyl ether........	108-20-3	500	2100	
Isopropyl glycidyl ether (IGE)..........	4016-14-2	50	240	
Kaolin.................	1332-58-7			
Total dust...........		....	15	
Respirable fraction..		....	5	
Ketene.................	463-51-4	0.5	0.9	
Lead inorganic (as Pb); see 1910.1025........	7439-92-1			
Limestone..............	1317-65-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Lindane................	58-89-9	....	0.5	X
Lithium hydride........	7580-67-8	....	0.025	
L.P.G. (Liquified				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
petroleum gas).......	68476-85-7	1000	1800	
Magnesite..............	546-93-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
Magnesium oxide fume...	1309-48-4			
Total Particulate....		....	15	
Malathion..............	121-75-5			
Total dust...........		....	15	X
Maleic anhydride.......	108-31-6	0.25	1	
Manganese compounds (as Mn)..............	7439-96-5	....	(C)5	
Manganese fume (as Mn).	7439-96-5	....	(C)5	
Marble.................	1317-65-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Mercury (aryl and inorganic)(as Hg)....	7439-97-6		(2)	
Mercury (organo) alkyl compounds (as Hg)....	7439-97-6		(2)	
Mercury (vapor) (as Hg)	7439-97-6		(2)	
Mesityl oxide..........	141-79-7	25	100	
Methanethiol; see Methyl mercaptan.				
Methoxychlor...........	72-43-5			
Total dust...........		....	15	
2-Methoxyethanol; (Methyl cellosolve)..	109-86-4	25	80	X
2-Methoxyethyl acetate (Methyl cellosolve acetate).............	110-49-6	25	120	X
Methyl acetate.........	79-20-9	200	610	
Methyl acetylene (Propyne)............	74-99-7	1000	1650	
Methyl acetylene propadiene mixture (MAPP)...............		1000	1800	
Methyl acrylate........	96-33-3	10	35	X
Methylal (Dimethoxy-methane)..	109-87-5	1000	3100	
Methyl alcohol.........	67-56-1	200	260	
Methylamine............	74-89-5	10	12	
Methyl amyl alcohol;				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
see Methyl Isobutyl carbinol............				
Methyl n-amyl ketone...	110-43-0	100	465	
Methyl bromide.........	74-83-9	(C)20	(C)80	X
Methyl butyl ketone; see 2-Hexanone.......				
Methyl cellosolve; see 2-Methoxyethanol.				
Methyl cellosolve acetate; see 2-Methoxyethyl acetate..............				
Methyl chloride........	74-87-3		(2)	
Methyl chloroform (1,1,1-Trichloro-ethane).............	71-55-6	350	1900	
Methylcyclohexane......	108-87-2	500	2000	
Methylcyclohexanol.....	25639-42-3	100	470	
o-Methylcyclohexanone..	583-60-8	100	460	X
Methylene chloride.....	75-09-2		(2)	
Methyl ethyl ketone (MEK); see 2-Butanone				
Methyl formate.........	107-31-3	100	250	
Methyl hydrazine (Monomethyl hydrazine)...........	60-34-4	(C)0.2	(C)0.35	X
Methyl iodide..........	74-88-4	5	28	X
Methyl isoamyl ketone..	110-12-3	100	475	
Methyl isobutyl carbinol............	108-11-2	25	100	X
Methyl isobutyl ketone; see Hexone...........				
Methyl isocyanate......	624-83-9	0.02	0.05	X
Methyl mercaptan.......	74-93-1	(C)10	(C)20	
Methyl methacrylate....	80-62-6	100	410	
Methyl propyl ketone; see 2-Pentanone......				
alpha-Methyl styrene...	98-83-9	(C)100	(C)480	
Methylene bisphenyl isocyanate (MDI).....	101-68-8	(C)0.02	(C)0.2	
Mica; see Silicates....				
Molybdenum (as Mo).....	7439-98-7			

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Soluble compounds....		....	5	
Insoluble Compounds				
Total dust.........		....	15	
Monomethyl aniline.....	100-61-8	2	9	X
Monomethyl hydrazine;				
see Methyl hydrazine.				
Morpholine............	110-91-8	20	70	X
Naphtha (Coal tar).....	8030-30-6	100	400	
Naphthalene...........	91-20-3	10	50	
alpha-Naphthylamine;				
see 1910.1004........	134-32-7			
beta-Naphthylamine;				
see 1910.1009........	91-59-8			
Nickel carbonyl (as Ni)	13463-39-3	0.001	0.007	
Nickel, metal and				
insoluble compounds				
(as Ni).............	7440-02-0	....	1	
Nickel, soluble				
compounds (as Ni)....	7440-02-0	....	1	
Nicotine..............	54-11-5	....	0.5	X
Nitric acid...........	7697-37-2	2	5	
Nitric oxide..........	10102-43-9	25	30	
p-Nitroaniline.........	100-01-6	1	6	X
Nitrobenzene..........	98-95-3	1	5	X
p-Nitrochlorobenzene...	100-00-5	....	1	X
4-Nitrodiphenyl;				
see 1910.1003........	92-93-3			
Nitroethane...........	79-24-3	100	310	
Nitrogen dioxide.......	10102-44-0	(C)5	(C)9	
Nitrogen trifluoride...	7783-54-2	10	29	
Nitroglycerin..........	55-63-0	(C)0.2	(C)2	X
Nitromethane..........	75-52-5	100	250	
1-Nitropropane.........	108-03-2	25	90	
2-Nitropropane.........	79-46-9	25	90	
N-Nitrosodimethylamine;				
see 1910.1016				
Nitrotoluene				
(all isomers)........		5	30	X
o-isomer............	88-72-2			
m-isomer............	99-08-1			
p-isomer............	99-99-0			
Nitrotrichloromethane;				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
see Chloropicrin.....				
Octachloronaphthalene..	2234-13-1	....	0.1	X
Octane................	111-65-9	500	2350	
Oil mist, mineral......	8012-95-1	....	5	
Osmium tetroxide (as Os).............	20816-12-0	....	0.002	
Oxalic acid...........	144-62-7	....	1	
Oxygen difluoride......	7783-41-7	0.05	0.1	
Ozone.................	10028-15-6	0.1	0.2	
Paraquat, respirable dust................	4685-14-7 1910-42-5 2074-50-2	....	0.5	X
Parathion.............	56-38-2	....	0.1	X
Particulates not otherwise regulated (PNOR)(f)...........				
Total dust...........		....	15	
Respirable fraction..		....	5	
PCB; see Chlorodiphenyl (42% and 54% chlorine)...........				
Pentaborane...........	19624-22-7	0.005	0.01	
Pentachloronaphthalene.	1321-64-8	....	0.5	X
Pentachlorophenol......	87-86-5	....	0.5	X
Pentaerythritol........	115-77-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Pentane...............	109-66-0	1000	2950	
2-Pentanone (Methyl propyl ketone).......	107-87-9	200	700	
Perchloroethylene (Tetrachloroethylene)	127-18-4		(2)	
Perchloromethyl mercaptan............	594-42-3	0.1	0.8	
Perchloryl fluoride....	7616-94-6	3	13.5	
Petroleum distillates (Naphtha)(Rubber Solvent)............		500	2000	
Phenol................	108-95-2	5	19	X
p-Phenylene diamine....	106-50-3	....	0.1	X
Phenyl ether, vapor....	101-84-8	1	7	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Phenyl ether-biphenyl mixture, vapor.......		1	7	
Phenylethylene; see Styrene..........				
Phenyl glycidyl ether (PGE)................	122-60-1	10	60	
Phenylhydrazine........	100-63-0	5	22	X
Phosdrin (Mevinphos)...	7786-34-7	....	0.1	X
Phosgene (Carbonyl chloride)...........	75-44-5	0.1	0.4	
Phosphine.............	7803-51-2	0.3	0.4	
Phosphoric acid........	7664-38-2	....	1	
Phosphorus (yellow)....	7723-14-0	....	0.1	
Phosphorus pentachloride........	10026-13-8	....	1	
Phosphorus pentasulfide	1314-80-3	....	1	
Phosphorus trichloride.	7719-12-2	0.5	3	
Phthalic anhydride.....	85-44-9	2	12	
Picloram...............	1918-02-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Picric acid...........	88-89-1	....	0.1	X
Pindone (2-Pivalyl-1, 3-indandione)........	83-26-1	....	0.1	
Plaster of paris.......	26499-65-0			
Total dust...........		....	15	
Respirable fraction..		....	5	
Platinum (as Pt).......	7440-06-4			
Metal................		....	....	
Soluble Salts........		....	0.002	
Portland cement........	65997-15-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Propane................	74-98-6	1000	1800	
beta-Propriolactone; see 1910.1013........	57-57-8			
n-Propyl acetate.......	109-60-4	200	840	
n-Propyl alcohol.......	71-23-8	200	500	
n-Propyl nitrate.......	627-13-4	25	110	
Propylene dichloride...	78-87-5	75	350	
Propylene imine........	75-55-8	2	5	X
Propylene oxide........	75-56-9	100	240	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Propyne; see Methyl acetylene				
Pyrethrum	8003-34-7	....	5	
Pyridine	110-86-1	5	15	
Quinone	106-51-4	0.1	0.4	
RDX: see Cyclonite				
Rhodium (as Rh), metal fume and insoluble compounds	7440-16-6	....	0.1	
Rhodium (as Rh), soluble compounds	7440-16-6	....	0.001	
Ronnel	299-84-3	....	15	
Rotenone	83-79-4	....	5	
Rouge				
Total dust		....	15	
Respirable fraction		....	5	
Selenium compounds (as Se)	7782-49-2	....	0.2	
Selenium hexafluoride (as Se)	7783-79-1	0.05	0.4	
Silica, amorphous, precipitated and gel	112926-00-8		(3)	
Silica, amorphous, diatomaceous earth, containing less than 1% crystalline silica	61790-53-2		(3)	
Silica, crystalline cristobalite, respirable dust	14464-46-1		(3)	
Silica, crystalline quartz, respirable dust	14808-60-7		(3)	
Silica, crystalline tripoli (as quartz), respirable dust	1317-95-9		(3)	
Silica, crystalline tridymite, respirable dust	15468-32-3		(3)	
Silica, fused, respirable dust	60676-86-0		(3)	
Silicates (less than 1% crystalline silica)				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Mica (respirable dust)................	12001-26-2		(3)	
Soapstone, total dust	....		(3)	
Soapstone, respirable dust.................	....		(3)	
Talc (containing asbestos): use asbestos limit: see 29 CFR 1910.1001.....			(3)	
Talc (containing no asbestos), respirable dust......	14807-96-6		(3)	
Tremolite, asbestiform; see 1910.1001...........				
Silicon................	7440-21-3			
Total dust...........		....	15	
Respirable fraction..		....	5	
Silicon carbide........	409-21-2			
Total dust...........		....	15	
Respirable fraction..		....	5	
Silver, metal and soluble compounds (as Ag).............	7440-22-4	....	0.01	
Soapstone; see Silicates........				
Sodium fluoroacetate...	62-74-8	....	0.05	X
Sodium hydroxide.......	1310-73-2	....	2	
Starch.................	9005-25-8			
Total dust...........		....	15	
Respirable fraction..		....	5	
Stibine................	7803-52-3	0.1	0.5	
Stoddard solvent.......	8052-41-3	500	2900	
Strychnine.............	57-24-9	....	0.15	
Styrene................	100-42-5		(2)	
Sucrose................	57-50-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Sulfur dioxide.........	7446-09-5	5	13	
Sulfur hexafluoride....	2551-62-4	1000	6000	
Sulfuric acid..........	7664-93-9	....	1	
Sulfur monochloride....	10025-67-9	1	6	

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
Sulfur pentafluoride...	5714-22-7	0.025	0.25	
Sulfuryl fluoride......	2699-79-8	5	20	
Systox; see Demeton...				
2,4,5-T (2,4,5-tri- chlorophenoxyacetic acid)...............	93-76-5	....	10	
Talc; see Silicates...				
Tantalum, metal and oxide dust...........	7440-25-7	....	5	
TEDP (Sulfotep)........	3689-24-5	....	0.2	X
Tellurium and compounds (as Te)....	13494-80-9	....	0.1	
Tellurium hexafluoride (as Te).............	7783-80-4	0.02	0.2	
Temephos...............	3383-96-8			
Total dust...........		....	15	
Respirable fraction..		....	5	
TEPP (Tetraethyl pyrophosphaate)......	107-49-3	....	0.05	X
Terphenylis...........	26140-60-3	(C)1	(C)9	
1,1,1,2-Tetrachloro-2, 2-difluoroethane.....	76-11-9	500	4170	
1,1,2,2-Tetrachloro-1, 2-difluoroethane.....	76-12-0	500	4170	
1,1,2,2-Tetrachloro- ethane..............	79-34-5	5	35	X
Tetrachoroethylene; see Perchloroethylene				
Tetrachloromethane; see Carbon tetrachloride.				
Tetrachloronaphthalene.	1335-88-2	....	2	X
Tetraethyl lead (as Pb)	78-00-2	....	0.075	X
Tetrahydrofuran........	109-99-9	200	590	
Tetramethyl lead, (as Pb).............	75-74-1	....	0.075	X
Tetramethyl succinonitrile.......	3333-52-6	0.5	3	X
Tetranitromethane......	509-14-8	1	8	
Tetryl (2,4,6-Trinitro- phenylmethyl- nitramine)...........	479-45-8	....	1.5	X
Thallium, soluble				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
compounds (as Tl)....	7440-28-0	....	0.1	X
4,4'-Thiobis(6-tert,				
Butyl-m-cresol)......	96-69-5			
Total dust...........		....	15	
Respirable fraction..		....	5	
Thiram.................	137-26-8	....	5	
Tin, inorganic				
compounds (except				
oxides) (as Sn)......	7440-31-5	....	2	
Tin, organic compounds				
(as Sn)..............	7440-31-5	....	0.1	
Titanium dioxide.......	13463-67-7			
Total dust...........		....	15	
Toluene................	108-88-3		(2)	
Toluene-2,				
4-diisocyanate (TDI).	584-84-9	(C)0.02	(C)0.14	
o-Toluidine............	95-53-4	5	22	X
Toxaphene; see				
Chlorinated camphene.				
Tremolite;				
see Silicates........				
Tributyl phosphate.....	126-73-8	....	5	
1,1,1-Trichloroethane;				
see Methyl chloroform				
1,1,2-Trichloroethane..	79-00-5	10	45	X
Trichloroethylene......	79-01-6		(2)	
Trichloromethane;				
see Chloroform				
Trichloronaphthalene...	1321-65-9	....	5	X
1,2,3-Trichloropropane.	96-18-4	50	300	
1,1,2-Trichloro-1,2,				
2-trifluoroethane....	76-13-1	1000	7600	
Triethylamine..........	121-44-8	25	100	
Trifluorobromomethane..	75-63-8	1000	6100	
2,4,6-Trinitrophenol;				
see Picric acid......				
2,4,6-Trinitrophenyl-				
methyl nitramine;				
see Tetryl...........				
2,4,6-Trinitrotoluene				
(TNT)................	118-96-7	....	1.5	X
Triorthocresyl				

TABLE Z-1. - LIMITS FOR AIR CONTAMINANTS (continued)

Substance	CAS No. (c)	ppm (a)(1)	mg/m(3) (b)(1)	Skin designation
phosphate............	78-30-8	....	0.1	
Triphenyl phosphate....	115-86-6	....	3	
Turpentine.............	8006-64-2	100	560	
Uranium (as U).........	7440-61-1			
Soluble compounds....		....	0.05	
Insoluble compounds..		....	0.25	
Vanadium...............	1314-62-1			
Respirable dust (as V2O5))...........		....	(C)0.5	
Fume (as V2O5).......		....	(C)0.1	
Vegetable oil mist.....				
Total dust...........		....	15	
Respirable fraction..		....	5	
Vinyl benzene; see Styrene..........				
Vinyl chloride; see 1910.1017........	75-01-4			
Vinyl cyanide; see Acrylonitrile				
Vinyl toluene..........	25013-15-4	100	480	
Warfarin...............	81-81-2	....	0.1	
Xylenes (o-, m-, p-isomers)..	1330-20-7	100	435	
Xylidine...............	1300-73-8	5	25	X
Yttrium................	7440-65-5	....	1	
Zinc chloride fume.....	7646-85-7	....	1	
Zinc oxide fume........	1314-13-2	....	5	
Zinc oxide.............	1314-13-2			
Total dust...........		....	15	
Respirable fraction..		....	5	
Zinc stearate..........	557-05-1			
Total dust...........		....	15	
Respirable fraction..		....	5	
Zirconium compounds (as Zr).............	7440-67-7	....	5	

* Footnote(1) The PELs are 8-hour TWAs unless otherwise noted; a (C) designation denotes a ceiling limit. They are to be determined from breathing-zone air samples.

Footnote(a) Parts of vapor or gas per million parts of contaminated air by volume at 25 degrees C and 760 torr.

Footnote(b) Milligrams of substance per cubic meter of air. When entry is in this column only, the value is exact; when listed with a ppm entry, it is approximate.

Footnote(c) The CAS number is for information only. Enforcement is based on the substance name. For an entry covering more than one metal compound measured as the metal, the CAS number for the metal is given - not CAS numbers for the individual compounds.

Footnote(d) The final benzene standard in 1910.1028 applies to all occupational exposures to benzene except in some circumstances the distribution and sale of fuels, sealed containers and pipelines, coke production, oil and gas drilling and production, natural gas processing, and the percentage exclusion for liquid mixtures; for the excepted subsegments, the benzene limits in Table Z-2 apply. See 1910.1028 for specific circumstances.

Footnote(e) This 8-hour TWA applies to respirable dust as measured by a vertical elutriator cotton dust sampler or equivalent instrument. The time-weighted average applies to the cotton waste processing operations of waste recycling (sorting, blending, cleaning and willowing) and garnetting. See also 1910.1043 for cotton dust limits applicable to other sectors.

Footnote(f) All inert or nuisance dusts, whether mineral, inorganic, or organic, not listed specifically by substance name are covered by the Particulates Not Otherwise Regulated (PNOR) limit which is the same as the inert or nuisance dust limit of Table Z-3.

Footnote(2) See Table Z-2.

Footnote(3) See Table Z-3

Footnote(4) Varies with compound.

Footnote(5) See Table Z-2 for the exposure limits for any operations or sectors where the exposure limits in 1910.1026 are stayed or are otherwise not in effect.

[54 FR 36767, Sept. 5, 1989; 54 FR 41244, Oct. 6, 1989; 55 FR 3724, Feb. 5, 1990; 55 FR 12819, Apr 6, 1990; 55 FR 19259, May 9, 1990; 55 FR 46950, Nov. 8, 1990; 57 FR 29204, July 1, 1992; 57 FR 42388, Sept. 14, 1992; 58 FR 35340, June 30, 1993; 61 FR 56746, Nov. 4, 1996; 62 FR 42018, August 4, 1997; 71 FR 10373, Feb. 28, 2006]

Appendix C. Example Calculation of the Indoor Air Quality Procedure

Source: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. (ASHRAE). *62.1 User's Manual, Ventilation for Acceptable Indoor Air Quality*; ANSI/ASHRAE Standard 62.1-2007; Atlanta, GA, 2007.

Example 6-AB—IAQ Procedure, Single Zone System

Q

Can you provide an example of how the IAQ Procedure can be applied to a single zone space such as a lecture hall?

A

The IAQ Procedure may be a good choice for this application given the following set of design considerations: new construction, a desired outdoor air intake rate of 5 cfm/person, perceived IAQ acceptability of 80% of occupants, an air handler with constant outdoor and supply airflows, a filter (air cleaner) location in the supply (mixed) airstream (location B in Figure D.1 in the Standard), and a supply airflow of 20,000 cfm.* The following table shows specific zone summary information.

Area	Volume	No. Of People	Supply Air, Cooling and Heating	Supply Location	Return Location	Zone Air Distribution Effectiveness†
12,790 ft^2	260,000 ft^3	600	20,000 cfm	ceiling	ceiling	0.8

Given these design criteria, the outdoor air intake flow (V_{ot}) required under § 6.2.3 of the VRP would be 6,584 cfm. This compares to 3,000 cfm using the IAQ Procedure.

For this example, the contaminants of concern in the outdoor air were carbon monoxide, nitrogen dioxide, ozone, and sulfur dioxide. Concentration values to be used for the mass balance analysis are shown below.

2nd Max 8-hr Value for CO	NO_2 Annual Mean Value	4th Max 8-hr Value for O_3	SO_2 Annual Mean Value
2.2 ppm	0.014 ppm	0.084 ppm	0.002 ppm

For indoor contaminants, both the contaminants of concern must be chosen as well as the generation rates of these contaminants from occupants, materials, and processes. Acetone, ammonia, hydrogen sulfide, methyl alcohol, and phenol were chosen to be indicators of human activities. The contaminants from building materials and processes were selected to be formaldehyde and total volatile organic compounds (TVOC). Each of these contaminants chosen are representative compounds in indoor and outdoor air and there is much data in the public domain from which concentrations and generation rates could be obtained (see references below). TVOC was chosen due to the fact that many of the published building studies include this as an air quality indicator—sometimes as the sole indicator of air quality.‡ For this application, no particulate contaminants of concern were chosen.

GENERATION RATES OF BIOEFFLUENTS FROM OCCUPANTS (Wang, 1975)
& OUTDOOR AIR CONCENTRATIONS (ASTDR, 1990, 1994, 1998, 1999)

Contaminant	Generation Rate, in mg/(min*person)	Concentration in Outdoor Air
Acetone	0.0352	0.007 ppm
Ammonia	0.0224	0.005 ppm
Hydrogen Sulfide	0.0019	0.00033 ppm
Methyl Alcohol	0.0517	negligible
Phenol	0.0066	0.000091 ppm

** The choice of the outdoor air intake rates to use with the IAQ Procedure can be based on a simple reduction of those prescribed by the VRP (i.e., 25%, 50%, 75%, etc.); based on some fixed value necessary to recover exhaust air volumes and maintain pressure differentials in the space (building); or based on economic considerations due to estimated HVAC system capital and/or operational savings possible by a reduction in heating and cooling requirements.*

† Referred to as "Air Change Effectiveness" in Appendix D of the Standard.

‡ For this example, the COC were chosen using the best available information and based upon agreement between the HVAC system designer, the building owner/operator, and the authority having jurisdiction. This could include published building studies and general IAQ studies, review of IAQ standards and guidelines, etc.

GENERATION RATES FROM BUILDING MATERIALS AND PROCESS (Offerman, 1993) & OUTDOOR AIR CONCENTRATIONS (Brightman, 1995; Girman, 1995; Womble, 1995)

Contaminant	Net Emission Rates (ug/m^3-h)	Concentration in Outdoor Air
TVOC (as carbon)	303	0.0685 mg/m^3
Formaldehyde	21	0.0068 mg/m^3

STANDARDS AND GUIDELINES FOR COMMON INDOOR AIR CONTAMINANTS
Target levels used in this example are shown in italics.

Compound	MW	ppm	mg/m^3	Time	Description
Acetone	58.08	*2.95*	*7*	*24 hrs*	*Newill, 1977*
		62	147	Immediate	Threshold-ED$_{50}$ (ASHRAE, 2001)
		500	1188	8 hrs	TLV-TWA (ACGIH, 2003)
		2.40	5.9	1 hr	Alberta Environment, 2004
Ammonia	17.03	*0.72*	*0.5*	*Yr*	*VDI, 1974*
		17	11.8	Immediate	Threshold-ED$_{50}$ (ASHRAE, 2001)
		25	17	8 hrs	TLV-TWA (ACGIH, 2003)
		2.0	1.4	1 hr	Alberta Environment, 2004
Carbon Monoxide	28.01	*9*	*10*	*8 hrs*	*NAAQS (EPA, 2003)*
		9	*10*	*8 hrs*	*ASHRAE 62 (ASHRAE, 1981)*
		25	29	8 hrs	TLV-TWA (ACGIH, 2003)
Formaldehyde	30.03	0.1	0.12	long term	Canadian Exposure Guidelines (ASHRAE, 2003)
		0.3	0.4	Ceiling	TLV-TWA (ACGIH, 2003)
		0.75	0.92	8 hrs	PEL-TWA (OSHA, 2002)
		0.027	*0.033*	*8 hrs*	*Cal-EPA, OEHHA, 1999*
Hydrogen sulfide	34.08	*0.03*	*0.042*	*24 hrs*	*CARB, 2003*
		10	14	8 hrs	TLV-TWA (ACGIH, 2003)
Methyl alcohol	32.04	*1.14*	*1.5*	*24 hrs*	*Newill, 1977*
		2.0	2.6	1 hr	Alberta Environment, 2004
		160	209	Immediate	Threshold-ED$_{50}$ (ASHRAE, 2001)
		200	262	8 hrs	TLV-TWA (ACGIH, 2003)
Nitrogen Dioxide	46.01	*0.053*	*0.1*	*Yr*	*NAAQS (EPA, 2003)*
		3	6	8 hrs	TLV-TWA (ACGIH, 2003)
Ozone	48	*0.080*	*0.157*	*8 hrs*	*NAAQS (EPA, 2003)*
		0.120	0.235	1 hr	ASHRAE 62 (ASHRAE, 2001)
		0.2	0.39	<2 hrs	TLV-TWA (ACGIH, 2003)
Phenol	94.01	*0.03*	*0.1*	*24 hrs*	*Newill, 1977*
		0.025	0.10	1 hr	Alberta Environment, 2004
		0.06	0.231	Immediate	Threshold-ED$_{50}$ (ASHRAE, 2001)
		5	19	8 hrs	TLV-TWA (ACGIH, 2003)
Sulfur Dioxide	64.07	*0.03*	*0.08*	*Yr*	*NAAQS (EPA, 2003)*
		2	5	8 hrs	TLV-TWA (ACGIH, 2003)
		2.7	7.07	Immediate	Threshold-ED$_{50}$ (ASHRAE, 2001)
TVOC	100	*0.24*	*1.0*	–	*Target Level (Tucker, 1988)*
		0.32	0.05–1.30	–	Nordic Standard (Etkin, 1996)
		0.73	3	–	Discomfort Range (Etkin, 1996)
		1.22	5	Immediate	Action Level (EPA, 1989)

The following mass-balance equation (from Appendix D of the Standard) determines the space contaminant (C_s) concentration for this particular system configuration. Using the information for formaldehyde as an example, the calculations are as follows.

$$C_s = \frac{N + eV_o(1 - E_f)C_o}{e(V_o + RV_r E_f)}$$

where:

N = generation rate of formaldehyde = $V * [0.021\ mg/(m^3 * hr)^{**}]$
[V=260,000 ft^3 (7,362 m^3)]
= (7,362 m^3)(0.021 mg/[m^3 * hr])
= 154.6 mg/hr

e = air change effectiveness = 0.8

V_o = volumetric flow of outdoor air = 3,000 cfm (5,097 m^3/hr)

E_f = air cleaning efficiency = 0.25 ††

C_o = concentration of formaldehyde in outdoor air = 0.0068 mg/m^3

RV_r = volumetric flow of recirculated air = 17,000 cfm (28,883 m^3/hr)

C_s = space concentration of formaldehyde = 0.0178 mg/m^3

Target concentration limit for formaldehyde = 0.033 mg/m^3 (see STANDARDS AND GUIDELINES)

% Target= [(C_S / Target)](100%)
= [(0.0178 mg/m^3) / (0.033 mg/m^3)]×(100%)
= 53.9%

This confirms that outdoor air intake rate of 5 cfm/person is sufficient to provide a space concentration of formaldehyde that would be below the established target concentration limit. The results of repeating this calculation for the mass balance analysis for all of the contaminants of concern used in this example are shown in the following table.

SPACE (ZONE) CONTAMINANT CONCENTRATION RESULTS FOR ALL CONTAMINANTS OF CONCERN

Contaminant	Units	Concentration Value	Target Concentration Limit	% Target
Acetone	[mg/m³]	0.134	7	2%
Ammonia	[mg/m³]	0.202	0.5	40%
Carbon monoxide	[ppm]	2.2	9	24%
Formaldehyde	[mg/m³]	0.0178	0.12	15%
Hydrogen sulfide	[mg/m³]	0.00708	0.04	18%
Methyl alcohol	[mg/m³]	0.189	1.5	13%
Nitrogen dioxide	[ppm]	0.00434	0.053	8%
Ozone	[ppm]	0.0261	0.08	33%
Phenol	[mg/m³]	0.0242	0.1	24%
Sulfur dioxide	[ppm]	0.000621	0.03	2%

For all of the contaminants used in this example, using an outdoor air intake rate of 5 cfm/person will provide a C_s value of 55% or less of the COC target concentration limits shown above. This model will therefore comply with the requirements of the IAQ Procedure.

** Offerman, F.J. et al. *"Indoor Emission Rates Before and After a Building Bake-Out."* Operating and Maintaining Buildings for Health, Comfort, and Productivity *Proceedings IAQ 94. (Philadelphia: ASHRAE Nov. 1993): 157-163.*

†† This is a conservative estimate of filter efficiency based on manufacturer's test data as well as data from NIST studies. Howard-Reed, C., et al, "Measurement and Simulation of the Indoor Air Quality Impact of Gaseous Air Cleaners in a Test House" Indoor Air *(July, 2002) Proceedings: 9th International Conference on Indoor Air Quality and Climate (Monterey, CA). Howard-Reed, C., et al, "Predicting the Performance of Gaseous Air Cleaners: Measurements and Model Simulations from a Residential-Scale Pilot Study" NISTIR 7114 (NIST 2004). The air cleaning efficiency (E_f) will most likely be different for each COC and in fact may require more than one type of filter or filter medium for best effectiveness. Because of this, it might be advisable to use a conservative value for E_f based on the lowest reported efficiency for each of the COC. Documentation as to the method(s) used to determine air cleaning efficiencies and the E_f for each individual COC should be available for review by all parties.*

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