ESTIMATION OF CARBON MONOXIDE EXPOSURES AND ASSOCIATED CARBOXYHEMOGLOBIN LEVELS IN DENVER RESIDENTS USING pNEM/CO (VERSION 2.0)

by

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Work Assignment No. 1-19 and 2-24

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March 15, 1999 (Draft)

DISCLAIMER

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ACKNOWLEDGMENTS

In 1992, the U.S. Environmental Protection Agency (EPA) funded the development of a probabilistic version of NEM applicable to carbon monoxide (pNEM/CO). This report describes an updated version of pNEM/CO developed in 1998 (hereafter referred to as Version 2.0) through the efforts of the ICF Kaiser Consulting Group (ICF), IT Air Quality Services (ITAQS), TRJ Environmental, Inc. (TRJ), and Jim Capel. This report also presents the results of applying the updated model to residents of Denver, Colorado.

The updated version of pNEM/CO consists of three principal parts: a main program which estimates carbon monoxide (CO) exposures within a defined population, a special module which estimates the carboxyhemoglobin (COHb) levels which result from these exposures, and a program which tabulates the exposure and COHb estimates. Supplementary programs are used to process air quality and population data for input into the main program.

Mr. Ted Johnson of TRJ was the principal author of this report. He developed the general pNEM/CO methodology described in Section 2 and many of the specific algorithms used to simulate various exposure factors within the model. Mr. Gary Mihlan of TRJ processed commuting data provided by ICF to create the origin-destination table for Denver. Ms. Jacky LaPointe and Ms. Kristen Fletcher reviewed the scientific literature on selected indoor sources of CO and provided recommendations for modifying pNEM/CO to account for these sources.

Mr. Jim Capel wrote the main pNEM/CO program, the COHb module, and the majority of supplementary programs. He also converted the Comprehensive Human Activity Database (CHAD) into an input database suitable for use with pNEM/CO. In addition, he set up all input data files and run streams required for application of pNEM/CO to Denver, ran the model, and tabulated the results.

Mr. Dib Paul served as the project manager for ITAQS. He also performed a literature review to identify data useful in implementing the ventilation rate algorithm. Mr. Andy Law of ITAQS was coauthor of Section 3 and developed input data for the mass-balance and gas-stove models described in that section. Mr. Sri Pangaluri of

ITAQS assisted Mr. Jim Capel in converting the CHAD database into an input database suitable for pNEM/CO.

Ms. Arlene Rosenbaum served as the project manager for ICF. Ms. Pat Stiefer of ICF prepared the census and commuting data files for Denver. Dr. Jonathan Cohen, Mr. Sergey Nikiforov, and Ms. Rosenbaum performed the statistical comparison of exertion levels for persons with and without heart disease described in Section 5.6.

The COHb module is based on algorithms developed by Dr. William F. Biller for the 1992 version of pNEM/CO under an earlier contract with EPA's Office of Air Quality Planning and Standards. Dr. Biller also developed the hourly average version of the mass balance model in the 1992 version of pNEM/CO which continues to be used in the current version. Mr. Harvey Richmond of EPA assisted in developing the COHb algorithm and in characterizing the distributions of many of the variables contained in the COHb algorithm.

The method for estimating ventilation (inhalation) rates described in Section 5 was developed by Mr. Ted Johnson, Dr. Gary Mihlan, Ms. Jill Mozier, and Mr. Mark Weaver of TRJ. The method is based on an approach suggested by Mr. Tom McCurdy of EPA's Office of Research and Development. Mr. McCurdy also provided estimates for various parameters used in implementing the method. The CHAD database was created jointly by Mr. McCurdy and by Mr. Yeshpal Lakkadi, Mr. Graham Glen, Mr. Luther Smith, Ms. Jo Ann Tippett, and Ms. Maria del Valle-Torres of ManTech Environmental Technology, Inc. The clinical data used to determine the relationship between ventilation rate and oxygen uptake rate were provided by Dr. William Adams through EPA Delivery Order No. 8D-0810-NAEX to the Regents of the University of California. Dr. Jonathan Cohen of ICF performed the statistical analyses of the Adams data which produced the parameter estimates listed in Table 5-1.

The authors gratefully acknowledge the assistance of Dr. Irving Billick and the Gas Research Institute, who provided references and reports containing useful information on gas stove emission rates and operating conditions.

The development of Version 2.0 of pNEM/CO and its application to Denver were funded by EPA under Contract Nos. 68-D3-0094 and 68-D6-0064. Mr. Harvey Richmond of EPA's Health and Ecosystem Effects Group was the EPA Work Assignment Manager for all work assignments associated with this effort. Mr.

Richmond also developed the prevalence estimates for ischemic heart disease presented in Section 2.5.2.

SECTION 1
INTRODUCTION

In 1997, the U.S. Environmental protection Agency (EPA) initiated its periodic review of the national ambient air quality standards (NAAQS) for carbon monoxide (CO) as required under the Clean Air Act Amendments of 1990. As part of its review, EPA will prepare a Staff Paper that provides the EPA Administrator, the Clean Air Scientific Advisory Committee (CASAC), and the public with the staff's interpretation of the scientific evidence reviewed in the revised Air Quality Criteria Document, also prepared by EPA, as well as the results of technical air quality and human exposure analyses conducted as part of this review. EPA presented a development plan for the CO NAAQS review (EPA, 1998) to the CASAC at a public meeting on November 16, 1998, which describes the scope of the review and presents the status and schedule for various aspects of the review, including the development of human exposure estimates to CO.

One of the key inputs to the review is the estimation of human exposure. Exposure is being characterized using an updated version of the probabilistic NAAQS Exposure Model for CO (pNEM/CO) which was previously developed in 1992 as part of the last review of the CO NAAQS (see Johnson et al., 1992). This report presents a description of the revised version of pNEM/CO (hereafter referred to as Version 2.0) and a preliminary application of the model to the Denver urban area. The purpose of this report is to obtain technical review of the proposed methodology from the CASAC and the general public. As described in its development plan, EPA then plans to make any necessary revisions to the model and to apply the model to study areas in both Denver and Los Angeles. EPA selected Denver as one of the study areas to provide a basis for comparison with the previous review and because it is one of the few areas where a personal exposure study has been conducted that can be used to provide a limited evaluation of the model. Los Angeles is being included because (1) Los Angeles poses the largest public health burden in terms of ambient CO levels and potential population exposure, (2) the city has an extensive ambient monitoring network, and (3) there is a study of personal, indoor, and ambient concentrations in Los Angeles that can be used to provide a limited evaluation of the model.

1.1 Applications of pNEM/CO to Denver, Colorado

The original version of pNEM applicable to CO (pNEM/CO) was developed for EPA in 1991. Unlike the pNEM/O3 model which provides only exposure estimates, pNEM/CO also provides an estimate of internal dose [the carboxyhemoglobin (COHb) level] associated with each exposure. Johnson et. al. (1992) have described the use of pNEM/CO to estimate CO exposures and resulting COHb levels in the residents of Denver, Colorado. In this 1992 application, researchers estimated exposures expected under recent air quality conditions and under conditions in which a specific NAAQS was just attained in the city.

Each version of pNEM has a modular structure, with separate computer subroutines being used to prepare input databases, calculate exposures, and tabulate results. This modular feature permits researchers to construct a new version of pNEM by combining features from existing versions with new components that address application-specific modeling needs. EPA has recently updated the pNEM/CO methodology to permit the use of 1990 census data. Analysts have also enhanced the algorithms in the model which simulate gas stove use, determine indoor CO concentrations, account for passive smoking, estimate ventilation (inhalation) rate, and model home-to-work commuting patterns. This report describes Version 2.0 of pNEM/CO and presents preliminary results of applying the model to the Denver area under recent air quality conditions. Once the methodology is reviewed and any necessary revisions are made, the model will be applied to both the Denver and Los Angeles study areas. A future technical report will include the estimated exposures under recent air quality conditions and under conditions in which the current CO NAAQS is just attained in each of these urban areas.

1.2 Report Organization

This report is divided into eight sections. Section 2 presents an overview of the updated pNEM/CO methodology. Section 3 outlines the methods used to select and process the fixed-site monitoring data used in applying pNEM/CO to Denver. Section 4 provides a detailed description of the mass balance model used to estimate CO concentrations for indoor and in-vehicle microenvironments. Section 5 provides a summary of the procedure used to estimate ventilation rate. Section 6 describes the development of origin-destination tables for home-to-work commuting trips in Denver. Section 7 presents the results of applying pNEM/CO to special populations within the Denver metropolitan area. A discussion of the limitations of Version 2.0 of pNEM/CO can be found in Section 8. Section 8 also provides recommendations for further research.

1.3 References for Section 1

Johnson, T., J. Capel, R. Paul, and L. Wijnberg. 1992. **Estimation of Carbon Monoxide Exposures and Associated Carboxyhemoglobin Levels in Denver Residents Using a Probabilistic Version of NEM**. Report prepared by International Technology Air Quality Services under EPA Contract No. 68-D0-0062. U.S. Environmental Protection Agency, Research Triangle Park, North Carolina.

U.S. Environmental Protection Agency. 1998. **Carbon Monoxide NAAQS Review Development Plan.** Office of Air Quality Planning and Standards, Research Triangle Park, North Carolina, November.

SECTION 2

OVERVIEW OF THE METHODOLOGY

Version 2.0 of pNEM/CO follows the same general approach used in the original 1992 version (Johnson et al., 1992). Figure 2-1 shows the conceptual overview of the logic and data flow of the model. The various inputs to the model (e.g., activity patterns, ambient monitoring data, air exchange rates, commuting data, population census data) are shown in the rounded boxes and the model calculations take place in the rectangular boxes (e.g., mass balance model for indoor microenvironments). The general pNEM methodology can be viewed as the following five steps:

1. Define a study area, one or more populations-of-interest, appropriate subdivisions of the study area, and an exposure period.
2. Divide the population-of interest into an exhaustive set of cohorts.
3. Develop an exposure event sequence for each cohort for the exposure period.
4. Estimate the pollutant concentration, ventilation rate, and physiological indicator (if applicable) associated with each exposure event.
5. Extrapolate the cohort exposures to each population-of-interest.

The remainder of this section describes how Version 2.0 implements each step of the pNEM/CO methodology. The preliminary application of the methodology to the Denver study area is used to illustrate the various aspects of the model.

2.1 Define Study Area, Populations-of-Interest, Subdivisions of Study Area, and Exposure Period

The pNEM/CO methodology provides estimates of the distribution of CO exposures and associated carboxyhemoglobin (COHb) levels within a defined population (the population-of-interest) for a specified exposure period. The exposure

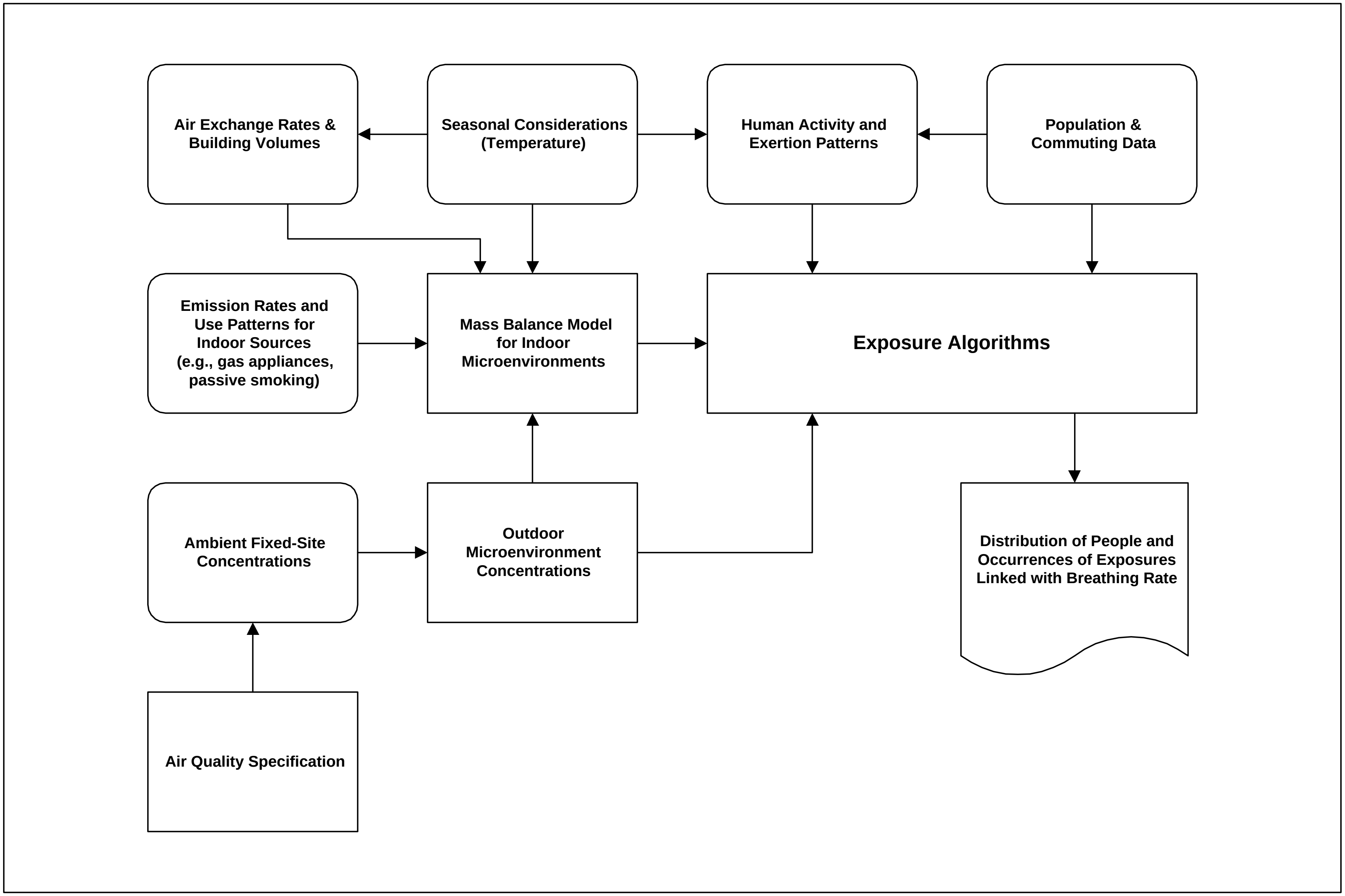

Figure 2-1. Conceptual Model and Data Flow of pNEM/CO

period is usually a recent calendar year for which good data are available with respect to ambient CO levels. The population-of interest is typically defined as people with specific demographic characteristics (e.g., adults with ischemic heart disease) who live and work within a defined set of exposure districts. Each exposure district is a contiguous set of census units surrounding one or more fixed-site CO monitors selected as representative of the district.

Analysts defined six exposure districts for the application of pNEM/CO to Denver. Section 3.1 describes in detail the process used to develop these districts. Briefly, analysts identified seven fixed-site monitors which (1) were located within 50 km of the center of Denver, (2) were located in areas of appropriate urban land use, and (3) reported sufficient air quality data for 1995 through 1997. Five of the seven sites were identical to sites used in the 1992 Denver analysis; the remaining two sites were located in downtown Boulder (28th Street and Marine Street). The locations of five sites used in the 1992 analysis were considered appropriate for defining five separate exposure districts with 10 km radii. However, the Boulder sites were considered too close together to support separate exposure districts. Consequently, analysts defined six exposure districts -- one for each of the 1992 Denver sites and a “composite” Boulder site. For purposes of constructing the associated exposure district, the composite site was assigned a location midway between the two Boulder sites.

The focus of the previous review of the CO NAAQS was on the population with ischemic heart disease. As the incidence of ischemic heart disease for individuals younger than age 18 is extremely small, EPA has chosen to define the population of interest as adults (18 and older) with ischemic heart disease who lived and worked within the six exposure districts.

The exposure period was defined as calendar years 1995, 1996, and 1997. Consequently, 21 “site-years” of fixed-site monitoring data were selected for the new Denver analysis (7 sites x three years/site). Each of the selected site-years of data was at least 96.6 percent complete. Table 2-1 provides descriptive statistics for these data sets after missing values were estimated. Section 3 outlines the methods used to select and process the Denver monitoring data.

Table 2-1. Descriptive Statistics for Hourly Average Values in Data Sets Selected to Represent Denver Exposure Districts After Estimation of Missing Values

Location	Monitor ID	Year	Descriptive statistics for hourly-average CO concentrations, ppm					
			50th	90th	95th	99th	99.5th	Maxi-mum
Littleton	005-0002	95	0.3	0.7	1.0	1.8	2.2	3.6
		96	0.3	0.7	1.0	1.8	2.2	4.3
		97	0.3	0.7	1.0	1.7	2.0	4.3
Broadway	031-0002	95	1.2	2.7	3.4	6.1	7.7	24.5
		96	1.1	2.5	3.2	5.6	6.9	21.6
		97	1.0	2.4	3.0	5.4	6.3	11.4
Albion	031-0013	95	0.9	2.5	3.4	5.5	6.4	14.6
		96	0.8	2.2	3.0	5.0	5.7	14.6
		97	0.8	2.1	2.8	4.7	5.4	11.6
Julian	031-0014	95	0.7	2.3	3.2	5.3	6.5	10.4
		96	0.6	2.0	2.9	4.7	5.5	9.1
		97	0.6	2.1	2.9	5.0	5.8	9.5
Arvada	059-0002	95	0.6	2.0	2.7	4.8	5.8	11.9
		96	0.5	1.7	2.4	4.1	4.9	7.9
		97	0.6	1.8	2.4	4.2	5.1	9.2
Boulder 28th St.	013-0010	95	0.8	2.1	2.8	4.8	5.5	10.6
		96	0.7	1.8	2.4	3.9	4.7	8.5
		97	0.7	1.7	2.4	3.9	4.5	9.0
Boulder Marine St.	013-1001	95	0.4	0.9	1.3	2.3	2.9	8.3
		96	0.4	0.9	1.1	2.0	2.5	4.5
		97	0.4	0.9	1.2	2.4	3.0	7.1
Composite Boulder monitor	---	95	0.7	1.5	2.0	3.3	3.8	9.5
		96	0.6	1.3	1.7	2.8	3.3	6.0
		97	0.6	1.3	1.7	3.0	3.6	7.3

2.2 Divide the Population-of-Interest into an Exhaustive Set of Cohorts

In a pNEM analysis, the population-of-interest is divided into a set of cohorts such that each person is assigned to one and only one cohort. Each cohort is assumed to contain persons with identical exposures during the specified exposure period. Cohort exposure is typically assumed to be a function of demographic group, location of residence, and location of work place. Specifying the home and work district of each cohort provides a means of linking cohort exposure to ambient CO concentrations. Specifying the demographic group provides a means of linking cohort exposure to activity patterns which vary with age, work status, and other demographic variables. In some analyses, cohorts are further distinguished according to factors relating to proximity to emission sources or time spent in particular microenvironments.

In the application of pNEM/CO (Version 2.0) to Denver, each cohort was identified as a distinct combination of (1) home district, (2) demographic group, (3) work district (if applicable), (4) residential cooking fuel, and (5) replicate number. The home district and work district of each cohort were identified according to the districts defined above. Table 2-2 lists 11 demographic groups defined for the Denver pNEM/CO analysis. Four of the demographic groups are identified as workers. Each cohort associated with one of these groups was identified by both home and work district. The remaining cohorts were identified only by home district. Note that although children were included within the demographic groups defined for the Denver analysis, the exposure estimates summarized in Section 7 are limited to the adult demographic groups.

The residential cooking fuel of each cohort was identified as either “natural gas” or “other.” This cohort index was used because a personal monitoring study (Johnson, 1984) conducted in Denver suggested that proximity to operating natural gas stoves contributed significantly to CO exposure. A review of the scientific literature concerning five other sources (kerosene space heaters, gas space heaters, wood stoves, fireplaces, and attached garages) indicated that each source either did not contribute significantly to indoor CO levels or was used in less than 1 percent of the Denver residences (Fletcher and LaPointe, 1998).

Table 2-2. Demographic Groups Defined for the Denver pNEM/CO Analyses and Number of Associated Cohorts

Demographic group	Includes commuting cohorts?	Number of cohorts associated with demographic group
1. Children, 0 to 17	no	60
2. Males, 18 to 44, working	yes	360
3. Males, 18 to 44, nonworking	no	60
4. Males, 45 to 64, working	yes	360
5. Males, 45 to 64, nonworking	no	60
6. Males, 65+	no	60
7. Females, 18 to 44, working	yes	360
8. Females, 18 to 44, nonworking	no	60
9. Females, 45 to 64, working	yes	360
10. Females, 45 to 64, nonworking	no	60
11. Females, 65+	no	60
Total		1,860

Earlier versions of pNEM/CO have used defined cohorts solely according to home district, demographic group, work district (if applicable), and residential cooking fuel. A new feature was installed in pNEM/CO (Version 2.0) which permitted the user to specify a “replication” value (n) such that the model will produce n cohorts for each combination of these four indices. Because pNEM/CO uses a Monte Carlo process to construct an activity pattern for each cohort, each of the n cohorts associated with a particular combination of home district, demographic group, work district, and residential cooking fuel is associated with a distinct exposure sequence. The replication feature permits the analyst to divide the population-of-interest into a larger number of smaller cohorts -- a process which decreases the “lumpiness” of the exposure simulation. A replication value of five (n = 5) was specified for the Denver exposure analyses described in this report. Consequently, the pNEM/CO model analyzed five times the number of cohorts it would have considered if the cohorts had been defined solely by home district, demographic group, work district, and residential cooking fuel.

Table 2-2 lists the number of Denver cohorts associated with each demographic group. Each of the seven nonworking demographic groups is associated with 60 cohorts, one for each combination of home district, residential cooking fuel, and replicate number (6 x 2 x 5 = 60). Each of the four working demographic groups is associated with 360 cohorts, one for each combination of home district, work district, residential cooking fuel, and replicate number (6 x 2 x 6 x 5 = 360). The total number of Denver cohorts is thus (7 x 60) + (4 x 360) or 1,860.

2.3 Develop an Exposure Event Sequence for Each Cohort for the Exposure Period

In the pNEM/CO methodology, the exposure of each cohort is determined by an exposure event sequence (EES) specific to the cohort. Each EES consists of a series of events with durations from 1 to 60 minutes. To permit the analyst to determine average exposures for specific clock hours, the exposure events are defined such that no event falls within more than one clock hour. Each exposure event assigns the cohort to a particular combination of geographic area and microenvironment. In addition, each event specifies whether or not the cohort is in the presence of smokers. Each event also provides an indication of respiration rate. In the original (1992) version of pNEM, this indicator was a classification of breathing rate as sleeping, slow, medium, or fast. In Version 2.0 of pNEM/CO, this indicator is a specific activity descriptor such as “raking” or “playing baseball.”

In typical pNEM applications, the EESs are determined by assembling activity diary records relating to individual 24-hour periods into a year-long series of records. Because each subject of a typical activity diary study provides data for only a few days, the construction of a year-long EES requires either the repetition of data from one subject or the use of data from multiple subjects. The latter approach is used in pNEM analyses to better represent the variability of exposure that is expected to occur among the persons included in the cohort.

In the pNEM/CO (Version 2.0) analysis, activity diary data were obtained from the Consolidated Human Activity Database (CHAD). CHAD is comprised of approximately 17,000 person-days of 24-hour time/activity data developed from eight surveys (Tippett et al., 1997). The surveys include probability-based recall studies conducted by EPA and the California Air Resources Board, as well as real-time diary studies conducted in individual U.S. metropolitan studies using both probability-based and volunteer subject panels. All ages of both genders are represented in CHAD. The data for each subject consist of one or more days of sequential activities, in which each activity is defined by start time, duration, activity type (140 categories), and microenvironment classification (110 categories). Activities vary from one minute to one hour in duration, with longer activities being subdivided into clock-hour durations to facilitate exposure modeling. A distribution of values for the ratio of oxygen uptake rate to body mass (referred to as metabolic equivalents or “METs”) is provided for each activity type listed in CHAD. The forms and parameters of these distributions were determined through an extensive review of the exercise and nutrition literature. The primary source of distributional data was Ainsworth et al. (1993), a compendium developed specifically to “facilitate the coding of physical activities and to promote comparability across studies.”

The CHAD database was processed to create a special database appropriate for input in pNEM/CO. This database consisted of diary records organized by study subject and calendar day. The diary records for one subject for one calendar day were designated a "person-day." The CHAD-derived database contained 14,048 usable person-days, each of which was indexed by the following factors:

1. Demographic group
2. Season: summer or winter
3. Temperature classification: cool or warm
4. Day type: weekday or weekend.

The demographic group index was determined by the demographic group to which the subject filling out the diary belonged. The season and day indices were based on the date of the calendar day. The temperature classification was based on the daily maximum temperature (in °F) of the associated geographic location on that date. The cool range was defined as temperatures below 55° in winter and temperatures below 84° in summer.

The EES for each cohort was determined by a computerized sampling algorithm. The algorithm was provided with the sequence of daily maximum temperatures reported by Denver in each of three years (1995, 1996, 1997) and with a list of cohorts. The temperature data were used to assign each calendar day in these years to one of the temperature ranges used in classifying the activity diary data. To construct the EES for a particular cohort, the algorithm selected a person-day from the CHAD-derived database for each calendar day in the three-year period according to the demographic group of the cohort and the season, day type, and temperature classification associated with the time period.

Each exposure event within an EES was defined by (1) district, (2) CHAD location descriptor, (3) microenvironment, (4) CHAD activity descriptor, and (5) passive smoking status. The district was either the home or work district associated with the cohort. The home/work determination was based on a decision rule which was applied to the activity diary data associated with the exposure event.

The CHAD location descriptor refers to the location code associated with the event in the CHAD database. The location descriptor was used to assign the event to a microenvironment and to determine the contribution of passive smoking (if applicable) to the CO concentration experienced during the event. Table 2-3 lists the 120 codes used to define the location descriptors of exposure events.

Table 2-4 lists the 13 microenvironments used for event assignments. Each microenvironment is identified as to a general location (e.g., outdoors) and a specific location (e.g., near road). The list includes two indoor microenvironments related to residences, five indoor microenvironments related to nonresidential buildings, three outdoor microenvironments, and three vehicle microenvironments. The majority of these microenvironments are aggregates of two or more of the CHAD location descriptors. Only location descriptions associated with similar average CO exposures were combined in defining the aggregate microenvironments. Researchers determined these similarities through an analysis of personal CO monitoring data obtained from the Denver activity diary study (Johnson, 1984). Table 2-3 shows the assignment of CHAD location descriptors to microenvironments.

Activity descriptors were defined according to activity classifications appearing in CHAD. CHAD provides a distribution of energy expenditure rate for each activity classification which was used in a later step to estimate a ventilation rate for each activity (see Section 5). Appendix A lists the CHAD descriptors and associated distributions for energy expenditure rate.

The effects of active smoking on CO exposure were not addressed in the exposure analysis described here. Because of the coding conventions used in the CHAD diary studies, passive smoking patterns could be determined for nonsmoking subjects only. Consequently, the activity diaries sampled in constructing EESs were limited to those of nonsmokers[a]. The diary record associated with each exposure event provided information on whether or not the subject was in the presence of smokers. This information was used to assign a passive smoking status to each event. [a]*(ALL CHAD DATA ARE CURRENTLY USED -- CHAD DATA WILL BE LIMITED TO NONSMOKERS IN NEXT VERSION).*

Table 2-3. Assignment of CHAD Location Codes to pNEM/CO Microenvironments *(MAY BE REVISED)*

CHAD Location Code	pNEM/CO Microenvironment Code
<30> Home	
30000: residence, general	1
30010: your residence	1
30020: other's residence	1
30100: residence, indoor	1
30120: your residence, indoor	1
30121: kitchen	1
30122: living room/ family room	1
30123: dining room	1
30124: bathroom	1
30125: bedroom	1
30126: study/ office	1
30127: basement	1
30128: utility room/ laundry room	1
30129: other indoor	1
30130: other's residence, indoor	1
30131: kitchen	1
30132: living room/ family room	1
30133: dining room	1
30134: bathroom	1
30135: bedroom	1
30136: study/ office	1
30137: basement	1
30138: utility room/ laundry room	1

CHAD Location Code	pNEM/CO Microenvironment Code
30139: other indoor	1
30200: residence, outdoor	9
30210: your residence, outdoor	9
30211: pool, spa	9
30219: other outdoor	9
30220: other’s residence, outdoor	9
30221: pool, spa	9
30229: other outdoor	9
30300: garage	7
30310: indoor garage	7
30320: outdoor garage	9
30330: your garage	7
30331: indoor garage	7
30332: outdoor garage	9
30340: other’s garage	7
30341: indoor garage	7
30342: outdoor garage	9
30400: other, residence	1
<31> Travel	
31000: travel, general	10
31100: motorized travel	
31110: car	10
31120: truck	11
31121: truck (pick-up or van)	11
31122: truck (other than pick-up or van)	11
31130: motorcycle/ moped/ motorized scooter	11

CHAD Location Code	pNEM/CO Microenvironment Code
31140: bus	11
31150: train/ subway/ rapid transit	11
31160: airplane	99
31170: boat	9
31171: motorized boat	9
31172: unmotorized boat	9
31200: non-motorized travel	9
31210: walk	9
31220: bicycle/ skateboard/ roller-skates	9
31230: in a stroller or carried by an adult	9
31300: waiting	9
31310: wait for bus, train, ride (at stop)	8
31320: wait for travel, indoors	5
31900: other travel	11
31910: other vehicle	11
<32-34> Other Indoor	
32000: other indoor, general	5
32100: office building/ bank/ post office	5
32200: industrial plant/ factory/ warehouse	6
32300: grocery store/ convenience store	5
32400: shopping mall/ non-grocery store	3
32500: bar/ night club/ bowling alley	4
32510: bar/ night club	
32520: bowling alley	
32600: repair shop	
32610: auto repair shop/ gas station	2

CHAD Location Code	pNEM/CO Microenvironment Code
32620: other repair shop	3
32700: indoor gym/ sports or health club	6
32800: childcare facility	
32810: childcare facility, house	1
32820: childcare facility, commercial	6
32900: public building/ library/ museum/ theater	5
32910: auditorium, sport’s arena, concert hall	4
32920: library, courtroom, museum, theater	5
33100: laundromat	5
33200: hospital/ health care facility/ doctor’s office	6
33300: beauty parlor/ barber shop/ hair dresser’s	5
33400: at work: no specific location, moving among locations	5
33500: school	6
33600: restaurant	4
33700: church	6
33800: hotel/ motel	5
33900: dry cleaners	6
34100: parking garage	12
34200: laboratory	5
34300: other, indoor (specify)	5
<35-36> Other Outdoor	
35000: other outdoor, general	9
35100: sidewalk/ street/ neighborhood	8
35110: within 10 yards of street	8
35200: public garage/ parking lot	12
35210: public garage	12

CHAD Location Code	pNEM/CO Microenvironment Code
35220: parking lot	12
35300: service station/ gas station	12
35400: construction site	9
35500: amusement park	9
35600: school grounds/ playground	9
35610: school grounds	
35620: playground	
35700: sports stadium and amphitheater	9
35800: park/ golf course	9
35810: park	
35820: golf course	
35900: pool, river, lake	9
36100: restaurant, picnic	9
36200: farm	9
36300: other outdoor (specify)	9

Table 2-4. Microenvironments Defined for the Denver pNEM/CO Analysis

Microenvironment			Activity diary locations included in microenvironment
Code	General location	Specific location	
1	Indoors	Residence	Indoors - residence
2	Indoors	Nonresidence A	Service station or auto repair
3	Indoors	Nonresidence B	Other repair shop Shopping mall
4	Indoors	Nonresidence C	Restaurant Other indoor location Auditorium
5	Indoors	Nonresidence D	Store Office Other public building
6	Indoors	Nonresidence E	Health care facility School Church Manufacturing facility
7	Indoors	Residential garage	Residential garage
8	Outdoors	Near road	Near road
9	Outdoors	Other locations	Outdoor residential garage Construction site Residential grounds School grounds Sports arena Park or golf course Other outdoor location
10	Vehicle	Automobile	Automobile
11	Vehicle	Other	Bus Truck Bicycle Motorcycle Train/subway Other vehicle
12	Outdoor	Public parking or fueling facility	Indoor parking garage Outdoor parking garage Outdoor parking lot Outdoor service station
99	Vehicle	Airplane	Airplane

2.4 Estimate the Pollutant Concentration, Ventilation Rate, and COHb Level Associated with Each Exposure Event

In the general pNEM methodology, the EES defined for each cohort is used to determine a corresponding sequence of exposures, event by event. Each exposure is defined by a pollutant concentration and a ventilation rate indicator. In some applications, a biokinetics model is used to determine the status of a physiological indicator at the end of each exposure event, based on the status of the indicator at the beginning of each event and the pollutant dose delivered during the event. The delivered dose is a function of the pollutant concentration and ventilation rate values assigned to the event and the demographic characteristics of the cohort.

2.4.1 Estimation of Pollutant Concentration

In the pNEM/CO analysis, each exposure event within a particular EES was indexed according to district d, microenvironment m, person-day p, clock hour h, and start time t. The exposure associated with a particular event, CEXP(d,m,p,h,t) was estimated by the expression

$$\text{CEXP}(d,m,p,h,t) = \text{CME}(d,m,p,h) + \text{SMOKE}(m,t). \tag{2-1}$$

CME(d,m,p,h) is the CO concentration determined for microenvironment m in district d for person-day p and hour h. SMOKE(m,t) is an assumed contribution from passive smoking specific to microenvironment and event.

The SMOKE(m,t) term represented the short-term contribution of passive smoking to CO exposure. The operation of this term was a function of two event descriptors: passive smoking status and CHAD location descriptor. If (1) the passive smoking status for an indoor event indicated the presence of smokers and (2) the location was one of the three microenvironments listed in Table 2-5, then the value of SMOKE(m,t) was set equal to the value specified in the table for the duration of the event. Otherwise, SMOKE(m,t) was set equal to zero. The values listed in Table 2-5 were based on statistical analyses (Johnson, Memorandum No. 7, 1998) of data obtained from a personal monitoring study conducted in Denver (Johnson, 1984) and a microenvironmental monitoring study performed in northern California (Ott et al., in press).

The three microenvironments listed in Table 2-5 include the indoor microenvironments that are expected to be most impacted by passive smoking. Version 2.0 of pNEM/CO currently treats the remaining ten microenvironments as being free from the effects of passive smoking. This assumption may underestimate CO levels in some of these microenvironments. However, analysts were unable to find sufficient data to develop realistic estimates for the contribution of passive smoking to these microenvironments.

The CME(d,m,p,h) term represented the component of exposure contributed by ambient (outdoor) CO concentrations and by the operation of residential gas stoves. An array of CME values was created for each cohort. Each array consisted of a set of year-long sequences of hourly-average CME values, one for each combination of microenvironment and district. The district was either the home or work district specified for the cohort. When an exposure event occurring during hour h assigned a cohort to a particular combination of microenvironment and district, the cohort was assigned the CO concentration specified for hour h in the designated microenvironment/district sequence.

Each year-long sequence of hourly average CME values for the indoor and motor vehicle microenvironments was generated by the mass-balance algorithm described in Section 4. Briefly, this algorithm estimated the hourly average indoor CO concentrations during hour h as a function of the indoor CO concentration during the preceding hour (i.e., hour h - 1), the CO concentration outdoors during hour h, the air exchange rate during hour h, and the indoor emissions of CO from gas stoves during hour h (if applicable). Values for the air exchange rate and gas stove emission rate were sampled from appropriate distributions on a daily basis. During each clock hour, gas stoves were probabilistically determined as “on” for 30 minutes, “on” for 60 minutes, or “off’ for the entire hour. The probability of being on varied with time of day according to use patterns observed during the Denver activity diary study.

Table 2-5. Non-Zero Passive Smoking Increments for Indicated CHAD Location Codes.

pNEM/CO microenvironment	Denver location category	CHAD location categories with non-zero passive smoking increments	Passive smoking increment, ppm
1: indoors, residence	2: indoors - residence	All CHAD codes assigned to pNEM/CO microenvironment no. 1	0.4
4: indoors, nonresidence C	5: restaurant	33600: restaurant	1.1
	bar[a]	32500: bar, night club, or bowling alley 32510: bar or nightclub 32520: bowling alley	5.3
	56: auditorium	32910: auditorium, sports arena, or concert hall	2.3
	62: other indoor locations	32000: other indoor, general 34300: other indoor, specify	1.2
5: indoors, nonresidence D	3: office	32100: office building, bank, or post office	0.6

[a] The location “bar” does not have a distinct location code in the Denver PEM database.

Ideally, passive smoking would have been modeled within the mass balance model described above rather than represented by a separate additive factor. Law (1998) attempted to account for passive smoking in the mass balance model, but found that there were insufficient data available for one of the key parameters required for the model, namely, the number of smokers actively smoking in various microenvironments. Consequently, EPA elected to treat passive smoking as an additive factor representing the average contribution of passive smoking to CO levels in each of three microenvironments listed in Table 5-2.

The outdoor CO concentration required by the mass-balance algorithm was determined for each hour through a Monte Carlo process. According to this process, the outdoor CO concentration estimated for a particular hour h was influenced by (1) the microenvironment, (2) the outdoor CO concentration estimated for the preceding hour for the specified microenvironment, and (3) the CO concentration estimated for hour h at the fixed-site monitor representing district d.

For a particular combination of microenvironment and district, the process consisted of stepping through the hours in the calendar year and selecting an outdoor CO concentration for each hour. The selection for a particular hour was made by randomly selecting a value from one of a set of empirical distributions established for the micoenvironment. Two methods were employed in making these selections. In Method A, the selection procedure accounted for both the current fixed-site CO concentration and the outdoor CO concentration determined for the preceding hour. In Method B, the selection procedure accounted only for the current fixed-site CO concentration. Method A was applied to the four microenvironments listed in Table 2-6. Method B was applied to the remaining microenvironments.

Twenty-five empirical distributions were established for each of the Method A microenvironments. Each distribution represented the distribution of outdoor CO concentrations expected to occur for a defined pair of events: (1) the fixed-site CO concentration falls within interval i and (2) the outdoor CO concentration of the previous hour falls within interval j.

The following five intervals were established for fixed-site concentrations.

Interval (i)	CO concentration, ppm Lower bound	Upper bound
1	0	1
2	1	2
3	2	4
4	4	8
5	8	na

The first interval includes 0 and 1. Each of the remaining intervals excludes the specified lower bound and includes the specified upper bound.

Five intervals were established for the previous outdoor CO concentration (interval j) for each of the four microenvironments. Table 2-6 lists the upper bounds of these intervals.

Table 2-6. Initial Values for Previous Outdoor Carbon Monoxide Concentration and Upper Bounds of Indexing Intervals (Interval j)

Microenvironment			Carbon monoxide concentration, ppm					
Code	General location	Specific location	Initial value[a]	Upper bound of indicated interval				
				1	2	3	4	5
1	Indoors	Residence	1.1	0	1.1	3.1	6.0	b
4	Indoors	Nonresidence C	3.1	1.2	3.1	6.1	10.6	b
5	Indoors	Nonresidence D	2.3	0.5	2.3	4.8	8.3	b
10	Vehicle	Automobile	5.0	1.8	5.0	10.0	16.3	b

[a] For outdoor concentration during previous hour. Value set equal to upper bound of second interval.

[b] Not bounded.

Each distribution was expressed as a cumulative probability distribution. Values were selected randomly from a distribution by first selecting a random number between zero and one and then determining the CO concentration associated with the random number on the cumulative distribution. For example, the random number 0.87 would select the concentration value associated with the 87th percentile of the cumulative distribution.

Table 2-7 presents the algorithm used to simulate a year-long sequence of hourly-average outdoor CO concentrations for each of the Method A microenvironments. The empirical distributions used in Step 7 were developed through a statistical analysis of data obtained from the 1982 - 1983 Denver activity diary study (Johnson, 1984). During this study, each of approximately 450 subjects carried a personal exposure monitor (PEM) for two 24-hour periods. Each PEM measured CO concentration continuously. The PEM readings were averaged by exposure event such that each event was associated with a single microenvironment and a single clock hour. Event durations ranged from one minute to one hour. The microenvironment assigned to each PEM was determined from entries made in the subject's activity diary.

The goal of the statistical analysis was to develop distributions representing the outdoor CO concentrations associated with each microenvironment. Originally, these distributions were to be developed using only outdoor PEM values. The Denver study

Table 2-7. Algorithm Used to Simulate a Year-Long Sequence of Hourly-Average Outdoor CO Concentrations for Each “Method A” Microenvironment

1. Identify microenvironment and district associated with simulation.

2. Go to first hour.

3. Set previous outdoor CO concentration equal to initial value listed in Table 2-6 for microenvironment.

4. See lookup table (Table 2-6) for microenvironment to determine interval index (j) for previous outdoor concentration.

5. Determine fixed-site CO concentration associated with hour for specified district and microenvironment.

6. See lookup table to determine interval index (i) for fixed-site CO concentration.

7. Locate cumulative distribution associated with indices i,j in supplemental array. If no cumulative distribution has been determined for (i,j), go back to previous hour and redo Steps 8 through 12 (requires drawing a new random number in Step 8).

8. Select random number between zero and one. Compare random number (RN) with probabilities listed in cumulative distribution identified in Step 7. RN will fall within one of the specified intervals, such that

   $$\mathrm{LBCF} < \mathrm{RN} \leq \mathrm{UBCF}$$

   where LBCF is the lower bound cumulative fraction and UBCF is the upper bound cumulative fraction.

9. Associated with LBCF is a lower bound pollutant concentration (LBPC). Associated with the UBCF is an upper bound pollutant concentration (UBPC). Use the following interpolation equation to estimate the current outdoor CO concentration value.

   $$\mathrm{CO} = \mathrm{LBPC} + (\mathrm{RN} - \mathrm{LBCF})(\mathrm{UBPC} - \mathrm{LBPC})/(\mathrm{UBCF} - \mathrm{LBCF})$$

10. Go to the next hour.

11. The current outdoor CO concentration as determined by Step 9 becomes the previous outdoor CO concentration.

12. Go to Step 4.

was found to contain relatively few outdoor PEM values, however, and these values were difficult to associate with specific indoor microenvironments.

An alternative approach was subsequently implemented in which each indoor PEM was assumed to represent the outdoor concentration at the same location one hour earlier, given that the indoor PEM value was not measured during a period when a gas stove was in operation. Consistent with this assumption, an indoor PEM value reported for hour h was indexed according to a fixed-site monitor concentration reported for h - 1. For outdoor and motor vehicle microenvironments, each PEM value was assumed to represent the current outdoor concentration. Consequently, each PEM value was indexed according to the fixed-site concentration associated with the current hour.

In indexing the indoor and outdoor PEM values according to fixed-site concentration, analysts limited the indexing procedure to PEM values which occurred within 10 km of at least one fixed-site monitor. In each case, the index was determined by the fixed-site concentration reported by the nearest monitor. As it was difficult to determine the nearest fixed-site monitor for PEM values associated with vehicle microenvironments, analysts used the average of the concentrations reported by all of the operating fixed-site monitors to index these PEM values.

The PEM values reported by a particular subject of the Denver study consisted of a sequence of CO concentrations which could be indexed by microenvironment. Whenever a particular PEM value was preceded by a PEM value reported for the same microenvironment, the value of the preceding PEM value was used to determine the preceding hour index (j). No index could be determined in cases where a particular PEM value was not preceded by a PEM value associated with the same microenvironment.

The initial result of this approach was a file listing PEM values indexed according to microenvironment, fixed-site CO interval (i), and previous PEM CO interval (j). This file was subsequently analyzed to determine the distribution of PEM values for each combination of Method A microenvironment, i value, and j value. The resulting distributions were accessed in Step 7 of the 12-step procedure described in Table 2-7.

Method B was applied to the nine microenvironments not listed in Table 2-6. In each of these cases, the Denver PEM data available for the microenvironment were judged to be insufficient for the purpose of accounting for both the current fixed-site CO concentration and the preceding outdoor CO concentration. An analysis of the activity diary data for these microenvironments indicated that people tended not to occupy these microenvironments for long time periods. Consequently, the decision was made to ignore the effects of the preceding outdoor concentration in the selection process.

Five empirical distributions were established for each of the Method B microenvironments, one for each of the five ranges used in Method B for classifying fixed-site concentrations. The outdoor value selected for each hour was randomly selected from one of these five distributions according to the fixed-site concentration associated with the hour. Apart from this use of the five rather than 25 empirical distributions, Method B was identical to Method A.

Methods A and B each require a complete (gapless) year of hourly average fixed-site monitoring values for each district. Section 3.2 describes the method used to fill in missing hourly-average values. The resulting filled-in data sets were assumed to represent existing conditions at each monitor.

2.4.2 The Air Quality Adjustment Procedure

The next application of version 2.0 of pNEM/CO will include exposure estimates associated with air quality just meeting the current 8-hour NAAQS for CO. It is anticipated that the approach used to adjust current CO ambient air quality levels to represent air quality under the current NAAQS will be similar to the approach described in Section 2.4.2 of Johnson et al. (1992).

2.4.3 Ventilation Rate

In addition to CO concentration, a ventilation rate (V_E) value was estimated for each exposure event. V_E is expressed as liters of air respired per minute (liters min^{-1}). The algorithm used to estimate V_E was developed for Version 2.0 of pNEM/CO and has not been used previously in pNEM analyses.   Section 5 provides a detailed description of the algorithm.

Briefly, the CHAD database provided an activity indicator for each exposure event. Each activity type was assigned a distribution of values for the metabolic equivalent of work (MET). MET is a dimensionless quantity defined by the ratio

$$\mathrm{MET} = \mathrm{EE}/\mathrm{RMR}, \tag{2-2}$$

where EE is the rate of energy expenditure during a particular activity (expressed in kcal/min), and RMR is a person's typical resting metabolic rate (also expressed in kcal/min). For example, activity no. 11300 -- "outdoor chores" -- was represented by a normal distribution of MET values with mean equal to 5 and a standard deviation equal to 1. Appendix A lists the distribution assigned to each of the CHAD activity codes.

A probabilistic procedure was used to assign a RMR value to each cohort for the entire 365-day exposure period. An EE value was calculated for each exposure event by the equation

$$\mathrm{EE}_a(i,j,k) = [\mathrm{MET}(i,j,k)][\mathrm{RMR}(k)], \tag{2-3}$$

in which $\mathrm{EE}_a(i,j,k)$ was the average energy expenditure rate (kcal min^{-1}) for cohort k during exposure event i on day j; MET(i,j,k) was a value for MET randomly selected from the distribution associated with activity type a; a was the activity type associated with exposure event e; and RMR(c,d) was the RMR value randomly generated for cohort k. Section 5.5 describes the methods used to randomly select or generate the required parameter values.

Energy expenditure requires oxygen which is supplied by ventilation (respiration). Let ECF(k) indicate an <u>e</u>nergy <u>c</u>onversion <u>f</u>actor defined as the volume of oxygen required to produce one kilocalorie of energy in person k. The oxygen uptake rate (VO_2) associated with a particular activity can be expressed as

$$\mathrm{VO}_2(i,j,k) = [\mathrm{ECF}(k)][\mathrm{EE}_a(i,j,k)], \tag{2-4}$$

in which $\mathrm{VO}_2(i,j,k)$ has units of liters oxygen min^{-1}, ECF(k) has units of liters oxygen kcal^{-1}, and EE(i,j,k) has units of kcal min^{-1}. In pNEM/CO, the value of $\mathrm{VO}_2(i,j,k)$ is determined from MET(i,j,k) by substituting Equation 2-3 into Equation 2-4 to produce the relationship

$$VO_2(i,j,k) = [ECF(k)][MET(i,j,k)][RMR(k)]. \qquad (2\text{-}5)$$

Section 5-5 describes the probabilistic methods used to estimate values of ECF(k) and RMR(k) for person k.

Ventilation rate (V_E) tends to increase as VO_2 increases up to the point of maximum oxygen uptake (VO_{2max}). The relationship is known to be non-linear, with the slope of the relationship usually increasing at higher values of VO_2. In Version 2.0 of pNEM/CO, the relationship between $V_E(i,j,k)$ and $VO_2(i,j,k)$ is modeled by the generic equation

$$\ln[V_E(i,j,k)/BM(k)] = a + (b)\{\ln[VO_2(i,j,k)/BM(k)]\} + d(k) + e(i,j,k) \qquad (2\text{-}6)$$

in which $V_E(i,j,k)$ is the V_E value associated with the ith event of day j for person k, BM(k) is the body mass assigned to person k, and a and b are constants determined by the age and gender of person k. The term d(k) is a random variable selected for each person from a normal distribution with mean equal to zero and standard deviation equal to σ_d. The term e(i,j,k) is a random variable selected for each individual event from a normal distribution with mean equal to zero and standard deviation equal to σ_e.

Section 5.3 provides values for each of the parameters appearing in Equation 2-6. The values of a, b, σ_d, and σ_e were determined through a statistical analysis of data relating V_E to VO_2 obtained from 32 clinical studies performed by Dr. William Adams. The data were stratified into six groups according to age and gender.

The V_E algorithm included a method for identifying “impossible” values which were occasionally generated by the estimation process. This method determined a maximum VO_2 value for each exposure event which accounted for the duration of the activity and for the age, weight, and gender of the person. No estimate of VO_2 (and the corresponding estimate of V_E) was permitted to exceed this limit. Section 5.4 provides a more detailed description of this procedure.

2.4.4 Carboxyhemoglobin Level

An algorithm developed by Biller and Richmond (included as an appendix in Johnson et al., 1992) was used by pNEM/CO to estimate the COHb level at the end of each exposure event. The algorithm is based on a differential equation proposed by Coburn, Forster, and Kane (1963). Inputs to the algorithm include

Percent COHb at the start of the event
Average CO exposure concentration during the event, ppm
Time duration of the event, min
Alveolar ventilation rate, ml/min
Haldane Constant
Atmospheric pressure at sea level, torr
Altitude above sea level, feet
Blood volume, ml
Total hemoglobin content of blood, gm/100 ml
Pulmonary CO diffusion rate, ml/min per torr
Endogenous CO production rate, ml/min

An updated version of the Biller and Richmond Appendix appears as Appendix E to this report and provides a detailed description of the COHb algorithm, the various physiological parameters that are inputs to the COHb algorithm, and a list of related references.

2.4.5 The Physiological Profile Generator

As discussed in Sections 2.4.3 and 2.4.4, the algorithms used to estimate V_E and COHb required values for various physiological parameters such as body mass, blood volume, and RMR. Appendix E provides a complete list of these parameters. A special algorithm within pNEM probabilistically generated a value for each parameter on the list (collectively referred to as a “physiological profile”) for each combination of cohort and calendar day processed by pNEM/CO. Each of the generated physiological profiles was internally consistent, in that the functional relationships among the various parameters were maintained. For example, blood volume was determined as a function of weight and height, where height was estimated as a function of weight. Weight was in turn selected from a distribution specific to gender and age. Appendix E describes the method used to estimate values for each parameter in the application of pNEM/CO to Denver.

2.4.6 Hourly Average Exposure Estimates

Algorithms within pNEM/CO provided four estimates for each exposure event: average CO concentration, average V_E, the product of average CO concentration and V_E (represented as “CO x V_E”), and the COHb level at the end of the event. These estimates were processed to produce time-weighted estimates of CO concentration, V_E, and CO x V_E for each clock hour, as well as end-of-hour estimates of COHb. The result was a year-long sequence of hourly values for CO, V_E, CO x V_E, and COHb for each of the 1860 Denver cohorts. These sequences were statistically analyzed to determine the value of various multihour exposure indicators of interest, including the largest eight-hour daily maximum CO concentration occurring each year and the number of times the end-of-hour COHb level exceeded a specified percentage value.

2.5 Extrapolate the Cohort Exposures to the Population-of-Interest and to Individual Sensitive Groups

2.5.1 General Population

The cohort-specific exposure estimates developed in Step 4 of the pNEM methodology (Section 2.4) were extrapolated to the general Denver population by estimating the population size of each cohort. Cohort populations were estimated in three steps. The population of each demographic group within a particular home district [Pop(d,h)] was first estimated from census data specific to that district. Each of these groups was subdivided into a group residing in homes with gas stoves and a group residing in homes with other cooking fuels. The population of each of these groups was determined by the expression

$$\mathrm{Pop}(d,h,f) = F(h,f) \times \mathrm{Pop}(d,h) \qquad (2\text{-}7)$$

where Pop(d,h,f) is the population of a group associated with demographic group d, home district h, and cooking fuel f. F(h,f) is the fraction of homes in Home district h that use cooking fuel f. F(h,f) was determined from BOC census data specific to each district (Bureau of Census, 1992).

The Pop(d,h,f) values provided an estimate of the population of each non-commuting cohort residing within home district h. The populations of the commuting cohorts (assumed to include all working cohorts) were determined by the expression

$$\text{Com}(d,h,f,w) = \text{Pop}(d,h,f) \times \text{Com}(h,w)/\text{Work}(h). \qquad (2\text{-}8)$$

Com(d,h,f,w) is the number of persons in the commuting cohort associated with demographic group d, home district h, cooking fuel f, and work district w; Com(h,w) is the number of workers in all demographic groups that commute from home district h to work district w; and Work(h) is the total number of workers in home district h. Estimates of Work(h) were developed from census data specific to each district. Section 6 describes the method used to estimate Com(h,w) from origin-destination data provided by the BOC.

2.5.2 Persons with Ischemic Heart Disease

The cohort-specific exposure estimates developed in Step 4 were also extrapolated to the sensitive population defined as persons with diagnosed and undiagnosed ischemic heart disease (IHD). The extrapolation was performed using the procedure described in Subsection 2.5.1 with a single variation: the following equation was substituted for Equation 2-8.

$$\text{Pop}(d,h,f) = \text{IHD}(d) \times F(h,f) \times \text{Pop}(d,h). \qquad (2\text{-}9)$$

The term IHD(d) is the fraction of persons in demographic group d with IHD.

Estimates of the prevalence of IHD by demographic group were provided by H. Richmond (memorandum, August 25, 1998). Table 2-8 lists these estimates as percentages. In each case, a total prevalence rate is provided which is the sum of a prevalence rate for diagnosed IHD and a prevalence rate for undiagnosed IHD. Estimates of diagnosed IHD were obtained from the National Health Interview Survey (Adams and Marano, 1995), in which U.S. prevalence rates were disaggregated by age and gender. The estimated prevalence of diagnosed IHD for children (age 0 to 17) is 0.01 percent. According to the National Health Interview Survey, approximately 8.0 million individuals are estimated to have diagnosed IHD in the civilian, non-institutionalized population. These estimates do not include individuals in the military or individuals in nursing homes or other institutions.

Table 2-9 lists the resulting population estimates by exposure district for (1) all adults and (2) adults with IHD. The total number of adults with IHD in the six-district study area is approximately 45,000. District No. 3 has the largest number of adults with IHD (about 14,000), accounting for 30 percent of the total. On average, 5.7 percent of the adults are estimated to have IHD.

In extrapolating the cohort-specific exposure estimates developed in Step 4 to persons with IHD, analysts assumed the activity patterns of IHD were similar to those of the general population. Section 5.5 presents the results of a statistical analysis performed to evaluate the reasonableness of this assumption.

The estimates of undiagnosed IHD in Table 2-8 were based on two assumptions: (1) there are 3.5 million persons in the U.S. with undiagnosed IHD and (2) persons with undiagnosed IHD are distributed within the population in the same proportions as persons with diagnosed IHD. The 3.5 million statistic was based on an estimate by the American Heart Association (1990) that there are between three and four million persons with undiagnosed IHD.

Table 2-8. Percentage of Persons with Ischemic Heart Disease (IHD) by Demographic Group

Demographic group	Percentage of persons with IHD		
	Diagnosed	Undiagnosed	Total
1. Children, 0 to 17	0.01	0.004	0.014
2. Males, 18 to 44, working	0.38	0.17	0.55
3. Males, 18 to 44, nonworking	0.38	0.17	0.55
4. Males, 45 to 64, working	8.19	3.60	11.8
5. Males, 45 to 64, nonworking	8.19	3.60	11.8
6. Males, 65+	19.2	8.45	27.7
7. Females, 18 to 44, working	0.13	0.06	0.19
8. Females, 18 to 44, nonworking	0.13	0.06	0.19
9. Females, 45 to 64, working	3.25	1.43	4.68
10. Females, 45 to 64, working	3.25	1.43	4.68
11. Females, 65+	12.3	5.41	17.7

Table 2-10. Estimates of Population Residing in Each Denver Exposure District.

Denver exposure district	All adults		Adults with ischemic heart disease	
	Number	Percent of total	Number	Percent of total
1	109,552	14.0	5,915 (5.4)[a]	13.3
2	77,098	9.9	4,360 (5.7)	9.8
3	218,083	28.0	13,527 (6.2)	30.3
4	148,997	19.1	9,811 (6.6)	22.0
5	142,036	18.2	7,699 (5.4)	17.3
6	84,253	10.8	3,266 (3.9)	7.3
All	780,019	100.0	44,578 (5.7)	100.0

[a] Number in parentheses is percentage of adults with ischemic heart disease.

2.6 References for Section 2

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SECTION 3

PREPARATION OF FIXED-SITE MONITORING DATA AND CREATION OF EXPOSURE DISTRICTS

3.1 Selection of Monitoring Sites and Definition of Exposure Districts

Analysts began the process of selecting CO monitoring sites for the current pNEM analysis by obtaining a “Quick Look” report for Colorado CO sites from the EPA Aerometric Information Retrieval System (AIRS) for the years 1993 through 1997. Appendix B contains a facsimile of this report. Analysts designated all sites within Adams, Arapahoe, Boulder, Denver, and Jefferson Counties which reported CO data between 1993 and 1997 as potential sites for the pNEM/CO analysis. Figure 3-1 shows the locations of the sites which met these criteria plotted on a map indicating population density. (The Greeley site did not qualify as a potential site, as it was located in Weld County. It is included in Figure 3-1 to show its relative location to the other sites). Table 3-1 lists the CO sites initially under evaluation and indicates the number of 1-hour values reported by each site during each year in the 1993-1997 period. Note that the list includes all five of the monitoring sites used in 1992 pNEM/CO analysis. These sites are identified by the codes A, B, C, L, and M. Site descriptions for these monitors are provided in Appendix A of the report by Johnson et al. (1992).

EPA specified that the pNEM/CO analysis for Denver must use three years of data for each monitoring site and that preference should be given to recent years. Table 3-2 lists the second highest daily maximum 8-hour concentration reported by each site in Table 3-1 for 1995, 1996, and 1997. Five of the sites did not meet the 75% completeness criterion for each of the three years: Commerce City, Englewood, Denver 031-0018, Denver 031-0019, and Denver 031-0020. These sites were dropped from further consideration.

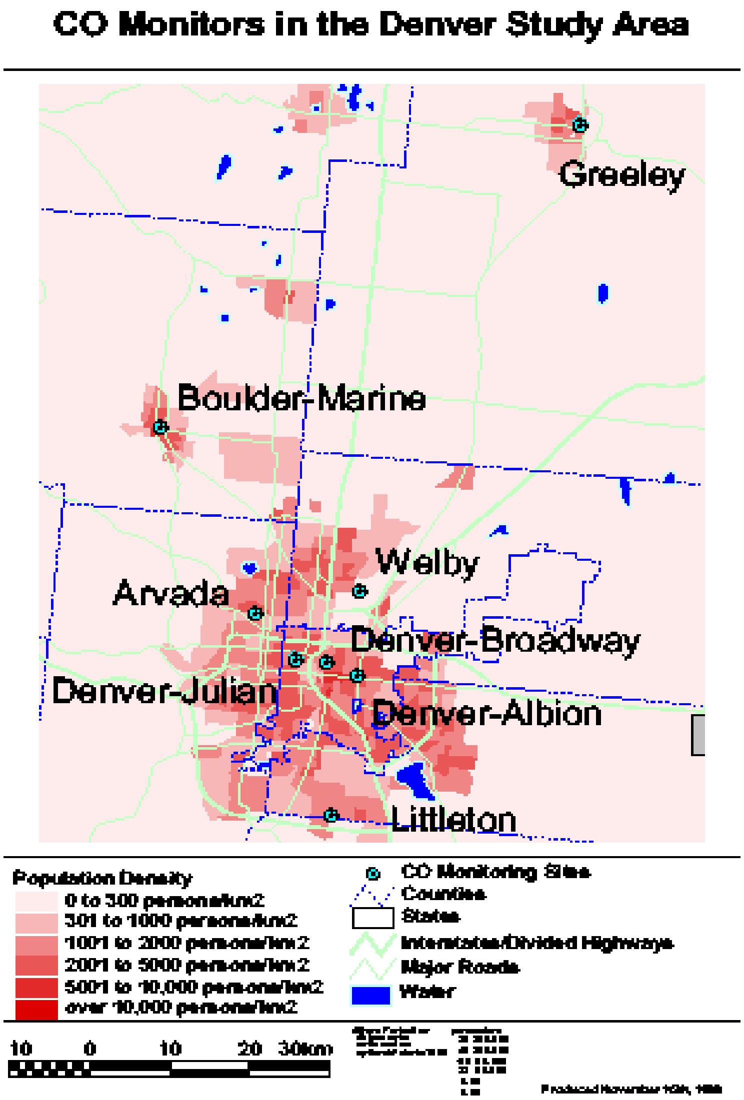

Figure 3-1. Monitoring Sites in the Greater Denver Metropolitan Area.

Table 3-1. Fixed-Site Monitors Reporting Carbon Monoxide Data for the Denver Area Between 1993 and 1997.

County	Monitor Description			1992 pNEM/CO monitor ID	Number of one-hour values reported by year				
	Site ID	City	Address		1993	1994	1995	1996	1997
Adams	001-3001	Welby	78th Ave. and Steele Street	-	8632	8687	8681	8712	8661
	001-7015	Commerce City	Rocky Mountain Arsenal	-	7919	3595	0	0	0
Arapahoe	005-0002	Littleton	8100 So. University Blvd. (Highlands)	M	8589	8705	8670	8677	8463
	005-0003	Englewood	3300 S. Huron Street	-	8717	7126	0	0	0
Boulder	013-0009	Longmont	440 Main Street	-	8701	8557	8690	8735	8617
	013-0010	Boulder	2150 28th Street	-	353	8639	8608	8576	8697
	013-1001	Boulder	2320 Marine Street	-	8708	8565	8651	8669	8517
Denver	031-0002	Denver	2105 Broadway (Broadway)	A	8687	8700	8697	8673	8687
	031-0013	Denver	14th and Albion St. (Albion)	C	8675	8665	8647	8516	8690
	031-0014	Denver	23rd and Julian (Julian)	B	8676	8543	8701	8736	8677
	031-0018	Denver	Blake St. side of Speer	-	1021	1591	0	0	0
	031-0019	Denver	Speer and Auraria Parkway	-	997	3049	3658	8694	8354
	031-0020	Denver	935 Colorado Blvd., UCHS	-	0	1370	2141	0	0
Jefferson	059-0002	Arvada	W. 57th Ave and Garrison	L	8723	8525	8680	8724	8697

Table 3-2. Three-Year Average Value of Second Largest Daily Maximum 8-Hour CO Concentration for Denver Area Monitors.

County	Monitor Description			1992 pNEM/CO monitor ID	Second high max 8-hour concentration, ppm				
	Site ID	City	Address		1995	1996	1997	avg	> 9 ppm
Adams	001-3001	Adams County	78th Ave. And Steele Street	-	5.1	3.9	4.3	4.4	0
	001-7015	Commerce City	Rocky Mountain Arsenal	-	-	-	-	-	-
Arapahoe	005-0002	Littleton	8100 So. University Blvd. (Highlands)	M	2.1	2.6	2.8	2.5	0
	005-0003	Englewood	3300 S. Huron Street	-	-	-	-	-	-
Boulder	013-0009	Longmont	440 Main Street	-	4.7	5.5	5.4	5.2	0
	013-0010	Boulder	2150 28th Street	-	5.2	4.3	3.9	4.5	0
	013-1001	Boulder	2320 Marine Street	-	3.7	2.5	3.3	3.2	0
Denver	031-0002	Denver	2105 Broadway (Broadway)	A	9.5	7.3	5.5	7.4	2
	031-0013	Denver	14th and Albion St. (Albion)	C	6.2	5.2	4.7	5.4	0
	031-0014	Denver	23rd and Julian (Julian)	B	5.9	5.7	6.2	5.9	0
	031-0018	Denver	Blake St. side of Speer	-	-	-	-	-	-
	031-0019	Denver	Speer and Auraria Parkway	-	(7.1)[a]	7.0	6.4	6.8	0
	031-0020	Denver	935 Colorado Blvd., UCHS	-	(6.0)[b]	-	-	-	-
Jefferson	059-0002	Arvada	W. 57th Ave and Garrison	L	4.6	4.3	4.9	4.6	0

[a] Number of values = 3658

[b] Number of values = 2141

Fixed-Site Monitors with 1995-1997 Data

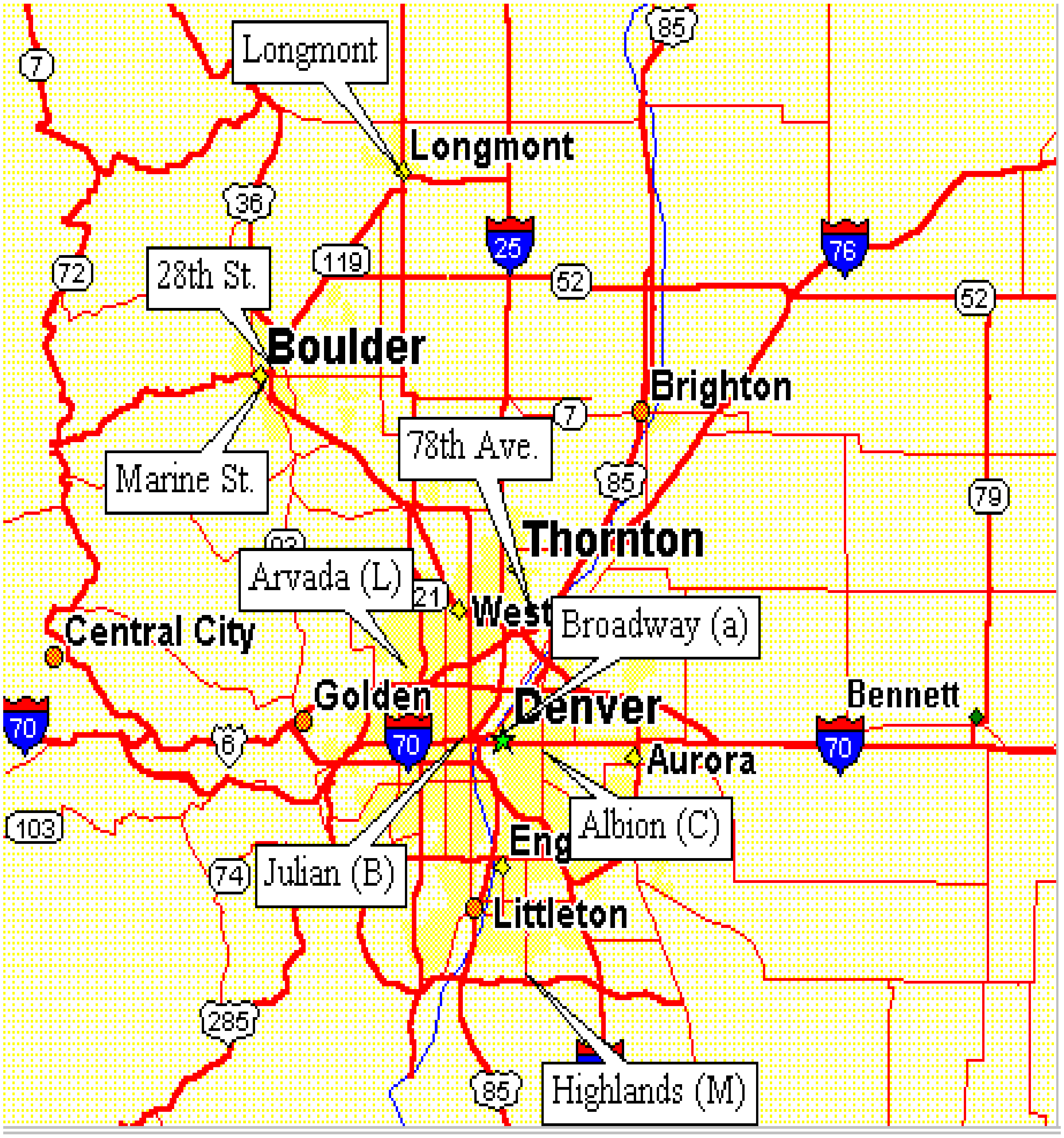

Figure 3-2. Monitoring Sites in the Denver Area Which Reported Data for 1995 Through 1997.

Figure 3-2 shows the locations of the remaining nine sites. Consistent with guidance received from EPA, analysts next omitted the 78th Avenue (Welby) and Longmont sites. The 78th Avenue site is located in a predominately agricultural area which was considered unrepresentative of urban residential locations. The Longmont site was considered to be too distant from other sites.

Seven sites remained at this stage of the selection procedure: the five sites used in the 1992 Denver analysis and two Boulder sites (28th Street and Marine Street). The locations of five sites used in the 1992 analysis were considered appropriate for defining five separate exposure districts with 10 km radii. However, the Boulder sites were considered too close together to support separate exposure districts. With EPA's approval, analysts defined six exposure districts -- one for each of the 1992 Denver sites and a "composite" Boulder site. For purposes of constructing the associated exposure district, the composite site was assigned a location midway between the two Boulder sites (UTM Zone 13: Northing 4429.6495, Easting 477.625). The outdoor CO concentration for hour h in this district was defined as the average of values reported by the two Boulder sites for hour h.

The exposure period was defined as calendar years 1995, 1996, and 1997. Consequently, 21 "site-years" of data were selected for the current Denver analysis (7 sites x three years/site). The statistics listed in Table 3-1 indicate that each of the selected site-years of data was at least 96.6 percent complete.

Table 3-3 provides site characteristics for each of the seven Denver-area monitors included in the exposure analysis. The information in the table was obtained from the Aerometric Information Retrieval System (AIRS) by Mr. David Lutz of EPA's Environmental Monitoring and Analysis Division. The table will be updated when additional information is provided by the State of Colorado.

3.2 Estimation of Missing Values

The pNEM/CO model requires that each input site-year of monitoring data be complete (gapless). The missing values in each data set were estimated using a time series model developed by Johnson and Wijnberg (1981). The time series model is based on the assumption that hourly average air quality values can be represented by a

Table 3-3. Characterization of Monitoring Sites Used in pNEM/CO for the Denver Urban Area.

City	Site Name and Address	AIRS ID	Land Use	Spatial Scale	Elevation (meters)	Monitor Height (meters)	Distance to Roads (meters)[a]	Traffic Volumes (vehicles per day)[b]
Littleton	Highlands 8100 University Blvd.	005-0002	site terminated 12/31/97	---	---	---	---	---
Denver	Camp 2105 Broadway	031-0002	commercial	microscale	1591	3	#1 - 6 #2 - 16 #3 - 7	#1 - 17200 #2 - 1000 #3 - 10000 #4 - 8000 #5 - 8000
Denver	NJHE 14th and Albion St.	031-0013	residential	neighborhood	1615	3	---	---
Denver	Carriage 23rd and Julian	031-0014	residential	neighborhood	1609	4	#1 - 51 #2 - 59	#1 - 5000 #2 - 1000
Arvada	W. 57th Ave. and Garrison	059-0002	residential	---	1641	5	179	#1 - 22000 #2 - 4000
Boulder	2150 28th St.	013-0010	commercial	microscale	---	3	9	28000
Boulder	2320 Marine St.	013-1001	residential	---	1619	4	#1 - 67 #2 - 179 #3 - 219	#1 - 500 #2 - 1000 #3 - 5000

[a] When the monitoring site is near more than one roadway, the distance is provided for each roadway separately.

[b] When the monitoring site is near more than one roadway, the traffic volume is provided for each roadway separately.

combination of cyclical, autoregressive, and random processes. The parameter values of these processes are determined by a statistical analysis of the reported data.

Tables 3-4 through 3-10 provide descriptive statistics by monitoring site for the 1-hour CO concentrations in each data set before and after estimation of the missing values. The statistics indicate that the addition of missing-value estimates did not significantly affect the distribution of any data set. Each table also provides descriptive statistics for running-average 8-hour concentrations after estimation of missing values.

Table 3-11 provides a comparison of the descriptive statistics (after estimation of missing values) for the 1-hour CO concentrations associated with each of the Boulder sites and with the composite site. Table 3-12 provides both 1-hour and 8-hour descriptive statistics for the Boulder “composite” site after estimation of missing values.

Table 3-4. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Littleton “Highlands” Site (005-0002, M) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8670	0.3	0.7	1.0	1.8	2.2	3.3	3.6
	1 h (s)	8760	0.3	0.7	1.0	1.8	2.2	3.3	3.6
	8 h (s)	8760	0.3	0.7	0.8	1.4	1.7	2.5	2.6
1996	1 h (o)	8677	0.3	0.7	1.0	1.8	2.2	4.1	4.3
	1 h (s)	8784	0.3	0.7	1.0	1.8	2.2	4.1	4.3
	8 h (s)	8784	0.3	0.6	0.8	1.5	1.6	2.9	2.9
1997	1 h (o)	8463	0.3	0.7	1.0	1.8	2.0	4.0	4.3
	1 h (s)	8760	0.3	0.7	1.0	1.7	2.0	4.0	4.3
	8 h (s)	8760	0.3	0.6	0.8	1.3	1.5	2.8	3.0

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-5. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Denver “Broadway” Site (031-0002, A) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8697	1.2	2.7	3.4	6.1	7.7	16.4	24.5
	1 h (s)	8760	1.2	2.7	3.4	6.1	7.7	16.4	24.5
	8 h (s)	8760	1.3	2.4	3.0	4.7	5.8	10.8	11.0
1996	1 h (o)	8673	1.1	2.5	3.2	5.7	6.9	16.7	21.6
	1 h (s)	8784	1.1	2.5	3.2	5.6	6.9	16.7	21.6
	8 h (s)	8784	1.2	2.2	2.8	4.3	4.9	8.7	9.0
1997	1 h (o)	8687	1.0	2.4	3.0	5.4	6.3	10.0	11.4
	1 h (s)	8760	1.0	2.4	3.0	5.4	6.3	10.0	11.4
	8 h (s)	8760	1.1	2.1	2.7	4.1	4.6	5.7	5.7

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-6. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Denver “Albion” Site (031-0013, C) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8647	0.9	2.5	3.4	5.5	6.4	13.6	14.6
	1 h (s)	8760	0.9	2.5	3.4	5.5	6.4	13.6	14.6
	8 h (s)	8760	1.1	2.2	2.7	3.7	4.3	8.5	8.5
1996	1 h (o)	8516	0.8	2.2	3.0	5.1	5.7	9.4	14.6
	1 h (s)	8784	0.8	2.2	3.0	5.0	5.7	9.4	14.6
	8 h (s)	8784	1.0	1.9	2.4	3.6	4.2	5.4	5.6
1997	1 h (o)	8690	0.8	2.1	2.8	4.7	5.4	10.6	11.6
	1 h (s)	8760	0.8	2.1	2.8	4.7	5.4	10.6	11.6
	8 h (s)	8760	0.9	1.9	2.3	3.4	3.9	4.8	4.8

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-7. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Denver “Julian” Site (031-0014, B) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8701	0.7	2.3	3.2	5.3	6.4	9.9	10.4
	1 h (s)	8760	0.7	2.3	3.2	5.3	6.5	9.9	10.4
	8 h (s)	8760	0.8	2.1	2.7	4.1	4.8	7.2	7.3
1996	1 h (o)	8736	0.6	2.0	2.9	4.7	5.5	8.2	9.1
	1 h (s)	8784	0.6	2.0	2.9	4.7	5.5	8.2	9.1
	8 h (s)	8784	0.7	1.8	2.4	3.6	4.0	7.2	7.3
1997	1 h (o)	8677	0.6	2.1	2.9	5.0	5.8	8.4	9.5
	1 h (s)	8760	0.6	2.1	2.9	5.0	5.8	8.4	9.5
	8 h (s)	8760	0.7	2.0	2.5	3.8	4.2	6.9	7.0

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-8. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Arvada Site (059-0002, L) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8680	0.6	2.0	2.7	4.8	5.8	8.9	11.9
	1 h (s)	8760	0.6	2.0	2.7	4.8	5.8	8.9	11.9
	8 h (s)	8760	0.8	1.8	2.3	3.1	3.5	5.0	5.1
1996	1 h (o)	8724	0.5	1.7	2.4	4.1	4.9	7.2	7.9
	1 h (s)	8784	0.5	1.7	2.4	4.1	4.9	7.2	7.9
	8 h (s)	8784	0.6	1.6	2.0	2.8	3.1	4.3	4.3
1997	1 h (o)	8697	0.6	1.8	2.4	4.2	5.1	7.7	9.2
	1 h (s)	8760	0.6	1.8	2.4	4.2	5.1	7.7	9.2
	8 h (s)	8760	0.6	1.6	2.1	3.0	3.3	5.0	5.1

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-9. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Boulder “28th Street” Site (013-0010) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8608	0.8	2.1	2.8	4.8	5.5	10.3	10.6
	1 h (s)	8760	0.8	2.1	2.8	4.8	5.5	10.3	10.6
	8 h (s)	8760	0.9	1.8	2.2	3.1	3.6	5.2	5.3
1996	1 h (o)	8576	0.7	1.8	2.4	4.0	4.7	8.4	8.5
	1 h (s)	8784	0.7	1.8	2.4	3.9	4.7	8.4	8.5
	8 h (s)	8784	0.8	1.6	1.9	2.8	3.1	5.4	5.6
1997	1 h (o)	8697	0.7	1.7	2.4	4.0	4.5	8.2	9.0
	1 h (s)	8760	0.7	1.7	2.4	3.9	4.5	8.2	9.0
	8 h (s)	8760	0.8	1.5	2.0	2.9	3.3	5.5	5.5

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-10. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Boulder “Marine Street” Site (013-1001) Before and After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (o)	8651	0.4	0.9	1.3	2.3	2.9	8.2	8.3
	1 h (s)	8760	0.4	0.9	1.3	2.3	2.9	8.2	8.3
	8 h (s)	8760	0.5	0.9	1.1	1.8	2.1	3.8	3.9
1996	1 h (o)	8669	0.4	0.9	1.1	2.1	2.5	4.3	4.5
	1 h (s)	8784	0.4	0.9	1.1	2.0	2.5	4.3	4.5
	8 h (s)	8784	0.4	0.8	1.0	1.5	1.8	2.5	2.5
1997	1 h (o)	8517	0.4	0.8	1.2	2.4	3.0	6.9	7.1
	1 h (s)	8760	0.4	0.9	1.2	2.4	3.0	6.9	7.1
	8 h (s)	8760	0.4	0.8	1.0	2.0	2.3	5.0	5.1

[a] 1 h (o): original 1-hour data set as down-loaded from AIRS.
1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

Table 3-11. Comparison of Descriptive Statistics for 1-Hour Carbon Monoxide Concentrations Reported by 28th Street, Marine Street, and Composite Sites in Boulder After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	28th	8760	0.8	2.1	2.8	4.8	5.5	10.3	10.6
	Marine	8760	0.4	0.9	1.3	2.3	2.9	8.2	8.3
	Comp.	8760	0.7	1.5	2.0	3.3	3.8	8.7	9.5
1996	28th	8784	0.7	1.8	2.4	3.9	4.7	8.4	8.5
	Marine	8784	0.4	0.9	1.1	2.0	2.5	4.3	4.5
	Comp.	8764	0.6	1.3	1.7	2.8	3.3	6.0	6.0
1997	28th	8760	0.7	1.7	2.4	3.9	4.5	8.2	9.0
	Marine	8760	0.4	0.9	1.2	2.4	3.0	6.9	7.1
	Comp.	8760	0.6	1.3	1.7	3.0	3.6	6.8	7.3

[a] 28th = 28th Street, Marine = Marine Street, Comp. = composite site (hour-by-hour average of 28th Street and Marine Street values).

Table 3-12. Descriptive Statistics for Carbon Monoxide Concentrations Reported by Boulder “Composite” Site After Estimation of Missing Values.

Year	Data set[a]	No. of obs.	Descriptive statistics for CO concentration, ppm						
			50th	90th	95th	99th	99.5th	second maximum	maximum
1995	1 h (s)	8760	0.7	1.5	2.0	3.3	3.8	8.7	9.5
	8 h (s)	8760	0.7	1.3	1.6	2.3	2.7	4.5	4.6
1996	1 h (s)	8764	0.6	1.3	1.7	2.8	3.3	6.0	6.0
	8 h (s)	8764	0.6	1.2	1.4	2.0	2.4	3.9	4.0
1997	1 h (s)	8760	0.6	1.3	1.7	3.0	3.6	6.8	7.3
	8 h (s)	8760	0.6	1.1	1.5	2.3	2.6	5.2	5.3

[a] 1 h (s): supplemented 1-hour data set (includes estimates of missing values)
8 h (s): supplemented 8-hour running average data set [based on 1 h (s) data].

3.3 References for Section 3

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SECTION 4

THE MASS-BALANCE MODEL

The 1992 application of pNEM/CO to Denver marked a milestone in the evolution of the NEM methodology in that it represented the first time that a mass-balance model had been incorporated directly into the NEM methodology. Researchers updated the mass balance model for use in Version 2.0 of pNEM/CO. This section provides an overview of the pNEM/CO mass-balance model together with descriptions of the algorithms used in the model to estimate air exchange rates and emissions from gas stoves. It also describes the data used for the input parameters to the mass-balance model.

4.1 Overview of the Model

The pNEM/CO methodology includes a mass-balance model which is used to estimate CO concentrations when a cohort is assigned to an indoor or motor vehicle microenvironment. The mass-balance model is based on the generalized mass-balance model presented by Nagda, Rector, and Koontz (1987). As originally proposed, this model assumed that pollutant concentration decays indoors at a constant rate. For use in pNEM/CO, the Nagda model was revised to incorporate an alternative assumption that the indoor decay rate is proportional to the indoor concentration. The resulting model can be expressed by the differential equation

$$\frac{dC_{in}}{dt} = (1 - F_B)\ \nu C_{out} + \frac{S}{cV} - m\nu C_{in} - F_d C_{in} - \frac{qFC_{in}}{cV} \qquad (4\text{-}1)$$

in which

C_{in} = Indoor concentration (units: mass/volume)

F_B = Fraction of outdoor concentration intercepted by the enclosure (dimensionless fraction)

F_d = Pollutant decay coefficient (1/time)

ν = Air exchange rate (1/time)

C_{out} = Outdoor concentration (mass/volume)

S = Indoor generation rate (mass/time)

cV = Effective indoor volume where c is a dimensionless fraction (volume)

m = Mixing factor (dimensionless fraction)

q = Flow rate through air-cleaning device (volume/time)

F = Efficiency of the air-cleaning device (dimensionless fraction)

As CO is a nonreactive pollutant, it is reasonable to assume 1) that the enclosure does not intercept any of the CO as it moves indoors, 2) that the CO does not decay once it enters the enclosure, and 3) that no CO is removed by air-filtration devices. Under these assumptions, the parameters F_B, F_d, and F in Equation 4-1 would be set equal to zero. If the additional assumptions are made that c and m are each equal to 1, the resulting differential equation is

$$\frac{dC_{in}}{dt} = \nu C_{out} + \frac{S}{V} - \nu C_{in} \qquad (4\text{-}2)$$

It can be shown that this equation has the following exact solution:

$$C_{in}(t) = k_1 C_{in}(t - \Delta t) + k_2 C_{out}(t - \Delta t) + k_3 \qquad (4\text{-}3)$$

where

$$k_1 = e^{-\nu \Delta t} \qquad (4\text{-}4)$$

$$k_2 = 1 - e^{-\nu\Delta t} \tag{4-5}$$

$$k_3 = S(1 - e^{\nu\Delta t})/\nu V \tag{4-6}$$

and Δt is a fixed time interval. Based on this relationship, the average indoor pollutant concentration of hour h [$\mathbf{C_{in}(h)}$] can be calculated by the expression

$$\mathbf{C_{in}}(h) = a_i C_{in}(h - 1) + a_2 \mathbf{C_{out}}(h) + a_3 \tag{4-7}$$

where $C_{in}(h - 1)$ is the indoor concentration at the end of the preceding hour and $\mathbf{C_{out}}(h)$ is the average outdoor concentration during hour h. The other variables appearing in Equation 4-7 are defined by the following equations:

$$a_1 = z(h), \tag{4-8}$$

$$a_2 = 1 - z(h), \tag{4-9}$$

$$a_3 = \frac{S}{\nu V}[1 - z(h)], \tag{4-10}$$

$$z(h) = (1 - e^{-\nu})/\nu. \tag{4-11}$$

Equation 4-7 was used to construct a sequence of hourly average values for each combination of microenvironment (indoor and motor vehicle) and exposure district.

In constructing each sequence, the value of $\mathbf{C_{out}}$ for a particular hour was set equal to the value for outdoor concentration determined for that hour by the algorithm described in Subsection 2.4.1. A value for air exchange rate (ν) was selected from a user-specified distribution each day at midnight and held constant for the entire day. This procedure was consistent with the procedure used to construct the EES for each cohort. As discussed in Section 2, each EES consisted of a series of person-days selected from an activity diary data base. Each person-day spanned a 24-hour period from midnight to midnight.

The term S/V represents the contributions of indoor sources to indoor levels. This term was included in the mass-balance equation when the microenvironment was indoors - residence and the cohort was characterized as using natural gas for cooking. The S parameter was assumed to represent emissions from a single gas stove in the residence, and the V parameter was assumed to represent the total volume of the residence.

Gas stove operation within the indoor - residence microenvironment was simulated by assuming a constant emission rate attributable to pilot light operation and a varying emission rate attributable to burner operation. Burner operation was assumed to occur in discrete "burner operation periods" (BOPs) of 60 minutes duration during normal dinner hours and of 30 minutes duration at other times. No more than one BOP was permitted to occur within a given clock hour, and each BOP began and ended with the same clock hour. A Monte Carlo process was used to randomly assign BOPs to clock hours throughout the year based on a table listing the probability of a BOP occurring within each hour of a typical day. This table was developed from an analysis of gas stove use patterns observed during the Denver Personal Monitoring Study (Johnson, 1984).

An average burner emission rate was determined for each midnight-to-midnight period by selecting annual gas use and emission factor values from user-specified distributions. Pilot lights were assumed to operate continuously at a constant emission rate. The simulated burner and pilot light emissions were summed for each clock hour and presented to the mass-balance model as an hourly average value for S. The residential volume (V) receiving the CO emissions was determined for each midnight-to-midnight period by selecting values from a distribution representing the housing stock in Denver.

The following subsections provide descriptions of the algorithms and data bases used to determine the air exchange rates, burner operation probabilities, burner emission rates, pilot light emission rates, and residential volumes used in the mass-balance model. Many of these algorithms require that values be selected at random from normal or lognormal distributions. This selection was conducted by first defining the distribution of interest by one of the following expressions:

$$\text{Normal:} \quad X = AM + (ASD)(z) \tag{4-12}$$

$$\text{Lognormal:} \quad X = (GM)(GSD)^{Z} \tag{4-13}$$

In these expressions, AM is the arithmetic mean, ASD is the arithmetic standard deviation, GM is the geometric mean, and GSD is the geometric standard deviation. The distribution type (normal vs. lognormal) and the corresponding values for the mean and standard deviation were determined by fitting distributions to representative data sets. A value for X was selected from a particular distribution by randomly selecting a value for Z from the unit normal distribution [N(0, 1)] and substituting it into the appropriate equation. Tables 4-1 and 4-2 list the distribution type and parameter values for each of the random variables used in the mass-balance model.

4.2 The Air Exchange Rate Algorithm

An air exchange rate (AER) value was estimated for each indoor microenvironment (IME) for each 24-hour period (midnight to midnight) of the exposure year. The estimation procedure consisted of randomly selecting AER values from a distribution specific to each IME.

Two distinct AER distributions were established for the residential IME: one representing windows open and one representing windows closed. The choice between windows open and windows closed was conditioned on the air conditioning (AC) system assigned to the residence and the outdoor temperature. For each 24-hour period, an AC algorithm was used to probabilistically specify the AC system for the residence (central, window units, or none). A window status algorithm was then used to probabilistically determine window status (closed or open). Based on this determination, a value of AER for the 24-hour period was selected from either the closed window distribution or the open window distribution.

The AC algorithm requires that the user specify the proportion of residences in the study area that have central AC, window units, and no AC. According to the 1995 American Housing Survey for Denver (Bureau of the Census, 1995), the breakdown for Denver is 25.3 percent central, 14.3 percent window, and 60.4 percent none. The algorithm as applied to Denver can be described as follows:

Table 4-1. Distributions of Parameter Values Used in the pNEM/CO Mass-Balance Model

Parameter	Distribution of parameter	Reference
Air exchange rate, exchanges/h: residence - windows closed	Lognormal distributions by season ***Season 1*** ○ Geometric mean = 0.450 ○ Geometric standard deviation = 1.960 ○ Lower bound = 0.120 ○ Upper bound = 1.683 ***Season 2*** ○ Geometric mean = 0.308 ○ Geometric standard deviation = 2.241 ○ Lower bound = 0.063 ○ Upper bound = 1.498 ***Season 3*** ○ Geometric mean = 0.653 ○ Geometric standard deviation = 2.010 ○ Lower bound = 0.166 ○ Upper bound = 2.566 ***Season 4*** ○ Geometric mean = 0.309 ○ Geometric standard deviation = 1.716 ○ Lower bound = 0.107 ○ Upper bound = 0.890	Johnson, Memorandum No. 1, 1998 Murray and Burmaster, 1995
Air exchange rate, exchanges/h: residence - windows open	Lognormal distribution ○ Geometric mean = 1.34 ○ Geometric standard deviation = 1.55 ○ Lower bound = 0.57 ○ Upper bound = 3.16	Johnson, Memorandum No. 1, 1998 Johnson, Weaver, Mozier, et al., 1998
Air exchange rate, exchanges/h: nonresidential, enclosed microenvironments, including motor vehicles	See Table 4-2	See Table 4-2
Annual gas usage by burners, kilojoules	Lognormal distribution ○ Geometric mean = 2.11×10^6 ○ Geometric standard deviation = 1.48 ○ Lower bound = 0.98×10^6 ○ Upper bound = 4.55×10^6	Menkedick et al., 1993
Annual gas usage by pilot lights, kilojoules	Lognormal distribution ○ Geometric mean = 3.37×10^6 ○ Geometric standard deviation = 1.84 ○ Lower bound = 1.02×10^6 ○ Upper bound = 11.13×10^6	Menkedick et al., 1993
Burner emission factor, mg/kilojoule	Lognormal distribution ○ Geometric mean = 0.0294 ○ Geometric standard deviation = 2.77 ○ Upper bound = 0.400	Davidson et al., 1987
Residential volume, cubic meters	Lognormal distribution ○ Geometric mean = 436 ○ Geometric standard deviation = 1.62 ○ Lower bound = 169 ○ Upper bound = 1122	Bureau of Census, 1995

Table 4-2. Distributions for Air Exchange Rate for Enclosed, Nonresidential Microenvironments

Microenvironment			Activity diary locations included in microenvironment	Distribution of Air Exchange Rate					
				Distribution type	Lognormal Parameters		Bounds		Source of data
Code	General location	Specific location			GM	GSD	Lower	Upper	
2	Indoors	Nonresidence A	Service station or auto repair	Lognormal	1.24	1.93	0.34	4.50	a
3	Indoors	Nonresidence B	Other repair shop Shopping mall	Lognormal	1.24	1.93	0.34	4.50	a
4	Indoors	Nonresidence C	Restaurant Other indoor location Auditorium	Lognormal	1.24	1.93	0.34	4.50	a
5	Indoors	Nonresidence D	Store Office Other public building	Lognormal	1.24	1.93	0.34	4.50	a
6	Indoors	Nonresidence E	Health care facility School Church Manufacturing facility	Lognormal	1.36	1.91	0.38	4.83	b
7	Indoors	Residential garage	Residential garage	Lognormal	1.24	1.93	0.34	4.50	a
10	Vehicle	Automobile	Automobile	Lognormal	39.7	1.76	13.1	120	c

Microenvironment			Activity diary locations included in microenvironment	Distribution of Air Exchange Rate					
				Distribution type	Lognormal Parameters		Bounds		Source of data
Code	General location	Specific location			GM	GSD	Lower	Upper	
11	Vehicle	Other	Bus Truck Bicycle Motorcycle Train/subway Other vehicle	Lognormal	39.7	1.759	13.1	120	c
99	Vehicle	Airplane	Airplane	NA	--	--	--	--	--

[a] Data set containing all non-school AER values provided by Turk et al. (1989) and CEC (Lagus Applied Technology, 1995).

[b] Data set containing all AER values provided by Turk et al. (1989) and CEC (Lagus Applied Technology, Inc., 1995).

[c] Ott, Switzer, and Willis (1994).

1. For each day, select a random number (RN) between zero and 1.
2. If RN $\leq$ 0.253, the AC system is "central."
3. If 0.253 < RN $\leq$ 0.396, the AC system is "window units."
4. If 0.396 <RN, the AC system is "none."

The window status algorithm was originally developed for applications of pNEM/O3 and has been described by Johnson et al. (1990). This algorithm determines window status based on AC system and the daily average temperature according to the probabilities listed in Table 4-3. The combination of window status algorithm and AER algorithm can be described as follows:

1. For each day, determine daily average temperature from a supplementary temperature file and AC system from AC system algorithm. Select RN between zero and 1.

2. Assume Step 1 specified 65 degrees and central AC. RN will be evaluated against percentage values listed in Table 4-3 for central AC - medium temperature range (i.e., 35.6, 29.4, and 34.6).

3. If RN $\leq$ 0.356, windows are closed all day. AER value is selected from the "windows closed" AER distribution.

4. If 0.356 < RN $\leq$ 0.650, windows are open all day. AER value is selected from the "windows open" AER distribution.

5. If 0.650 < RN, windows are open for 58.2 percent of the day (see last column). AER is determined by the expression

   $$\text{AER} = (0.582)(\text{open AER}) + (0.418)(\text{closed AER}) \qquad (4\text{-}14)$$

   where open AER is selected from the open window AER distribution and closed AER is selected from the closed window AER distribution.

4.3 Air Exchange Rate Distributions

A review of scientific literature was conducted to identify references relating to air exchange rates (AERs). Of the references identified, only a few were found to contain sufficient data to construct a distribution of AERs relating to a particular building type such as residence or office. The three most useful studies were conducted by Murray and Burmaster (1995), Turk et al. (1989), and Lagus Applied Technology (1995).

Table 4-3. Percentage of Person-Days With Indicated Window Ratio by Air Conditioning System And Temperature Range

Air conditioning system	Temperature range[a]	Percentage of person-days with indicated window ratio[b]			Mean of ratios not equal to 0 or 1
		Ratio = 0	Ratio = 1	0 < Ratio = <1	
Central	Low	86.0	0.8	13.2	0.260
	Medium	35.6	29.4	34.6	0.582
	High	62.1	12.9	25.0	0.503
Room units	Low	73.2	2.0	24.7	0.316
	Medium	12.0	44.2	43.8	0.618
	High	17.1	34.3	48.6	0.521
No air conditioning	Low	80.0	1.0	19.0	0.276
	Medium	4.7	59.1	36.2	0.716
	High	1.4	70.8	27.8	0.774

[a] Low: 31° to 62°F.
Medium: 63° to 75°F.
High: 76°F and above.

[b] Ratio = (minutes windows open)/(minutes spent in residence).

4.3.1 Residential Locations

An article by Murray and Burmaster (1995) described their analysis of residential air exchange rate data compiled by the Brookhaven National Laboratory (BNL). The BNL data included AERs for 2,844 residences in the United States, classified according to four geographic regions and the four seasons. The data for Denver were included in Region 2. The BNL data for Region 2 includes a large number of AER values for winter and spring, but small sample sizes for summer and autumn (n = 2 and 23, respectively). Statistical methods were used to estimate the geometric mean and standard deviation for the seasons with limited data (Johnson, Memorandum No. 1, 1998). The resulting seasonal AER distributions for Region 2 (which includes Denver) are included in Table 4-1. The lower and upper bounds of the distributions are based on the 2.5th and 97.5th percentile of the distributions.

Note that the Region 2 estimates presented by Murray and Burmaster were based solely on data derived from the BNL database. Pandian et al. (1998) recently identified errors in a version of the BNL database previously used by Pandian, Ott, and Behar (1993) and provided corrected estimates of AER for various geographic regions. In evaluating other researcher's use of the BNL database, Pandian et al. concluded that the errors they identified did not affect the AER statistics presented by Murray and Burmaster. This conclusion is supported by the corrected statistics presented by Pandian et al. (1998) for a region containing Denver which are consistent with the statistics presented by Murray and Burmaster (1995) for Region 2.

For residences with windows open, the AER distribution in Version 2.0 of pNEM/CO is based on a study of a single residence. The American Petroleum Institute (API) conducted a study of a typical suburban house over a 24-hour time period (Johnson, Weaver, Mozier, et al., 1998). In that study, researchers altered the ventilation characteristics of the house each hour according to a prepared script, and measured the resulting hourly average AER. Analysts determined that the data for hours when windows were open could be characterized by a lognormal distribution with a geometric mean of 1.34 air changes per hour, and a geometric standard deviation of 1.55 (Johnson, Memorandum No. 1, 1998). The upper and lower bounds of the distribution have been set at 0.57 and 3.16, which correspond to the 2.5th and 97.5th percentiles, respectively.

4.3.2 Nonresidential Locations

Two AER distributions are used in pNEM/CO to represent non-residential buildings. Microenvironment Nos. 2 through 5 are represented by a lognormal distribution with geometric mean = 1.24 and geometric standard deviation = 1.93. Microenvironment No. 6 is represented by a lognormal distribution with geometric mean = 1.36 and geometric standard deviation = 1.91. These distributions were developed from statistical analyses of AER data provided by two studies. The first study, conducted by Turk et al. (1989), measured AERs in 40 public buildings identified as schools (n = 7), offices (n = 25), libraries (n = 3), and multipurpose buildings (n = 5). The second study was conducted by the California Energy Commission (Lagus Applied Technology, Inc., 1995), and included 49 public buildings identified as schools (15), offices (22), and retail stores (13).

Microenvironment Nos. 2 through 5 are similar in that each includes various types of public buildings but omits schools. To determine a representative distribution of AER for these microenvironments, analysts combined all non-school data from the Turk and CEC studies into a single data set containing 68 values. These values could be well-fit by a lognormal distribution with geometric mean of 1.24 air changes per hour and a geometric standard deviation of 1.93. As indicated in Table 4-2, AER values for Microenvironments Nos. 2 through 5 were randomly selected from this distribution. Values were not permitted to fall below 0.34 or exceed 4.50, corresponding to the 2.5th and 97.5th percentiles of the distribution.

Microenvironment No. 6 differs from Microenvironments Nos. 2 through 5 in that it includes school and non-school buildings. Consequently, analysts used the complete set of AER values from the Turk and CEC studies to represent this microenvironment. The resulting data set could be well fit by a lognormal distribution with geometric mean = 1.36 air changes per hour and geometric standard deviation = 1.91. AER values for Microenvironment No. 6 were randomly selected from this distribution. Values were not permitted to fall below 0.38 or exceed 4.83, corresponding to the 2.5th and 97.5th percentiles of the distribution.

4.3.3 Vehicle Locations

A point estimate of 36 air changes per hour was used for in-vehicle locations in the 1992 version of pNEM/CO. This value was obtained from Hayes (1991) based on his analysis of data presented by Peterson and Sabersky (1975).

In a study reported by Ott, Switzer, and Willis (1994), researchers measured an AER value of 13.1 air changes per hour in a car moving at 20 mph with windows closed. AER values of 67 to 120 were measured in the car at the same speed with windows open.

Peggy Jenkins (1998) has indicated that additional data on AER in vehicles will be available soon from the California Air Resources Board. These data should provide a better basis for determining an AER distribution for vehicles. Until these data are available, AER values for vehicles will be sampled from a lognormal distribution with geometric mean = 39.7 and geometric standard deviation = 1.76. This approach is based on the assumption that the AER distribution has a lognormal distribution and that the 2.5th and 97.5th percentiles of this distribution correspond to the lowest and highest reported AER values for vehicles (13 and 120 air changes per hour, respectively).

4.4 Probability of Stove Use

The operation of gas stove burners in residences is simulated in the mass-balance model by specifying when the burners are on, the emission rate of the burners during operation, and the volume of the residence where it is located.

As discussed above, burner operation was assumed to occur in discrete BOPs such that use always began and ended within a single clock hour. BOP duration was assigned a value of either 30 or 60 minutes, depending on the time of day. These values were based on responses to a questionnaire administered by GEOMET to 4312 survey participants. Each participant provided data on the type of cooking facilities in the home, frequency of cooking, and average time spent in meal preparation (Koontz, Mehegan, and Nagda, 1992).

Table 4-4 presents a summary of data from this survey by type of meal (breakfast, lunch, and dinner). The values listed for average weekly time spent cooking breakfast, lunch, and dinner are 66, 71, and 288 minutes, respectively. The total time for all three meals is 425 minutes per week. The average daily cooking time based on this weekly value is 425/7 or 61 minutes.

Table 4-4. Statistics on Gas Stove Use Obtained from a Survey by Koontz et al. (1992)

Data item	Breakfast	Lunch	Dinner	Sum
Weekly duration of gas stove use, minutes	66	71	288	425
Weekly frequency of gas stove use	2.5	2.2	5.0	9.7
Average duration of use, minutes	26	32	58	

In addition to duration, the data in Table 4-4 provide an indication as to the frequency that a gas stove is used to prepare meals in the typical residence. In one week, the stove will be used to prepare 2.5 breakfasts, 2.2 lunches, and 5.0 dinners -- a total of 9.7 meals per week. On an average day, the number of meals prepared on a gas stove is 9.7/7 or 1.4.

Dividing the weekly cooking time associated with each meal type by the average frequency of the meal yields average BOPs for breakfast, lunch, and dinner of 26, 32, and 58 minutes, respectively. Based on these results, pNEM/CO uses a value of 60 minutes for BOPs that occur during normal dinner hours and 30 minutes for BOPs that occur at other times.

In pNEM/CO, stove operation is determined on an hourly basis by comparing a randomly selected number between 0 and 1 with AP(h), the probability of a gas stove being operated during the indicated clock hour h (h = 1, 2, ..., 24). If the random number is less than AP(h), the stove is "on" for a duration of M(h) minutes, where M(h) is either 30 or 60 minutes, depending on the value of h. If the random number is greater than or equal to AP(h), the gas stove is "off" for the entire hour.

Table 4-5 lists the values of AP(h) and M(h) used in the pNEM/CO analysis by clock hour. These values were developed to (1) reflect diurnal patterns in gas stove usage specific to Denver, (2) yield an average daily duration for stove use of approximately 61 minutes, and (3) yield an average daily frequency of stove use of approximately 1.4.

Diurnal patterns in stove use were determined through an analysis of data from the Denver Personal Monitoring Study (Johnson, 1984). In this analysis, the diary entries and background questionnaire provided by each study subject were used to determine (1) when the subject was in a residence having a gas stove and (2) whether the stove was on. As working subjects would not always be present when other family members were operating a gas stove, it was assumed that workers would tend to under-report stove use in their residences. It was further assumed that nonworkers would use gas stoves more than the average person and that the diaries of nonworkers would tend to over-represent typical gas stove use. Consequently, the decision was made to average the worker and nonworker data and then adjust these results so that the adjusted P(h) values would yield 1.4 hours of stove use "events" per day, on average.

Table 4-6 presents the relevant data. For each clock hour, the table lists values of p(h) for workers and nonworkers calculated as

$$P(h) = [N(\text{stove on, GSR})]/[N(\text{GSR})] \tag{4-15}$$

where N(stove on, GSR) is the number of diary entries indicating the subject was in a

Table 4-5. Probability of Gas Stove Use by Clock Hour and Assumed Burner Operation Period

Clock hour	AP(h): probability of gas stove operation	M(h): assumed burner operation period, minutes	Product of AP(h) and M(h), minutes
1	0.025	30	0.76
2	0.023	30	0.68
3	0.023	30	0.69
4	0.023	30	0.70
5	0.023	30	0.70
6	0.026	30	0.77
7	0.049	30	1.46
8	0.058	30	1.73
9	0.081	30	2.43
10	0.073	30	2.20
11	0.062	30	1.86
12	0.075	30	2.25
13	0.085	30	2.54
14	0.071	30	2.14
15	0.067	60	4.01
16	0.064	60	3.86
17	0.107	60	6.41
18	0.130	60	7.80
19	0.091	60	5.49
20	0.058	60	3.45
21	0.052	60	3.11
22	0.047	60	2.79
23	0.040	30	1.21
24	0.035	30	1.04
Total	1.386		60.04

Table 4-6. Proportion of PEM Values in Gas Stove Residences with Stove in Operation by Clock Hour and Work Status

Clock hour	Nonworkers		Workers		Average P(h)	AP(h): adjusted P(h)
	n	P(h)	n	P(h)		
1	63	0.111	149	0.041	0.076	0.025
2	59	0.085	139	0.051	0.068	0.023
3	5	0.086	136	0.052	0.069	0.023
4	58	0.086	134	0.053	0.070	0.023
5	58	0.086	133	0.053	0.070	0.023
6	62	0.097	141	0.057	0.077	0.026
7	67	0.119	175	0.173	0.146	0.049
8	84	0.179	151	0.167	0.173	0.058
9	119	0.269	134	0.216	0.243	0.081
10	87	0.230	86	0.209	0.220	0.073
11	80	0.200	70	0.171	0.186	0.062
12	76	0.253	76	0.197	0.225	0.075
13	72	0.296	70	0.214	0.255	0.085
14	62	0.213	80	0.215	0.214	0.071
15	51	0.216	59	0.186	0.201	0.067
16	64	0.266	75	0.120	0.193	0.064
17	96	0.396	122	0.246	0.321	0.107
18	103	0.456	174	0.326	0.391	0.130
19	151	0.251	244	0.299	0.275	0.091
20	148	0.149	341	0.196	0.173	0.058
21	102	0.147	236	0.165	0.156	0.052
22	82	0.183	176	0.097	0.140	0.047
23	82	0.159	193	0.083	0.121	0.040
24	75	0.133	148	0.075	0.104	0.035
					4.167	1.386

gas stove residence when the stove was on and N(GSR) is the total number of diary entries indicating the subject was in a gas stove residence. In calculating these values, a stove was considered on during a particular clock hour if the subject's activity diary indicated at least 1 minute of use during the hour.

The column labeled "average P(h)" lists the arithmetic mean of the worker and nonworker P(h) values. These probabilities sum to 4.2 over 24 hours. It is desirable that the probabilities sum to 1.4, as this will produce an average of 1.4 BOPs per day. The values labeled "adjusted P(h)" were calculated by multiplying the average values by 0.333 (1.4/4.2). The adjusted values sum to 1.4.

The AP(h) values are listed also in Table 4-5. To the right of each AP(h) value is the assumed value of M(h); that is, the number of minutes the stove will be assumed to operate if the stove is determined to be "on" during the hour. The product of AP(h) and M(h) is listed in the far right column. Summing these values over all 24 hours provides an estimate of the average number of minutes per day that a gas stove will be operated according to the algorithm. The sum is approximately 60 minutes, a value very close to the desired value of 61 minutes.

4.5 Gas Stove Emission Rate

The gas stove algorithm in pNEM/CO is based on the assumption that the mass of CO emitted by a gas stove during a particular hour (h) can be estimated by the equation

$$\text{MASSCO}(h) = (\text{ERBURN})[M(h)]/60 + (\text{ERPILOT})(1\text{ hr}) \tag{4-16}$$

where MASSCO(h) is expressed in mg, ERBURN is the hourly burn emission rate in mg per hour, and ERPILOT is the hourly pilot light emission rate in mg per hour. M(h) is the duration of burner use during hour h expressed in minutes. The pilot light is assumed to on continuously during the one hour period.

M(h) is zero for each hour in which the algorithm assigns the stove a status of "off." If the stove status is "on" for a particular hour, M(h) is assigned a value of 30 or 60 minutes according to Table 4-6.

ERBURN is determined by the equation

$$ERBURN = (AUB/365.2)(EFBURN)(Y') \qquad (4\text{-}17)$$

where AUB is the annual fuel usage of the burners in kilojoules, 365.2 is the number of hours per year that the burners are operated assuming 60 minutes of use per day (Table 4-6), EFBURN is the burner emission factor in mg of CO per kilojoule, and Y' is an adjustment factor which varies sinusoidally throughout the year. The values of AUB, EFBURN, and Y' are held constant within each 24-hour period.

Values of AUB are randomly selected from a lognormal distribution with geometric mean = 2.11 million kilojoules and geometric standard deviation = 1.48. This distribution is based on the distribution of annual burner gas use measured by the Northern Illinois Gas Company (NIGAS) in 57 homes (Menkedick et al., 1993). The value of AUB is not permitted to exceed 4.55 million kilojoules. This value represents the 97.5th percentile of the distribution.

The seasonal adjustment factor (Y') is determined by the equation

$$Y'(j) = 1.00 - (0.190)\{\sin[-1.616 + (2\pi)(j)/365]\}. \qquad (4\text{-}18)$$

in which j is the Julian date. This equation was derived by Johnson (Memorandum No. 1, 1998) from a sinusoidal pattern observed in a study conducted by NIGAS (Wilkes and Koontz, 1995). The NIGAS data indicate that gas use in the winter is approximately 46 percent higher than in the summer.

Values of EFBURN are randomly selected from a lognormal distribution with geometric mean = 0.0294 mg/kilojoule and geometric standard deviation = 2.77. Values of EFBURN are not permitted to exceed 0.400 mg/kilojoule. These values are based on the results of an analysis of data reported by Davidson et al. (1987) and represent a well-adjusted stove. As such, the assumed geometric mean is probably low with respect to the overall population of gas stoves.

Consistent with the above discussion, the following algorithm is used to estimate a value of ERBURN for each 24-hour period.

1. Go to the next day of the current sequence. The Julian date of this day is j.

2. Randomly select a value for AUB from a lognormal distribution with geometric mean = 2.11 million kilojoules per year and geometric standard deviation = 1.48.

3. Randomly select a value of EFBURN from a lognormal distribution with geometric mean = 0.0294 mg/kilojoule and geometric standard deviation = 2.77.

4. Use Equation 4-18 to calculate Y'(j).

5. ERBURN = (EFBURN)(AUB)(Y')/365.2 for all hours of the day.

The resulting value of ERBURN is inserted into Equation 4-16 as required.

The ERPILOT value in Equation 4-16 is determined by the equation

$$\text{ERPILOT} = (\text{AUP}/8760)(\text{EFPILOT}) \tag{4-19}$$

where AUP is the annual fuel usage by all pilot lights in kilojoules, 8760 is the number of hours per year that the pilot lights are in operation, and EFPILOT is the pilot light emission factor in mg of CO per kilojoule. The value of AUP is constant over each 24-hour period and is randomly selected from a specified lognormal distribution. The value of EFPILOT is assumed to be constant within each 24-hour period and is set equal to the value determined for EFBURN in Equation 4-17.

The distribution for gas usage by pilot lights (AUP) is based on data from the NIGAS study discussed previously. The total gas usage (burners plus pilot lights) for 33 stoves had an arithmetic mean of 57.1 therms and a standard deviation of 18.3 therms. Total gas use was also measured for 57 stoves that did not have pilot lights; the arithmetic mean gas use for stoves without pilot lights was 21.8 therms. The difference between the two samples, 57.1 - 21.8 = 35.3 therms, provides an estimate of the mean fuel usage for pilot lights only. The square root of the differences in variances, $(18.3^2 - 8.9^2)^{1/2} = 16.0$ therms, provides an estimate of the standard deviation. Therefore, AUP is assumed to have an arithmetic mean of 35.3 therms (3,500 ft^3) and an arithmetic standard deviation of 16.0 therms (1,600 ft^3).

The ratio of standard deviation to mean is 0.45, indicating that the distribution is skewed. Consequently, it was assumed that the underlying distribution is lognormal.

The corresponding geometric mean and geometric standard deviation for this distribution are 3,215 ft^3 = 3.37 million kilojoules per year and 1.84 (dimensionless), respectively. The lower and upper bounds for permitted AUP values are 1.02 and 11.13 million kilojoules per year, respectively, corresponding to the 2.5th and 97.5th percentile of the specified lognormal distribution.

The value of MASSCO(h) determined by Equation 4-16 is used as the value of S for hour h in Equation 4-10, regardless of the value of M(h). This approach permits the use of the hourly average exact solution (Equation 4-7) to the mass-balance equation (Equation 4-2). The practical result of this simplification is a slight smoothing in the simulated hour-to-hour variation in indoor CO concentrations with respect to the pattern which would be simulated by a model with finer time resolution.

4.6 Residential Volume

In the application of pNEM/CO to Denver, residence volume was randomly selected from a lognormal distribution based on data from the 1995 American Housing Survey for Denver, Colorado (Bureau of the Census, 1995). Table 4-7 lists frequency data on residential square footage from the survey specific to Denver. These data can be closely fit by a lognormal distribution with a geometric mean of 1926 and a geometric standard deviation of 1.62. The geometric mean agrees well with the median listed in the survey data (2020). (The geometric mean of a “perfect” lognormal distribution is equal to its median).

Assuming an eight-foot ceiling and using 1 cubic meter = 35.315 cubic feet, the residential volumes can be modeled by a lognormal distribution with a geometric mean of 436 m^3 and a geometric standard deviation of 1.62. The upper and lower bounds of the distribution have been set at 169 and 1,122 m^3, respectively, corresponding to the 2.5th and 97.5th percentiles of the distribution.

Table 4-7. Statistics on Square Footage of Occupied Units in Denver, Colorado (Bureau of the Census, 1995).

Range of square footage for occupied units	Denver residences	
	Number in thousands	Cumulative percent
less than 500	1.0	0.2
500 to 749	9.3	2.5
750 to 999	34.1	10.6
1,000 to 1,499	75.6	28.6
1,500 to 1,999	86.0	49.2
2,000 to 2,499	86.7	69.8
2,500 to 2,999	49.8	81.7
3,000 to 3,999	53.4	94.5
4,000+	23.2	100.00
Total[a]	419.1	--

[a] Omits 38,500 units which did not report square footage values.

4.7 References for Section 4

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SECTION 5

ESTIMATION OF VENTILATION RATE

This section provides a brief summary of the algorithm used to estimate ventilation rate in Version 2.0 of pNEM/CO. It also presents distributions and estimating equations for each variable parameter in the algorithm. The section also discusses the rationale behind the decision not to explicitly account for the potential effects of angina in the algorithm. The section begins with a brief discussion of the physiological principles incorporated into the new algorithm.

5.1 The Metabolic Equivalence Concept

McCurdy (1999) has recommended that ventilation rate be estimated as a function of energy expenditure rate. The energy expended by an individual during a particular activity can be expressed as

$$EE = (MET)(RMR) \tag{5-1}$$

in which EE is the average energy expenditure rate (kcal min^{-1}) during the activity and RMR is the resting metabolic rate of the individual expressed in terms of number of energy units expended per unit of time (kcal min^{-1}). MET (the “metabolic equivalent of work”) is a ratio specific to the activity and is dimensionless. If RMR is specified for an individual, then Equation 5-1 requires only an activity-specific estimate of MET to produce an estimate of the energy expenditure rate for a given activity. EPA has recently developed the Consolidated Human Activity Database (CHAD) which contains 24-hour sequences of activity-specific values of MET indexed by gender, age, and other useful descriptors. As discussed below, equations for estimating RMR as a function of body mass (BM) can be obtained from the literature for the demographic groups of interest to a particular exposure assessment.

The MET concept provides a means for estimating the ventilation rate associated with each activity. For convenience, let $EE_a(i,j,k)$ indicate the energy expenditure rate associated with the i-th activity of day j for person k. Equation 5-1 can now be expressed as

$$EE_a(i,j,k) = [MET(i,j,k)][RMR(k)] \tag{5-2}$$

in which RMR(k) is the average value for resting metabolic rate specific to person k. Note that MET(i,j,k) is specific to a particular activity performed by person k.

5.2 Oxygen Requirements for Energy Expenditure

Energy expenditure requires oxygen which is supplied by ventilation (respiration). Let ECF(k) indicate an <u>e</u>nergy <u>c</u>onversion <u>f</u>actor defined as the volume of oxygen required to produce one kilocalorie of energy in person k. The oxygen uptake rate (VO_2) associated with a particular activity can be expressed as

$$VO_2(i,j,k) = [ECF(k)][EE_a(i,j,k)], \tag{5-3}$$

in which $VO_2(i,j,k)$ has units of liters oxygen min^{-1}, ECF(k) has units of liters oxygen $kcal^{-1}$, and EE(i,j,k) has units of kcal min^{-1}. The value of $VO_2(i,j,k)$ can now be determined from MET(i,j,k) by substituting Equation 5-2 into Equation 5-3 to produce the relationship

$$VO_2(i,j,k) = [ECF(k)][MET(i,j,k)][RMR(k)]. \tag{5-4}$$

The analyst must provide values of ECF(k) and RMR(k) for person k. Methods for estimating these values are provided in Section 5.4.

5.3 Estimating V_E from VO_2

Ventilation rate (V_E) tends to increase as VO_2 increases up to the point of maximum oxygen uptake (VO_{2max}). The relationship is known to be non-linear, with the slope of the relationship usually increasing at higher values of VO_2. In Version 2.0 of pNEM/CO, the relationship between V_E(i,j,k) and VO_2(i,j,k) is modeled by the generic equation

$$\ln[VE(i,j,k)/BM(k)] = a + (b)\{\ln[VO2(i,j,k)/BM(k)]\} + d(k) + e(i,j,k) \qquad (5\text{-}5)$$

in which V_E(i,j,k) is the V_E value associated with the ith event of day j for person k, BM(k) is the body mass assigned to person k, and a and b are constants determined by the age and gender of person k according to Table 5-1. The term d(k) is a random variable selected for each person from a normal distribution with mean equal to zero and standard deviation equal to σ_d. The term e(i,j,k) is a random variable selected for each individual event from a normal distribution with mean equal to zero and standard deviation equal to σ_e. Table 5-1 lists values of σ_d and σ_e by age and gender.

The values of a, b, σ_d, and σ_e listed in Table 5-1 were determined through a statistical analysis of data obtained from 32 clinical studies performed by Dr. William Adams. During each study, a panel of subjects were put through a test sequence of increasing levels (steps) of exertion on either a cycle ergometer or a treadmill. At each step, researchers measured test time, machine setting, the subject's ventilation rate (V_E), the subject's oxygen uptake rate (VO_2), and the subject's heart rate (HR). In most cases, researchers also established a maximum value of VO_2 (VO_{2max}) for each sequence of steps. Subject-specific data on age, gender, body mass, lean body mass, height, and other relevant parameters were also recorded.

Johnson (1998) performed a series of statistical analyses on these data to determine whether the data would support the development of subject-specific equations relating VER (the ratio of V_E to VO_2) to VO_2 expressed as a percentage of VO_{2max}. The data for most subjects were found to lack sufficient measurements of V_E at low values of VO_2 to properly "anchor" the lower end of the assumed relationship, although the relationship between V_E and VO_2 at high exertion rates was usually well characterized. Supplemental analyses of the Adams data by EPA researchers suggested that a strong relationship existed between V_E/BM and VO_2/BM (where BM was the body mass of the subject providing the values of V_E and VO_2) when data from multiple subjects were combined according to age and gender.

Based on these findings, EPA elected to develop an equation relating V_E to VO_2 applicable to each of six groups of subjects defined by the age and gender categories listed in Table 5-1. Jonathan Cohen of ICF used regression analysis to fit Equation 5-5 to cross-sectional data for the subjects belonging to each of the six groups. Appendix D describes these analyses in detail. The resulting regression coefficients were used as estimates of a, b, σ_d, and σ_e.

In summary, Equation 5-4 was used to convert event-specific values of MET to corresponding values of VO_2. Equation 5-5 was then used to convert the VO_2 value to a value of V_E. Section 5.4 describes two tests for reasonableness that were performed on the VO_2 estimates prior to converting them to V_E values. Section 5.5 presents a step-by-step description of the algorithm that was used to probabilistically determine the various parameter values required by Equations 5-4 and 5-5.

Table 5-1. Regression-Based Estimates for Parameters of Equation 5-5.

Subject characteristics		Regression results[a]				
					Standard deviation	
Age group	Gender	Number of test values	Intercept (a)	Slope (b)	Person-level errors (σ_d)	Test-level errors (σ_e)
18 - 44	Female	1473	4.357	1.276	0.1351	0.1182
	Male	3145	3.991	1.197	0.1228	0.1395
45 - 64	Female	60	3.454	1.021	0.1106	0.0769
	Male	641	4.018	1.165	0.1107	0.1112
65+	Female	45	2.956	0.908	0.0886	0.0338
	Male	317	3.730	1.071	0.1082	0.0632

[a] Based on regression analysis of data provided by Dr. William Adams. See Appendix D for details.

5.4 Tests to Identify Unrealistic Values of Oxygen Uptake Rate

A person’s maximum ventilation rate is determined by his or her maximum oxygen uptake rate (VO_{2max}) and the V_E/VO_2 ratio in effect under maximum oxygen uptake conditions. As work increases, energy is provided primarily by aerobic (oxygen-based) processes up to the point of VO_{2max}, referred to as the point of maximal aerobic power (MAP). The additional energy required for higher work rates is provided primarily by anaerobic processes. Consequently, the work rate where VO_{2max} is reached is less than a person’s maximum work rate.

Astrand and Rodahl (1977) state that most individuals cannot maintain a work rate equal to 100 percent of MAP (i.e., a work rate where VO_2 equals VO_{2max}) for more than about five minutes. As the duration of work increases, there is a progressive decrease in the average VO_2 level that can be maintained. Astrand and Rodahl also state that a VO_2 level equal to 50 percent of VO_{2max} cannot be maintained for a whole working day.

Erb (1981) has developed estimates of the percentage of “maximum work capacity” that can be maintained by young and middle-aged adults for durations of one to nine hours (Table 5-2). These values -- which apply to normally active, non-trained adults -- appear to be functionally equivalent to the percentage of VO_{2max} (designated $PCTVO_{2max}$) that can be maintained for the indicated time period and are so labeled in Table 5-2. According to Erb, a person can maintain 64 percent of VO_{2max} for one hour and 33 percent of VO_{2max} for nine hours without straining.

The following expression provides a close fit to values Erb proposed for durations of one to nine hours:

$$PCTVO_{2max}(t) = 121.2 - (14.0)[\ln(t)]. \qquad (5\text{-}6)$$

Note that t is duration in minutes and ln indicates the natural (base e) logarithm. Equation 5-6 provides an estimate of approximately 100 percent for t = 5 minutes, consistent with the statement by Astrand and Rodahl that 100 percent of VO_{2max} can be maintained for up to 5 minutes. These findings suggest that it is reasonable to assume that (1) $PCTVO_{2max}$ should not exceed 100 percent for events with durations between 0 and 5 minutes, (2) Equation 5-6 can be used to determine the upper limit of $PCTVO_{2max}$ for events of durations between 5 minutes and 540 minutes (9 hours), and (3) the

$PCTVO_{2max}$ values in Table 5-2 can be used as upper limits for VO_2 averaged over multi-hour periods from one to nine hours in duration. A conservative assumption (i.e., one which may permit unrealistically high VO_2 values) is that the value for nine hours (33 percent) applies to longer time periods.

The concepts discussed above were the basis of two tests applied to VO_2 estimates produced by Version 2.0 of pNEM/CO. The first test was applied to VO_2 values associated with individual exposure events. The second test was applied to running-average values of VO_2 with durations of 1 to 24 hours.

The first test was based on the assumption that the $PCTVO_{2max}$ value associated with an individual (event -specific) VO_2 value could not exceed an upper limit calculated by Equation 5-6. This test was carried out by comparing each event-specific VO_2 value generated for a cohort with a permitted upper limit (PUL) value obtained from the following equation.

$$\text{Permitted upper limit of } VO_2 = (\text{Upper limit of } PCTVO_{2max})(VO_{2max})/100. \qquad (5\text{-}7)$$

When the event duration ranged between 5 minutes and nine hours, the value for the upper limit of $PCTVO_{2max}$ in Equation 5-7 was obtained from Equation 5-6 using the value of VO_{2max} assigned to the cohort by the physiological profile generator. Outside this range, $PCTVO_{2max}$ was assumed to equal 100 percent for durations less than 5 minutes and to equal 33 percent for durations greater than nine hours. If the VO_2 value exceeded the PUL determined by Equation 5-7, the VO_2 value was set equal to the calcuated PUL. Otherwise, the value of VO_2 was not affected by Test 1.

The second test assumed that “running-average” VO_2 values (expressed as a percentage of the VO_{2max} value) could not exceed the values specified by Erb in Table 5-2. This test was implemented by first averaging the event-specific VO_2 values generated for a cohort by clock hour to produce 24 one-hour VO_2 values. Running-average VO_2 values for all possible sequential periods of 1 to 24 hours in duration were then calculated from these one-hour values. Each running-average VO_2 value was used to calculate the value

$$\text{Test Ratio} = (\text{running average } VO_2)/(\text{permitted upper limit of } VO_2) \qquad (5\text{-}8)$$

in which the “permitted upper limit” (PUL) is a value specific to the indicated averaging time. If any test ratio exceeded 1.0, then all event-specific VO_2 values for the person-day were proportionally reduced so that the largest test ratio equaled exactly 1.0.

Table 5-2. Values of the Upper Limit of $PCTVO_{2max}$ for Specified Averaging Times.

Averaging time (hours)	Upper limit of $PCTVO_{2max}$, percent
1	64
2	54
3	48
4	44
5	41
6	39
7	37
8	35
9	33
10 to 24	33[a]

[a] Conservative estimate based on nine-hour value proposed by Erb (1981). All other values in this column are identical to values proposed by Erb (1981).

Equation 5-7 was used to determine PULs for running-average VO_2 values. In this application, the upper limit of $PCTVO_{2max}$ was obtained from Table 5-2 according to the period of the running average.

The value for VO_{2max} required by the two tests was determined by the physiological profile generator using the equation

$$VO_{2max} = (NVO_{2max})(BM), \tag{5-9}$$

in which BM was body mass in kg and NVO_{2max} was maximum oxygen uptake rate per kg of body mass. As discussed in the next section, values of NVO_{2max} and BM were randomly sampled from distributions specific to the age and gender of the cohort.

5.5 The Probabilistic Algorithm

Table 5-3 presents a probabilistic algorithm for estimating ventilation rate which incorporates the physiological principles discussed above. This algorithm was programmed into Version 2.0 of pNEM/CO as described in Section 2 of this report. Table 5-4 lists the parameters appearing in the algorithm and indicates the functional form and source of data for each parameter.

To run the model, the algorithm requires distributions for BM, NVO_{2max}, and ECF specific to age and gender. Table 5-5 lists distributions for BM by age and gender based on articles by Brainard and Burmaster (1992) and by Burmaster et al. (1994). Table 5-6 lists distributions for NVO_{2max} obtained through a review of the literature. Table 5-7 lists distributions of ECF based on data provided by Esmail, Bhambhani, and Brintnell (1995). Analysts reviewed these data and selected the most appropriate distribution for each parameter for each combination of gender and age ($0 < age < 100$ years). These distributions (listed in Appendix C) were incorporated into the ventilation rate algorithm.

The ventilation rate algorithm also requires an equation for estimating RMR for each combination of age and gender. Analysts reviewed a list of equations previously compiled by McCurdy (1998) and determined that a set of equations developed by Schofield (1985) provided good coverage of all age and gender combinations. These equations were determined through regression analyses and have the functional form

$$RMR = a + (b)(BM) + e, \qquad (5\text{-}10)$$

in which e is assumed to be normally distributed with mean = zero and standard deviation = σ_e. Table 5-8 lists Schofield's values of a, b, and σ_e for 12 age/gender combinations. These values are the basis of the RMR equations listed in the Appendix C which have been incorporated into the ventilation rate algorithm.

Table 5-3. Algorithm Used in Version 2.0 of pNEM/CO to Estimate Ventilation Rates as a Function of Energy Expenditure Rate.

1. Go to first/next cohort. Cohort = k.

2. Obtain age, gender, and height of cohort k from physiological profile generator.

3. Obtain appropriate values of $NVO_{2max}(k)$, BM(k), and ECF(k) for Cohort k by randomly selecting values from appropriate distributions according to age and gender determined in Step 2. Substitute BM(k) value in appropriate equation to determine RMR(k). Calculate

   $$VO_{2max}(k) = [NVO_{2max}(k)][BM(k)].$$

4. Obtain values for parameters of Equation 5-5 from Table 5-1 according to age and gender determined in Step 2. Randomly select a value of z(k) for cohort from a normal distribution with mean equal to zero and standard deviation equal to 1. Determine e(k) value for cohort by following expression

   $$e(k) = [z(k)][\sigma_d].$$

5. Go to first/next day. Day = j.

6. Go to first/next exposure event. Event = i. Randomly select a value of z(i,j,k) value for the event from a normal distribution with mean equal to zero and standard deviation equal to 1. Determine e(i,j,k) value for event by the following expression

   $$e(i,j,k) = [z(i,j,k)][\sigma_e].$$

7. Note activity classification of exposure event. Select MET value from distribution assigned to activity classification. This value is denoted MET(i,j,k).

8. Convert the MET(i,j,k) value to a corresponding $VO_2(i,j,k)$ value by Equation 5-4, i.e.,

   $$VO_2(i,j,k) = [ECF(k)][MET(i,j,k)][RMR(k)].$$

9. Determine upper limit of $PCTVO_{2max}(i,j,k)$ by Equation 5-6. If duration is less than 5 minutes, upper limit of $PCTVO_{2max}(i,j,k)$ equals 100 percent. If duration is greater than 540 minutes (9 hours), upper limit of $PCTVO_{2max}(i,j,k)$ equals 33 percent.

10. Test 1: Determine the permitted upper limit for VO_2 by Equation 5-7 using the value of $PCTVO_{2max}(i,j,k)$ determined in Step 9. If VO_2 for event exceeds upper limit, set VO_2 equal to the upper limit.

11. If last exposure event of day, go to Step 12. Otherwise, go to Step 6.

12. Test 2: Average event-specific VO_2 values for day by clock hour to produce 24 one-hour VO_2 values. Calculate running-average VO_2 values for all possible sequences of 1 to 24 hours in duration from these one-hour values. Obtain $PCTVO_{2max}$ value for each duration from Table 5-2. Use Equation 5-7 to calculate permitted upper limit of VO_2 for each duration. Use Equation 5-8 to determine test ratio for each running-average VO_2 value. If any test ratio exceeds 1.0, reduce all event-specific VO_2 values proportionally so that largest test ratio of resulting adjusted VO_2 values equals exactly 1.0.

13. Following completion of Test 2 (Step 12), use Equation 5-5 and parameter values obtained in Steps 3, 4, and 6 to convert each event-specific VO_2 value of day to a corresponding V_E value.

14. If last day, go to Step 15. Otheriwse, go to Step 5.

15. If last cohort, end. Otherwise, go to Step 1.

Table 5-4. Parameters Used in Probabilistic Algorithm for Estimating Ventilation Rates in Version 2.0 of pNEM/CO.

Parameter	Abbreviation	Functional Form	Source of Data
Body mass	BM	Lognormal distribution	Brainard and Burmaster (see Table 5-5)
Energy Conversion Factor	ECF	Point estimate	Esmail et al., 1995 (see Table 5-7)
Metabolic Equivalence	MET	Distribution specified in CHAD Database	McCurdy, 1998 (see Appendix A)
Resting metabolic rate	RMR	Regression equations specific to age and gender	Schofield, 1985, as compiled by McCurdy, 1998 (see Table 5-8)
Normalized oxygen uptake rate	NVO_{2max}	Normal distribution	Research summarized in Table 5-6

Table 5-5. Parameters for Lognormal Distributions Fitted to Body Mass (BM) Data in Kilograms Organized by Age and Gender.

Age, years	Males				Females			
	ln(BM)		BM		ln(BM)		BM	
	μ	σ	GM	GSD	μ	σ	GM	GSD
0.5 - 1	2.23	0.132	9.3	1.141	2.16	0.145	8.7	1.156
1	2.46	0.119	11.7	1.126	2.38	0.128	10.8	1.137
2	2.60	0.120	13.5	1.127	2.56	0.112	12.9	1.119
3	2.75	0.114	15.6	1.121	2.69	0.137	14.7	1.147
4	2.87	0.133	17.6	1.142	2.83	0.133	16.9	1.142
5	2.99	0.138	19.9	1.148	2.98	0.163	19.7	1.177
6	3.13	0.145	22.9	1.156	3.10	0.174	22.2	1.190
7	3.21	0.151	24.8	1.163	3.19	0.174	24.3	1.190
8	3.33	0.181	27.9	1.198	3.31	0.156	27.4	1.169
9	3.43	0.165	30.9	1.179	3.46	0.214	31.8	1.239
10	3.59	0.195	36.2	1.215	3.57	0.199	35.5	1.220
11	3.69	0.252	40.0	1.287	3.71	0.226	40.9	1.254
12	3.78	0.224	43.8	1.251	3.82	0.213	45.6	1.237
13	3.88	0.215	48.4	1.240	3.92	0.216	50.4	1.241
14	4.02	0.181	55.7	1.198	3.99	0.187	54.1	1.206
15	4.09	0.159	59.7	1.172	4.00	0.156	54.6	1.169
16	4.20	0.168	66.7	1.183	4.06	0.167	58.0	1.182
17	4.19	0.167	66.0	1.182	4.08	0.165	59.1	1.179
18	4.25	0.159	70.1	1.172	4.07	0.147	58.6	1.158
19	4.26	0.154	70.8	1.166	4.10	0.149	60.3	1.161
18 - 74[a]	4.34	0.17	76.7	1.19	4.17	0.20	64.7	1.22

[a] Derived from Brainard and Burmaster (1992). All other statistics derived from Burmaster et al. (1994).

Table 5-6. Descriptive Statistics for VO_2 and VER Measured at Maximal Exertion by Various Researchers.

		VO_{2max}, liters/min$_X$			NVO_{2max}, ml/min per kg			Maximum ratio of V_E to VO_2			
Population group	n	Mean	S.D.	C.V.[a]	Mean	S.D.	C.V.	Mean	S.D.	C.V.	Source
Females, 20-29	8	2.23	0.26	0.12	39.9	4.7	0.12	34.1	6.0	0.18	Åstrand (1960)
Females, 30-39	12	2.13	0.28	0.13	37.3	5.2	0.14	35.2	5.7	0.16	
Females, 40-49	8	2.01	0.19	0.09	32.5	2.7	0.08	31.8	4.7	0.15	
Females, 50-65	16	1.85	0.25	0.14	28.4	2.7	0.10	33.1	4.0	0.12	
Females, 20-25	32	2.88	0.24	0.08	48.4	2.8	0.06	32.3	2.8	0.09	
Males, 20-29	4	4.19	NR	NR	52.2	NR	NR	31.8	NR	NR	
Males, 30-39	13	3.01	0.54	0.18	39.8	7.3	0.18	34.6	6.0	0.17	
Males, 40-49	9	2.99	0.32	0.11	39.2	5.5	0.14	33.8	5.3	0.16	
Males, 50-59	66	2.54	0.36	0.14	33.1	4.9	0.15	26.9	4.6	0.17	
Males, 60-69	8	2.23	0.29	0.13	31.4	5.3	0.17	33.1	5.8	0.18	
Males, 20-33	29	4.16	0.39	0.09	58.6	4.5	0.08	29.4	3.0	0.10	
Males, 11	18	1.65	0.30	0.18	45.4	8.06	0.18	37.4	7.00	0.19	Mercier et. al. (1991)
Males, 12	15	1.85	0.31	0.17	47.4	8.13	0.17	35.0	5.42	0.15	
Males, 13	15	2.26	0.39	0.17	46.0	6.97	0.15	31.0	3.02	0.10	
Males, 14	15	2.62	1.12	0.43	45.7	4.26	0.09	33.2	7.28	0.22	
Males, 15	13	2.70	0.50	0.19	47.5	4.69	0.10	34.4	5.05	0.15	
Males, 21-27	13	3.91	0.52	0.13	54.5	7.61	0.14	NR	NR	NR	Katch and Park (1975)
Males and Females, 20-29	80	3.09	0.83	0.27	45.3	7.54	0.17	NR	NR	NR	Heil et. al. (1995)
Males and Females, 30-39	81	3.19	0.86	0.27	43.8	8.15	0.19	NR	NR	NR	

Population group	n	VO_{2max}, liters/min$_X$			NVO_{2max}, ml/min per kg			Maximum ratio of V_E to VO_2			Source
		Mean	S.D.	C.V.[a]	Mean	S.D.	C.V.	Mean	S.D.	C.V.	
Males and Females, 40-49	79	3.13	0.92	0.29	42.9	9.04	0.21	NR	NR	NR	Heil et al. (1995)
Males and Females, 50-59	78	2.84	0.91	0.32	36.8	8.93	0.24	NR	NR	NR	
Males and Females, 60-69	74	2.31	0.72	0.31	30.7	7.98	0.26	NR	NR	NR	
Males and Females, 70-79	47	1.91	0.56	0.29	27.2	5.67	0.21	NR	NR	NR	
Males, 20-79	210	3.54	0.71	0.20	44.0	9.42	0.21	NR	NR	NR	
Females, 20-79	229	2.14	0.51	0.24	33.8	8.65	0.26	NR	NR	NR	
Males, 10-17	6	NR	NR	NR	46.6	5.8	0.12	NR	NR	NR	Mermier et. al. (1993)
Males, 18-72	15	NR	NR	NR	45.7	16.7	0.37	NR	NR	NR	
Females, 7-17	6	NR	NR	NR	38.0	5.0	0.13	NR	NR	NR	
Females, 21-72	16	NR	NR	NR	32.2	8.9	0.28	NR	NR	NR	
Male, 23-33	20	NR	NR	NR	48.3	4.9	0.10	NR	NR	NR	Rowland et. al. (1987)
Male, 9-13	20	NR	NR	NR	57.9	6.9	0.12	NR	NR	NR	

[a] C.V. = (std. dev.)/(mean), dimensionless.

Table 5-7. Estimates of the Energy Conversion Factor (ECF) Based on Data in Esmail, Bhambhani, and Brintnell (1995).

Group	Number of subjects	Test	Mean VO_2, liters min^{-1}	Mean GEC[a], kcal min^{-1}	Ratio of means[b]
Women	20	wheel-turn	0.81	4.1	0.198
		push-pull	0.80	4.0	0.200
		overhead-reach	0.87	4.4	0.198
Men	Not reported	wheel-turn	1.13	5.7	0.198
		push-pull	1.16	5.6	0.207
		overhead-reach	1.13	5.7	0.198

[a] GEC: gross energy cost.

[b] Data were not available for calculating the mean of subject-specific ratios.

Table 5-8. Regression Equations for Predicting Basal Metabolic Rate Provided by Schofield (1985) as Compiled by McCurdy (1998).

Gender	Age, years	Regression coefficients[a]		
		a	b	σ_e
Female	< 3	-0.130	0.244	0.25
Female	3 - 9.9	2.033	0.085	0.29
Female	10 - 17.9	2.898	0.056	0.47
Female	18 - 29.9	2.036	0.062	0.50
Female	30 - 59.9	3.538	0.034	0.47
Female	≥ 60	2.755	0.038	0.45
Male	< 3	-0.127	0.244	0.29
Male	3 - 9.9	2.110	0.095	0.28
Male	10 - 17.9	2.754	0.074	0.44
Male	18 - 29.9	2.896	0.063	0.64
Male	30 - 59.9	3.653	0.048	0.70
Male	≥ 60	2.459	0.049	0.69

[a] Regression equation: BMR(MJ/day) = a + (b)(BM) + e, σ_e = standard deviation of e. Basal metabolic rate (BMR) is assumed to be equivalent to resting metabolic rate (RMR).

5.6 Effect of Cardiovascular Disease on Exertion Levels

As discussed in Section 2.5.2, analysts assumed the exercise patterns of people with IHD were similar to those of the general population. To determine the validity of this assumption, Cohen, Nikiforov, and Rosenbaum (1999) analyzed activity/exertion data from the National Human Activity Pattern Survey (NHAPS) representing subjects with and without heart disease. Subjects were classified as having heart disease if they reported that a doctor had told them they had angina. The NHAPS database provided a 24-hour sequence of activities for each subject as reported in a recall-style diary (Robinson and Blair, 1995). A Monte Carlo algorithm based on the METS principle described in Section 5.1 was applied 100 times to each 24-hour sequence. In each application (iteration), the algorithm generated an energy expenditure rate (EE) in kcal min^{-1} for each activity in the sequence. The resulting distributions of EE values were statistically analyzed to determine whether they differed according to the health status of the associated NHAPS subjects. Researchers also analyzed differences in time spent in outdoor and in-vehicle microenvironments.

Cohen, Nikiforov, and Rosenbaum (1999) provide detailed results for the following activity/exertion indicators: average and 95th percentile of the maximum daily 8-hour EE value; percentage of time spent outdoors or in a vehicle; average percentage of time at light, moderate, and heavy exertion; and occurrence of moderate or high EE values. Tables 5-9 and 5-10 are illustrative of the general results of the analysis. The tables provide means and standard deviations for each indicator stratified by gender and age. The T test is used to test for differences in means; the F test for differences in standard deviations. The non-parametric Wilcoxon test is used to compare the central tendencies of the angina and non-angina distributions without the normality assumption required by the T test. The Kolmogorov-Smirnov test compares the overall distributions of each group.

Although the results in Tables 5-9 and 5-10 suggest that mean values for the various indicators tend to be lower for angina subjects in each age and gender group than for corresponding non-angina subjects, there are exceptions to this pattern. For example, the tables show that angina subjects tend to have lower mean values for the average maximum 8-hour exertion than the non-angina subjects. However, the mean is actually higher for angina subjects aged 0 - 54 years of either gender and for males 75 years or older. The mean average maximum 8-hour exertions are consistently higher for males of all age groups, with or without angina, compared to females. Similar patterns are found for the 95th percentile of the maximum 8-hour exertion.

The comparisons of the percentages of time spent outdoors or in a vehicle also vary across age and gender subgroups. The largest, and most surprising, angina vs. non-angina difference is for the mean percentage of time spent outdoors by males aged 0 - 54 years: angina subjects have a mean of 17% compared to the mean of 9% for non-angina subjects. However the angina subjects in the 55 - 64 and 65 - 74 age groups of either gender spend less time outdoors, on average, than non-angina subjects.

Table 5-9. Results of Statistical Tests Performed on CHAD Data Evaluating the Association Between Angina and Various Variables Representing Physical Exertion and Time Spent in Selected Microenvironments (Data for Males Only).

Variable	Age group	T Test Comparison of Means			F Test Comparison of Standard Deviations			Wilcoxon Test p-value	Kolmogorov-Smirnov Test p-value
		Mean		p-value	Standard deviation		p-value		
		Angina	Non-angina		Angina	Non-angina			
Average maximum 8 hr exertion (Mcal)	0 - 54	1.85	1.59	0.00	0.49	0.55	0.34	0.02	0.02
	55 - 64	1.48	1.77	0.00	0.48	0.48	0.86	0.01	0.02
	65 - 74	1.39	1.49	0.36	0.47	0.48	0.96	0.41	0.82
	75+	1.27	1.20	0.52	0.44	0.42	0.65	0.51	0.95
95th percentile of maximum 8 hr exertion (Mcal)	0 - 54	2.94	2.68	0.17	1.06	1.30	0.13	0.22	0.06
	55 - 64	2.40	2.90	0.04	1.21	1.14	0.61	0.02	0.03
	65 - 74	1.91	2.17	0.14	0.78	0.94	0.31	0.26	0.63
	75+	1.73	1.67	0.71	0.69	0.76	0.68	0.55	0.88
Percentage of time spent outdoors	0 - 54	16.9	8.9	0.02	19.2	13.8	0.00	0.01	0.01
	55 - 64	9.3	10.0	0.79	14.3	13.9	0.78	0.65	1.00
	65 - 74	6.4	10.4	0.13	11.4	14.3	0.20	0.12	0.13
	75+	8.2	7.1	0.72	12.6	10.1	0.16	0.58	0.66
Percentage of time spent in vehicle	0 - 54	6.0	6.1	0.92	7.6	8.1	0.63	0.89	0.52
	55 - 64	4.0	6.9	0.00	3.8	9.6	0.00	0.18	0.19

Percentage of time spent in vehicle (cont.)	65 - 74	7.2	5.9	0.51	9.0	7.8	0.29	0.82	0.93
	75+	2.3	3.3	0.14	2.5	3.9	0.05	0.44	0.54
Percentage of time spent outdoors or in vehicle	0 - 54	22.8	14.9	0.02	19.3	15.5	0.05	0.02	0.02
	55 - 64	13.3	16.9	0.24	15.3	16.2	0.76	0.17	0.22
	65 - 74	13.6	16.3	0.45	15.9	15.9	1.00	0.19	0.29
	75+	10.5	10.4	0.98	12.9	10.4	0.19	0.69	0.41
Average percentage of time with exertion above 2.39 kcal/min = 0.010MJ/min (light)	0 - 54	34.8	27.8	0.00	13.3	15.2	0.34	0.02	0.05
	55 - 64	24.6	30.1	0.06	14.5	12.0	0.14	0.06	0.14
	65 - 74	21.9	23.3	0.63	13.2	12.5	0.64	0.67	0.84
	75+	18.2	15.9	0.41	11.1	10.4	0.63	0.39	0.74
Average percentage of time with exertion above 5.97 kcal/min = 0.025MJ/min (moderate)	0 - 54	6.6	4.5	0.05	6.4	4.3	0.00	0.02	0.01
	55 - 64	3.4	5.4	0.01	3.6	4.4	0.17	0.01	0.01
	65 - 74	2.3	3.3	0.08	2.5	3.5	0.06	0.20	0.40
	75+	2.0	1.6	0.53	2.4	2.4	0.92	0.43	0.59
Average percentage of time with exertion above 9.55 kcal/min = 0.040MJ/min (heavy)	0 - 54	0.66	0.74	0.59	0.79	0.99	0.11	0.55	0.15
	55 - 64	0.57	0.85	0.19	1.07	1.22	0.40	0.05	0.17
	65 - 74	0.16	0.39	0.01	0.36	0.72	0.00	0.06	0.04
	75+	0.13	0.16	0.79	0.33	0.51	0.05	0.55	0.96

Table 5-10. Results of Statistical Tests Performed on CHAD Data Evaluating the Association Between Angina and Various Variables Representing Physical Exertion and Time Spent in Selected Microenvironments (Data for Females Only).

Variable	Age group	T Test Comparison of Means			F Test Comparison of Standard Deviations			Wilcoxon Test p-value	Kolmogorov-Smirnov Test p-value
		Mean		p-value	Standard deviation		p-value		
		Angina	Non-angina		Angina	Non-angina			
Average maximum 8 hr exertion (Mcal)	0 - 54	1.30	1.27	0.69	0.31	0.38	0.34	0.72	0.73
	55 - 64	1.21	1.27	0.33	0.32	0.33	1.00	0.56	0.22
	65 - 74	1.05	1.10	0.29	0.30	0.31	0.94	0.31	0.44
	75+	0.96	0.98	0.63	0.33	0.30	0.34	0.44	0.66
95th percentile of maximum 8 hr exertion (Mcal)	0 - 54	1.98	2.01	0.86	0.82	0.91	0.69	0.99	0.86
	55 - 64	1.79	1.92	0.41	0.80	0.77	0.68	0.33	0.28
	65 - 74	1.42	1.51	0.26	0.53	0.57	0.57	0.31	0.62
	75+	1.27	1.31	0.59	0.56	0.52	0.43	0.43	0.47
Percentage of time spent outdoors	0 - 54	3.6	5.1	0.42	7.3	9.6	0.20	0.43	0.91
	55 - 64	4.3	4.6	0.88	9.5	8.2	0.23	0.23	0.63
	65 - 74	2.8	4.1	0.14	5.5	7.3	0.02	0.49	0.53
	75+	3.8	2.3	0.40	12.0	4.6	0.00	0.76	1.00
Percentage of time spent in vehicle	0 - 54	4.5	5.4	0.55	5.5	6.0	0.72	0.40	0.35
	55 - 64	4.2	5.6	0.35	7.5	7.2	0.71	0.06	0.12

Percentage of time spent in vehicle (cont.)	65 - 74	5.3	4.2	0.23	5.9	6.2	0.77	0.15	0.19
	75+	2.8	2.9	0.86	4.4	4.3	0.91	0.72	0.96
Percentage of time spent outdoors or in vehicle	0 - 54	8.2	10.5	0.36	9.9	11.3	0.57	0.18	0.27
	55 - 64	8.5	10.2	0.48	12.2	10.4	0.22	0.04	0.05
	65 - 74	8.1	8.3	0.88	8.2	9.4	0.26	0.99	0.86
	75+	6.6	5.2	0.45	12.4	6.3	0.00	0.77	0.97
Average percentage of time with exertion above 2.39 kcal/min = 0.010MJ/min (light)	0 - 54	23.5	21.4	0.49	12.3	12.2	0.86	0.41	0.69
	55 - 64	19.0	21.0	0.33	10.3	10.5	1.00	0.51	0.54
	65 - 74	14.0	15.5	0.26	8.5	9.5	0.31	0.43	0.76
	75+	11.3	11.8	0.73	9.8	8.6	0.24	0.51	0.89
Average percentage of time with exertion above 5.97 kcal/min = 0.025MJ/min (moderate)	0 - 54	1.44	1.59	0.71	1.66	1.97	0.44	0.73	0.74
	55 - 64	0.79	1.31	0.05	1.27	2.07	0.00	0.04	0.06
	65 - 74	0.65	0.68	0.87	1.35	1.56	0.22	0.51	0.88
	75+	0.75	0.43	0.23	1.73	1.31	0.01	0.84	0.67
Average percentage of time with exertion above 9.55 kcal/min = 0.040MJ/min (heavy)	0 - 54	0.10	0.18	0.06	0.17	0.32	0.00	0.63	0.80
	55 - 64	0.10	0.09	0.96	0.28	0.20	0.01	0.67	1.00
	65 - 74	0.03	0.03	0.89	0.08	0.11	0.00	0.85	0.99
	75+	0.03	0.02	0.44	0.08	0.08	0.90	0.28	0.83

The comparisons in Tables 5-9 and 5-10 of the mean percentages of time above the light, moderate or high exertion levels show a variety of patterns for different age groups, genders, and exertion levels. Overall, age and gender were found to have very significant effects on the summary statistics under evaluation. As angina patients tend to be much older and tend to include more females than the general population, researchers performed additional analyses in which the results were adjusted for gender and age by stratification (comparing subjects in a given age/gender subgroup), or by fitting a general linear model (with separate terms for age, gender, and angina effects and their interactions). These analyses showed that, overall, angina subjects tended to have less extreme exertion levels. More specifically, the maximum 8-hour exertion energies tended to be lower, as did the percentages of time above moderate or high exertion rate thresholds. The differences between angina and non-angina subjects in percentages of time spent outdoors or in a vehicle were not generally statistically significant.

The large sample of NHAPS subjects produced, in many cases, statistically significant differences in the exertion rate summaries between angina and non-angina subjects. However, those differences were generally numerically small compared to the mean values. EPA has concluded that the differences in activity and exertion between angina and non-angina subjects, although statistically significant, are not large enough to warrant adjusting the pNEM/CO modeling approach to account for an angina/non-angina difference.

5.6 References for Section 5

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SECTION 6
ESTIMATION OF COMMUTING PATTERNS

In applying the previous (1992) version of pNEM/CO to Denver, analysts used an iterative algorithm described by Johnson, Capel, and Byrne (1991) to develop an “origin-destination” table indicating the pattern of commuting trips made by working cohorts among the defined exposure districts. Version 2.0 of pNEM/CO required a similar origin-destination table for the Denver study area. Researchers identified a special commuting database developed by the Bureau of Census (1994) as a promising alternative to the commuting algorithm for creating this table. This section describes the method used to develop an origin-destination table for Denver using the Bureau of Census (BOC) database.

6.1 The BOC Commuting Database

Table 6-1 presents the format of the BOC database. The following two data items were used in the analyses which follow.

- WF: weighted count of workers in specified flow.
- WA: weighted count of workers allocated to this tract of work.

WF is the total number of workers estimated by BOC to commute (“flow”) from the indicated residence census tract to the indicated work census tract. Each value of WF is a weighted estimate based on responses to the 1990 census “long form.” The estimate includes both (1) people who explicitly indicated they lived and worked in the indicated census tracts and (2) other people who the BOC allocated to the flow based on supplemental information. WA indicates only the number of people who fall into the second category. As WA increases as a percentage of WF, confidence in the value of WF is reduced.

Table 6-1. Format of Commuting Database Obtained from the Bureau of Census.

Bytes	Data item	Explanation of codes
1 - 2	FIPS state code of place of work	01 - 56 = Alabama - Wyoming 99 = did not work in U.S.
3 - 5	FIPS county code of place of work	000 = did not work in U.S. NNN = county code
6 - 11	Census tract/BNA code of place of work	000000 = did not work in U.S. 000100...999999 = legal tract code range
12 - 14	Census MCD code of place of work	000 = did not work in New England state NNN = MCD code in New England (FIPS State = 09, 23, 25, 33, 44, 50)
15 - 18	Census place code of place of work	0000 = did not work in U.S. 0001...9998 = census place code 9999 = did not work in a place
19	Blank	
20 - 21	FIPS state code of residence	01 - 56 = Alabama - Wyoming 99 = did not work in U.S.
22 - 24	FIPS county code of residence	NNN = county code
25 - 30	Census tract/BNA code of residence	000100...999999 = legal tract code range
31 - 33	Census MCD code of place of residence	000 = did not live in New England state NNN = MCD code in New England (FIPS State = 09, 23, 25, 33, 44, 50)
34 - 37	Census place code of residence	0001...9998 = census place code 9999 = did not live in a place
38	Blank	
39 - 44	Weighted count of workers in this flow, including all place of work allocation (everyone forced into a tract of work)	
45 - 50	Weighted count of workers allocated to this tract of work	
51 - 56	Weighted count of workers allocated to this place of work	
57 - 62	Weighted count of workers allocated to this county or MCD (in 6 New England states) of work	

To develop an origin-destination table for a particular study area, analysts first identify the census tracts included within each exposure district defined within the study area. Next, the flows among the individual census tracts in each district are combined to determine flows among the districts. Each district-to-district flow originating in a particular district is then converted to a fraction of the total workers commuting from the district. These fractions are organized by home and work districts to create the required origin-destination table. Section 6.2 describes the application of this approach to the exposure districts defined for the application of Version 2.0 of pNEM/CO to Denver.

6.2 The Denver Exposure Districts

As described in Section 2.1, analysts defined six exposure districts for application of the Version 2.0 of pNEM/CO to the Denver study area. Five of the districts are centered on individual fixed-site CO monitors in the Denver metropolitan area. The sixth district is centered on a point midway between two monitors located in Boulder, CO. Figure 6-1 shows the locations of these seven fixed-site monitors. Table 6-2 identifies the monitor(s) associated with each district.

Each district was defined as a collection of census tracts as delineated by the BOC for the 1990 decennial census. The census tracts were drawn from a comprehensive listing of the census tracts located in the following nine counties:

Adams
Arapahoe
Boulder
Clear Creek
Denver
Douglas
Gilpin
Jefferson
Weld.

In developing the districts, analysts assigned each census tract located within 10 km of one or more district centers to the nearest district. People residing in the remaining census tracts were excluded from the pNEM/CO analysis, based on the assumption that pNEM/CO could not accurately estimate the exposures of people who lived more than 10 km from a monitoring station.

Table 6-2 lists the number of census tracts assigned to each of the six exposure

Monitors Defining Exposure Districts

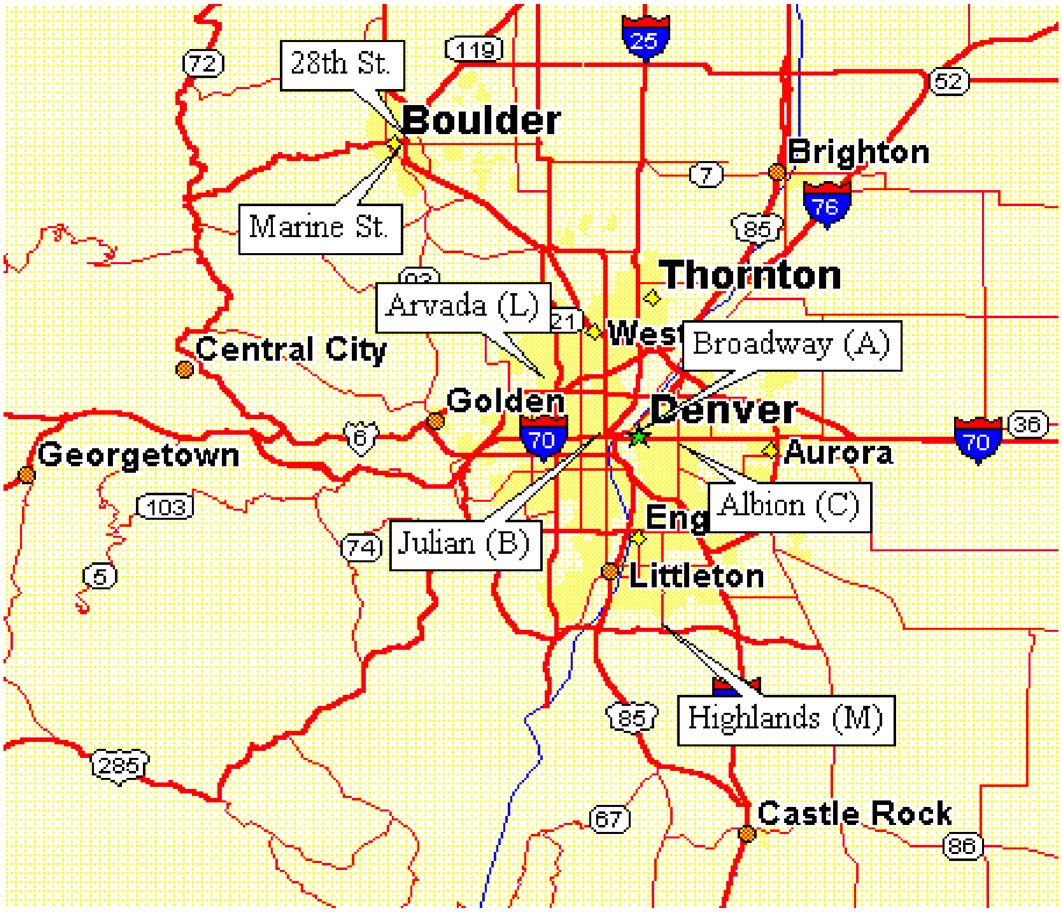

Figure 6-1. Fixed-Site CO Monitoring Sites Used to Define Denver Exposure Districts.

Table 6-2. Exposure Districts Defined for Denver pNEM/CO Analysis.

District no.	Monitor(s) included in district			Number of census tracts assigned to district
	AIRS ID	City	Address	
1	005-0002	Littleton	8100 So. University Blvd. (Highlands)	47
2	031-0002	Denver	2105 Broadway (CAMP)	44
3	031-0013	Denver	14th and Albion St. (NJHE)	116
4	031-0014	Denver	23rd and Julian (Carriage)	61
5	059-0002	Arvada	W. 57th Ave. and Garrison	55
6	013-0010 013-1001	Boulder	2150 28th Street 2320 Marine Street	28
19	Remaining census tracts in nine county region			242

districts and the number of remaining census tracts (designated “District 19”). Among the home districts (1 through 6), the number of census tracts contained within a district ranges from 28 (No. 6: Boulder) to 116 (No. 3: 14th and Albion). The six home districts account for 351 (59 percent) of the 593 census tracts in the nine-county area.

6.3 Origin-Destination Table for Denver

Analysts defined six “home” exposure districts and seven “work” exposure districts. The six home districts were the six monitor-derived exposure districts listed in Table 6-2. The seven “work” districts included the six districts in Table 6-2 and a seventh district (District 19) containing all areas not included in the six home districts. Each flow value in the BOC database was assigned to the appropriate combination of home and work districts according to the residence and work census tracts listed for the flow. Table 6-3 lists the sums of the flows assigned to each combination of home and work district. It also presents each sum as a fraction of the total flow originating at the

Table 6-3. Number and Fraction of Commuters Associated with Each Combination of Home and Work District.

Home district	Statistic	Work District							Totals by Home District
		Districts containing CO monitors						District 19[a]	
		1	2	3	4	5	6		
1	Commuters	35,045	15,334	14,929	3,974	1,499	470	18,288	89,539
	Fraction[b]	0.391	0.171	0.167	0.044	0.017	0.005	0.204	1.000
2	Commuters	2,184	27,440	8,649	3,457	1,789	669	4,511	48,699
	Fraction	0.045	0.563	0.178	0.071	0.037	0.014	0.093	1.000
3	Commuters	12,804	42,602	64,969	7,844	2,651	1,434	22,028	154,332
	Fraction	0.083	0.276	0.421	0.051	0.017	0.009	0.143	1.000
4	Commuters	5,207	26,728	13,773	28,053	9,283	898	14,563	98,505
	Fraction	0.053	0.271	0.140	0.285	0.094	0.009	0.148	1.000
5	Commuters	2,811	22,282	11,666	14,765	39,110	3,428	19,675	113,737
	Fraction	0.025	0.196	0.103	0.130	0.344	0.030	0.173	1.000
6	Commuters	814	4,149	1,771	766	1,305	44,630	6,839	60,274
	Fraction	0.014	0.069	0.029	0.013	0.022	0.740	0.113	1.000
Totals by Work District		58,865	138,535	115,757	58,859	55,637	51,529	85,904	565,086

[a] District 19 includes all census tracts in the nine-county area that are not located in Districts 1 through 6.

[b] Fraction = $(Com_{ij})/(Com_i)$

Com_{ij} = number of workers commuting from home district i to work district j

Com_i = total number of workers commuting from home district i to all work districts (including District 19)

indicated home district. For example, the flow from Home District No. 1 to Work District No. 2 is 15,334. Listed under this value is the fraction 0.171, calculated by dividing 15,334 by the total flow (89,539) from Home District No. 1 to all districts.

Home District No. 3, the district containing the largest number of census tracts, is associated with the largest number of commuters (154,332). Home District No. 2 has the smallest number of commuters (48,699). Work District No. 2 is associated with the largest number of commuters (138,535); Work District No. 6 (Boulder) has the smallest number of commuters (51,529). Note that these values include only those commuters which move among the home and work districts listed in Table 6-2.

Table 6-3 accounts for the commuting patterns of 565,086 workers. Of these, 85,904 workers (15 percent) reside in one of the six home districts but work in District 19 (i.e., at a location more than 10 km from the nearest fixed-site monitor). People working in District 19 were excluded from the pNEM/CO analysis of Denver, based on the assumption that pNEM/CO could not accurately estimate the exposures of people who worked more than 10 km from a monitoring station. Consequently, the working cohorts are limited to people with residential and work locations within Districts 1 through 6.

6.4 Data Quality

It should be noted that the BOC Commuting Database is not a perfect representation of the commuting patterns of Denver residents. The data were acquired from the census “long form” which the BOC administered to about one-sixth of the Denver residents. The BOC extrapolated the data from this subset of the population to the remainder of the population using various assumptions and supplemental information.

Analysts defined WR as the ratio of WA (number of workers allocated to a particular home-work combination by indirect methods) to WF (total number of workers associated with the home-work combination); i.e.,

$$WR = (WA)/(WF) \tag{6-1}$$

WR provided a crude indication of the uncertainty associated with each WF value in the database.

Table 6-4 presents the population-weighted mean value of WR (expressed as a percentage) for each of the 42 combinations of home and work district. The 42 WR values range from 10.28 percent (Home District No. 6, Work District No. 3) to 43.90 percent (Home District No. 1, Work District No. 5). The largest values (indicating the highest degree of uncertainty) are associated with Work Districts Nos. 5 and 19.

Table 6-4 also provides an aggregate WR value for all flows originating in each home district. The six values range from 22.14 percent (Home District No. 1) to 28.59 percent (Home District No. 2). Aggregate WR values for all flows ending in each work district can also be found in Table 4. The values range from 18.46 percent (Work District No. 1) to 35.27 percent (Work District No. 19).

The overall aggregate value of WR is 23.98 percent. In general, this analysis indicates that less than 25 percent of the commute trips were estimated indirectly using supplemental data.

6.5 References for Section 6

Bureau of the Census. 1994. “STP154: Census Tract of Work by Census Tract of Residence.” Journey-to-Work and Migration Statistics Branch, Population Division, U. S. Bureau of the Census.

Johnson, Ted R., J. E. Capel, and D. M. Byrne. 1991. “The Estimation of Commuting Patterns in Applications of the Hazardous Air Pollutant Model (HAPEM).” Paper No. 91-172.6. Presented at the 84th Annual meeting of the Air and Waste Management Association, Vancouver, British Columbia, June 16 - 21.

Table 6-4. Percentage of Commuters (WR) Assigned by BOC to Each Home-Work Combination Based on Supplemental Data.

Home District	Work District							All work districts
	Districts containing CO monitor(s)							
	1	2	3	4	5	6	19	
1	15.21	18.47	23.93	23.70	43.90[a]	21.70	34.93[a]	22.14
2	23.99	30.09[a]	22.68	22.36	29.29[a]	22.87	38.40[a]	28.59[a]
3	19.31	22.87	16.21	32.66[a]	35.16[a]	24.48	35.28[a]	22.27
4	30.44[a]	22.96	35.05[a]	14.95	33.14[a]	35.63[a]	36.14[a]	25.79[a]
5	24.55	17.72	25.12[a]	21.38	25.73[a]	33.07[a]	24.18	24.18
6	32.56[a]	21.43	10.28	11.49	31.34[a]	22.47	38.60[a]	24.06
All home districts	18.46	22.96	20.74	19.91	26.93[a]	22.97	35.27[a]	23.98

[a] Value exceeds 25 percent.

SECTION 7

EXPOSURE ESTIMATES FOR DENVER RESIDENTS WITH ISCHEMIC HEART DISEASE

The pNEM/CO methodology was used to develop estimates of CO exposure and resulting COHb levels within a population-of-interest (POI) defined as “all adults with ischemic heart disease (IHD) who reside and work within the Denver study area.” Adults are defined as persons 18 years and older. The Denver study area is defined as the aggregation of the six exposure districts specified in Section 2.1.

This section presents selected results for two scenarios:

1. Existing conditions - indoor sources “on”
2. Existing conditions - indoor sources “off.”

In these descriptions, the qualifier “existing conditions” refers to the air quality conditions reported by the Denver fixed-site monitors during 1995. The term “indoor sources” refers to gas stoves and passive smoking only. Indoor sources “on” indicates pNEM/CO was run in the standard mode in which CO contributions from gas stoves and passive smoking are treated according to the procedures described in Section 2. Indoor sources “off” indicates that pNEM/CO was run with the CO contribution from these sources set equal to zero.

Tables 7-1 through 7-3 present modeling results for the POI. This group is estimated to contain 44,545 persons. Note that each listed exposure statistic is the arithmetic mean of statistics obtained from 10 runs of pNEM/CO. Because pNEM/CO contains a variety of stochastic (probabilistic) factors, each run of the model produces a different set of exposure estimates. Consequently, the means presented in Tables 7-1 through 7-3 provide an indication of the central tendency of each exposure statistic. The range of values for the 10 runs is listed in parentheses next to each mean value.

Table 7-1 presents estimates of the number of person-days in which members of the POI experienced a 1-hour daily maximum CO exposure at or above each of the

Table 7-1. Number of Person-Days Under Existing Conditions in Which Denver Adults with Ischemic Heart Disease Were Estimated to Experience a 1-Hour Daily Maximum Carbon Monoxide Exposure At or Above the Specified Concentration. DRAFT

CO concentration, ppm	Indoor sources on		Indoor sources off	
	Number of person-days	Percentage	Number of person-days	Percentage
60	2.95E04 (2.49E04 - 3.33E04)[a]	0.18 (0.15 - 0.20)	2.95E04 (2.49E04 - 3.31E04)	0.18 (0.15 - 0.20)
50	3.56E04 (3.30E04 - 3.88E04)	0.22 (0.20 - 0.24)	3.56E04 (3.30E04 - 3.88 E04)	0.22 (0.20 - 0.24)
45	4.26E04 (3.78E04 - 4.68E04)	0.26 (0.23 - 0.29)	4.24E04 (3.76E04 - 4.67E04)	0.26 (0.23 - 0.29)
40	7.11E04 (6.73E04 - 7.51E04)	0.44 (0.41 - 0.46)	7.11E04 (6.74E04 - 7.51E04)	0.44 (0.41 - 0.46)
35	9.83E04 (9.07E04 - 1.02E05)	0.60 (0.56 - 0.63)	9.81E04 (9.07E04 - 1.02E05)	0.60 (0.56 - 0.63)
30	1.26E05 (1.14E05 - 1.33E05)	0.77 (0.70 - 0.82)	1.25E05 (1.13E05 - 1.32E05)	0.77 (0.70 - 0.81)
25	1.76E05 (1.64E05 - 1.89E05)	1.08 (1.01 - 1.16)	1.75E05 (1.63E05 - 1.89E05)	1.08 (1.00 - 1.16)
20	3.98E05 (3.73E05 - 4.30E05)	2.44 (2.29 - 2.65)	3.23E05 (3.04E05 - 3.50E05)	1.99 (1.87 - 2.15)
15	1.57E06 (1.52E06 - 1.59E06)	9.63 (9.35 - 9.77)	1.43E06 (1.38E06 - 1.45E06)	8.77 (8.50 - 8.93)
10	3.54E06 (3.48E06 - 3.58E06)	21.8 (21.4 - 22.0)	3.48E06 (3.42E06 - 3.52E06)	21.4 (21.0 - 21.6)
0	1.63E07 (1.63E07 - 1.63E07)	100 (100 - 100)	1.63E07 (1.63E07 - 1.63E07)	100 (100 - 100)

[a] Values in parentheses indicate range of 10 runs.

Table 7-2. Number of Person-Days Under Existing Conditions in Which Denver Adults with Ischemic Heart Disease Were Estimated to Experience an 8-Hour Daily Maximum Carbon Monoxide Exposure At or Above the Specified Concentration. DRAFT

CO concentration, ppm	Indoor sources on		Indoor sources off	
	Number of person-days	Percentage	Number of person-days	Percentage
25+	6.5E01 (9 - 1.19E02)	0.00 (0.00 - 0.00)	5.3E01 (8 - 1.19E02)	0.00 (0.00 - 0.00)
20	2.68E03 (2.03E03 - 3.17E03)	0.02 (0.01 - 0.02)	1.39E03 (7.27E02 - 1.90E03)	0.01 (0.00 - 0.01)
15	3.42E04 (3.16E04 - 3.94E04)	0.21 (0.19 - 0.24)	1.80E04 (1.59E04 - 2.02E04)	0.11 (0.10 - 0.12)
12	1.18E05 (1.14E05 - 1.22E05)	0.73 (0.70 - 0.75)	9.28E04 (9.00E04 - 9.70E04)	0.57 (0.55 - 0.60)
9	3.71E05 (3.56E05 - 3.81E05)	2.28 (2.19 - 2.35)	3.16E05 (3.05E05 - 3.24E05)	1.94 (1.88 - 1.99)
6	1.24E06 (1.23E06 - 1.27E06)	7.65 (7.58 - 7.83)	1.14E06 (1.13E06 - 1.15E06)	6.99 (6.93 - 7.06)
0	1.63E07 (1.63E07 - 1.63E07)	100 (100 - 100)	1.63E07 (1.63E07 - 1.63E07)	100 (100 - 100)

[a] Values in parentheses indicate range of 10 runs.

Table 7-3. Number of Person-Hours Under Existing Conditions in Which Denver Adults with Ischemic Heart Disease Were Estimated to Experience an End-of-Hour Carboxyhemoglobin Level At or Above the Specified Percentage. DRAFT

CO concentration, ppm	Indoor sources on		Indoor sources off	
	Number of person-hours	Percentage	Number of person-hours	Percentage
6.0	7 (0 - 34)	0.00 (0.00 - 0.00)	7 (0 - 34)	0.00 (0.00 - 0.00)
5.0	73 (6 - 2.12E02)	0.00 (0.00 - 0.00)	72 (5 - 2.12E02)	0.00 (0.00 - 0.00)
4.0	1.01E03 (6.18E02 - 1.97E03)	0.00 (0.00 - 0.00)	1.01E03 (6.1E02 - 1.97E03)	0.00 (0.00 - 0.00)
3.0	1.35E03 (1.14E04 - 1.45E04)	0.00 (0.00 - 0.00)	8.46E03 (6.06E03 - 1.02E04)	0.00 (0.00 - 0.00)
2.9	1.87E04 (1.65E04 - 2.14E04)	0.00 (0.00 - 0.01)	1.09E04 (7.97E03 - 1.34E04)	0.00 (0.00 - 0.00)
2.8	2.61E04 (2.36E04 - 2.89E04)	0.01 (0.01 - 0.01)	1.46E04 (1.13E04 - 1.67E04)	0.00 (0.00 - 0.00)
2.7	3.53E04 (3.17E04 - 3.88E04)	0.01 (0.01 - 0.01)	1.91E04 (1.58E04 - 2.24E04)	0.00 (0.00 - 0.01)
2.6	4.92E04 (4.32E04 - 5.49E04)	0.01 (0.01 - 0.01)	2.65E04 (2.23E04 - 3.12E04)	0.01 (0.01 - 0.01)
2.5	6.79E04 (5.93E04 - 7.54E04)	0.02 (0.02 - 0.02)	3.74E04 (3.21E04 - 4.45E04)	0.01 (0.01 - 0.01)
2.4	9.56E04 (8.61E04 - 1.03E05)	0.02 (0.02 - 0.03)	5.40E04 (4.66E04 - 6.24E04)	0.01 (0.01 - 0.02)
2.3	1.36E05 (1.24E05 - 1.45E05)	0.03 (0.03 - 0.04)	8.06E04 (7.18E04 - 9.26E04)	0.02 (0.02 - 0.02)
2.2	1.93E05 (1.83E05 - 2.05E05)	0.05 (0.05 - 0.05)	1.21E05 (1.12E05 - 1.35E05)	0.03 (0.03 - 0.03)
2.1	2.74E05 (2.62E05 - 2.90E05)	0.07 (0.07 - 0.07)	1.78E05 (1.64E05 - 1.95E05)	0.05 (0.04 - 0.05)
2.0	3.81E05 (3.64E05 - 3.98E05)	0.10 (0.09 - 0.10)	2.57E05 (2.38E05 - 2.75E05)	0.07 (0.06 - 0.07)
1.5	1.88E06 (1.77E06 - 2.02E06)	0.48 (0.45 - 0.52)	1.50E06 (1.37E06 - 1.65E06)	0.38 (0.35 - 0.42)
1.0	1.08E07 (9.86E06 - 1.39E07)	2.77 (2.53 - 3.55)	9.78E06 (8.79E06 - 1.28E07)	2.51 (2.25 - 3.28)
0.5	1.25E08 (1.16E08 - 1.33E08)	32.0 (29.7 - 34.1)	1.19E08 (1.10E08 - 1.27E08)	30.5 (28.2 - 32.6)
0	3.90E08 (3.90E08 - 3.90E08)	100 (100 - 100)	3.90E08 (3.90E08 - 3.90E08)	100 (100 - 100)

[a] Values in parentheses indicate range of 10 runs.

indicated CO concentrations. Table 7-2 is similar in format; it presents estimates of the number of person-days in which members of the POI experienced an 8-hour daily maximum exposure at or above each indicated CO concentration. The maximum possible value in each of these tables is about 16. 3 million (denoted 1.63E07 in the tables) -- the product of the number of persons in the POI (44,545) and the number of days in the exposure period (365).

Table 7-3 presents estimates of the number of person-hours in which members of the POI experienced an end-of-hour COHb level at or above each of the indicated levels. The maximum possible value in this table is about 390 million (3.90E08) - the product of the number of persons in the POI (44,545) and the number of hours in the exposure period (8760).

The results presented in Tables 7-1 through 7-3 are preliminary results and are intended mainly to show the types of exposure estimates that are produced by the model. These estimates are subject to revision as further refinements to the model are made based on comments from EPA, CASAC, and the general public on the proposed Version 2.0 methodology.

SECTION 8

PRINCIPAL LIMITATIONS OF THE pNEM/CO METHODOLOGY

The pNEM/CO methodology was developed specifically to meet the requirements of OAQPS for a computer-based model capable of simulating the CO exposures and resulting COHb levels of specific population groups under alternative NAAQS. In addition to meeting these needs, the designers of pNEM/CO have attempted to create a model which is flexible in application and easy to upgrade. The model was deliberately constructed as a collection of stand-alone algorithms organized within a modular framework. For this reason, analysts can revise individual algorithms without the need to make major changes to other parts of the model.

The structure of each algorithm in pNEM/CO is largely determined by the characteristics of the available input data. For example, the algorithm used to construct a season-long exposure event sequence for each cohort is constrained by the fact that none of the available time/activity studies provides more than three days of diary data for any one subject. To make maximum use of the available diary data, the pNEM/CO sequencing algorithm constructs each exposure event sequence by sampling data from more than one subject. The other pNEM/CO algorithms are similarly designed to make best use of available data bases.

The exposure and COHb estimates presented in this report represent preliminary estimates based on the current Version 2.0 methodology. It is anticipated that some additional and revised data will become available over the next several months which will require running the model again to produce the estimates that will be considered during the current review of the CO NAAQS. In addition, the model may be revised based on comments from other EPA reviewers, CASAC, and/or the general public.

This section presents a brief discussion of the principal limitations in the pNEM/CO methodology as applied to Denver adults with IHD. These limitations are usually the result of limitations in the input data bases. The available data were typically collected for purposes other than use in a population exposure model. Consequently, these data frequently represent special sets of conditions which differ from those assumed by pNEM/CO. In these situations, analysts must exercise a certain degree of judgment in adapting the data for use in pNEM/CO. The limitations are organized according to six major components of the model: time/activity patterns, ventilation (inhalation) rates, air quality adjustment, the mass balance model, estimation of cohort populations, and the COHb algorithm.

8.1 Time/Activity Patterns

In the general pNEM/CO methodology, the exposure-related activities of each cohort are represented by a multi-day exposure event sequence which spans a specified time period (typically a calendar year). Each sequence is constructed by an algorithm which selects 24-hour (midnight-to-midnight) activity patterns from a specially prepared data file. This time/activity data file was derived from CHAD, a database developed by EPA which combines data from a variety of diary studies and telephone surveys in which subjects reported their daily activities.

In the application of pNEM/CO to Denver residents with IHD, the special data file consisted of diary data from CHAD subjects identified as adults. As these data were obtained primarily from healthy subjects, the data should adequately characterize the spectrum of activity patterns associated with the general adult population. However, the time/activity data may be somewhat unrepresentative of adults with IHD, the sensitive population group under analysis. To determine whether the data misrepresents the target group, researchers conducted the analysis described in Section 5.6. EPA has concluded that the differences in activity and exertion between angina and non-angina subjects, although statistically significant, do not appear to be large enough to significantly impact the validity of pNEM/CO modeling results which do not adjust for an angina/non-angina difference.

Section 7 presents pNEM/CO results for Denver, Colorado. The majority of time/activity data used in these model runs were obtained from locations other than Denver. Although the algorithm which constructs exposure event sequences attempts to account for effects of local climate on activity, it is unlikely that this adjustment corrects for all inter-city differences in people’s activities. Time/activity patterns are likely to be affected by a variety of local factors, including topography, land-use, traffic patterns, mass transit systems, and recreational opportunities.

The average subject in the CHAD-derived database provided less than two days of diary data. For this reason, the construction of each year-long exposure event sequence required either the repetition of data from one subject or the use of data from multiple subjects. The latter approach was used in the pNEM/CO analyses described in this report to better represent the variability of exposure expected to occur among the adults in each cohort. The principal deficiency of this approach is that it may not adequately account for the day-to-day repetition of activities common to individual adults. Using activities from different subjects may underestimate multiple occurrences of high exposure situations (e.g., long commutes) for segments of the population who engage in highly repetitive activities.

8.2 Ventilation (Inhalation) Rates

One of the advanced features of pNEM/CO is its ability to probabilistically estimate a ventilation rate (V_E) value for each exposure event, where V_E is expressed as liters of air respired per minute (liters min^{-1}). The algorithm used to estimate V_E was developed specifically for Version 2.0 of pNEM/CO and has not been used previously in pNEM analyses. As described in Section 5, the exposure event sequence for each cohort provides an activity descriptor (e.g., “raking”) for each event. Analysts provide a distribution of possible MET values for each activity descriptor type. The ventilation rate algorithm selects a value of MET for each exposure event from the appropriate distribution and converts it to a corresponding energy expenditure rate according to a resting metabolic rate assigned to the cohort.

The algorithm next converts each energy expenditure rate to a corresponding oxygen uptake rate (VO_2). Finally, the algorithm converts the resulting VO_2 value to V_E through the use of one of six equations specific to gender and age. In essence, the algorithm determines the quantity of air that a person in the cohort must breathe to obtain the oxygen needed to burn the calories required by the activity associated with each exposure event.

Most of the steps in converting an activity descriptor for an event to a V_E value for the event employ equations and parameter values which are relatively well-supported by clinical data (see Section 5). Perhaps the weakest link in the algorithm is the step which requires the analyst to provide a distribution of possible MET values for each event descriptor. These distributions are currently based on distributions provided by the developers of CHAD. Because there were often insufficient data available to accurately define a distribution for each activity descriptor, the developers tended to follow a conservative approach and over-estimate the variability of each distribution. Consequently, the V_E values produced by the ventilation rate algorithm may exhibit an excessive degree of variability. To prevent the occurrence of “impossible” values arising from this variability, the ventilation rate algorithm includes test routines which identify and adjust VO_2 values that exceed limits based on activity duration and the physiological characteristics of the cohort.

The ventilation rate estimated for a particular exposure event is not explicitly affected by the ventilation rates estimated for preceding events. Consequently, the algorithm does not adequately account for excess post-exercise oxygen consumption (EPOC), a condition experienced when individuals are engaged in strenuous exertion that results in an oxygen debt that impacts oxygen uptake and ventilation rates after cessation of the strenuous exercise. EPA is considering adding an adjustment approach to account for EPOC in future versions of pNEM.

Finally, healthy subjects provided most of the clinical data used to estimate the parameters of the ventilation rate algorithm. These data may not be entirely representative of adults with IHD, the sensitive population group included in this exposure analysis.

8.3 Estimation of Cohort Populations

Subsection 2.5.1 of this report describes the procedure used to estimate cohort populations for the general Denver population. Each cohort is defined by demographic group, cooking fuel, and work location. Ideally, the population of each cohort would be estimated from census data specific to each combination of these factors. In actuality, census data are available for each factor separately. Consequently, the population-estimation routines within pNEM/CO assume that the factors are independent in developing cohort estimates. However, it is likely that some factors are correlated. For example, pNEM/CO applies the same commuting pattern to all working demographic groups residing in a particular district because commuting data specific to the pNEM/CO demographic groups are not available from BOC. This assumption ignores the probable correlations between gender and work location.

Version 2.0 of pNEM/CO marks the first use of a new commuting database provide by the BOC. Although an improvement over earlier sources of commuting data, the BOC commuting database is not a perfect representation of the commuting patterns of Denver residents. The data were acquired from the census “long form” which the BOC administered to about one-sixth of the Denver residents. The BOC extrapolated the data from this subset of the population to the remainder of the population using various assumptions and supplemental information.

Section 2.5.2 describes the method used to estimate cohort populations for the sensitive population defined as persons with diagnosed and undiagnosed IHD. The method used the procedure applied to the general population with an additional step which accounted for the fraction of each demographic group who had IHD (diagnosed and undiagnosed). Table 2-9 lists estimates of these fractions. The estimates for diagnosed IHD are considered relatively reliable on a national scale, as they were obtained from data disaggregated by age and gender obtained from the National Health Interview Survey. According to the National Health Interview Survey, approximately 8.0 million individuals are estimated to have diagnosed IHD in the civilian, non-institutionalized population. These estimates do not include individuals in the military or individuals in nursing homes or other institutions. There is likely to be some geographic variation in the fraction of persons with IHD, but here is insufficient information available to account for this variation.

The estimates of undiagnosed IHD are considered less certain. These estimates are based on two assumptions: (1) there are 3.5 million persons in the U.S. with undiagnosed IHD and (2) persons with undiagnosed IHD are distributed by age and gender within the population in the same proportions as persons with diagnosed IHD. The 3.5 million statistic is based on an estimate by the American Heart Association (1990) that there are between three and four million persons with undiagnosed IHD.

8.4 The Mass-Balance Model

The pNEM/CO methodology uses the mass-balance model described in Section 4 to estimate CO concentrations in various enclosure types. The mass-balance model provides hourly average CO concentrations for each enclosure category as a function of outdoor CO concentration, air exchange rate (AER), and indoor emissions of CO from gas stoves.

The outdoor CO concentrations were derived from fixed-site monitoring data through a Monte Carlo process. According to this process, the outdoor CO concentration estimated for a particular hour h was influenced by (1) the microenvironment, (2) the outdoor CO concentration estimated for the preceding hour for the specified microenvironment, and (3) the CO concentration estimated for hour h at the fixed-site monitor representing district d. The probabilities incorporated into the process were developed through a statistical analysis of data obtained from the 1982 - 1983 Denver personal monitoring study (Johnson, 1984). Although these data are specific to the city analyzed in this report (Denver), they were collected more than a decade ago and may not be representative of current conditions in Denver. More recent personal monitoring data for Denver are not available.

The mass-balance model uses hourly-average CO concentrations measured by a relatively small number of fixed-site monitors (six individual sites plus one composite site). This monitoring network is unlikely to fully represent the geographically variability of outdoor CO concentrations in the Denver study area. In addition, some of these sites may be affected by specific CO sources which are not typical of general CO emission patterns. (However, there are no known major CO point sources near any of the fixed-site monitors used in this exposure analysis.) These potential deficiencies in the fixed-site data may be somewhat mitigated by the use of probabilistic relationships in pNEM/CO to estimate outdoor CO concentrations for the mass-balance model. The relationships are based on personal monitoring data representing a wide assortment of locations within the Denver study area.

The AER values for residential buildings with closed windows were obtained from lognormal distributions fit to seasonal AER data collected by Brookhaven National Laboratory (BNL). The BNL data for the region containing Denver included a large number of AER values for winter and spring, but small sample sizes for summer and winter. Consequently, analysts were required to use statistical methods to estimate the geometric mean and standard deviation for the seasons with limited data.

The AER distribution for residences with windows open is based on data collected in a single test residence in North Carolina over a single 24-hour period. These data may not be representative of Denver residences with open windows.

AER distributions for non-residential buildings are based on statistical analysis of data for 89 buildings. As none of the buildings was located in Denver, the distributions may not accurately represent non-residential buildings in Denver.

The AER distribution for vehicles is based on very limited data from two studies. The California Air Resources Board has indicated that additional data on AER in vehicles will soon be available. These data are expected to provide an improved basis for determining the AER for vehicles.

The mass-balance model simulates the operation of gas stove burners in residences by specifying when the burners are on, the emission rate of the burners during operation, and the volume of the residence where it is located. The probabilistic burner use patterns used in pNEM/CO are considered relatively reliable, as they are based on survey data for 4312 users and on diaries completed by several hundred subjects of the Denver personal monitoring study. Burner emission rates are based on fuel use patterns observed in 57 Illinois homes and emission factors representing a well-adjusted stove. It is not known whether Denver fuel use patterns differ significantly from those of Illinois residents. The use of emission factor data representing a well-tuned stove probably underestimates emissions from the overall population of gas stoves.

Residential volumes for Denver homes are randomly selected from a lognormal distribution based on Denver square footage data from the 1995 American Housing Survey. These data are considered to be relatively reliable.

Version 2.0 of pNEM/CO does not directly account for certain indoor sources (e.g., kerosene heaters, woodstoves, fireplaces, charcoal grills and hibachis used in the living area of homes, or motor vehicle operation in attached garages) which are likely to produce some high-end CO personal exposures. However, it should be noted that these situations are not directly related to the CO contribution from the ambient air. The model also does not capture high-end CO exposures that are due to malfunctioning gas stoves, ovens, or other gas appliances or the improper use of these gas appliances. The fact that some of these potentially high-end CO exposure scenarios are not considered within pNEM/CO may at least partially explain why past comparisons of the model predictions with actual personal exposure data collected in Denver showed the model under-predicting the upper tail of CO exposure distribution for the population (Law et al., 1997).

8.5 The COHb Algorithm

This algorithm provides an estimate of the COHb level at the end of each exposure event. The algorithm is based on a differential equation proposed by Coburn, Foster, and Kane (1963). EPA's draft updated criteria document (EPA, 1999, p.5-35) states that the nonlinear CFK equation is the most widely used predictive model of COHb formation, and it still is considered the best all-around model for COHb prediction. Various tests of the CFK equation indicate that the model predicts COHb levels accurately unless one is dealing with very high CO exposures of short duration (e.g., hundreds of ppm CO in a few minutes).

A special algorithm within pNEM/CO probabilistically generates a value for each parameter of the CFK equation (collectively referred to as a "physiological profile"). The algorithm ensures that the functional relationships among the various parameters are maintained. A report by Richmond and Johnson (Appendix E of this report) discusses the limitations of data used to estimate the distributions and predictive equations associated with each of the parameters appearing in the CFK equation.

8.6 References

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Appendix A

Distribution of Energy Expenditure Rates Associated with CHAD Location Descriptors

Distributions for Energy Expenditure Rates By Activity Code, Age, and Occupation (if applicable).

Notes:

1. Activities coded as 10... are activities with codes beginning with 10.
2. OCC: occupational categories.
3. DN: distribution number
4. DL: distribution type (T = triangular, N = normal, U = uniform, E = exponential, P = point)
5. Activities starting with 17... are calculated based on age.

Age = 1 if respondent < 25 years
Age = 2 if respondent 25 - 39 years
Age = 3 if respondent > 40 years

ACTIVITY	AGE	OCC	DN	DL	MEAN	MED	SD	MIN	MAX	FLAG	LEFT	RIGHT
10...	X	ADMIN	4	L	1.7	1.7	0.3	1.4	2.7	0	0.16	0.01
10...	X	PROF	5	T	2.9	2.7	1	1.2	5.6	0	0	0
10...	X	ADMSUP	4	L	1.7	1.7	0.3	1.4	2.7	0	0.16	0.01
10...	X	TECH	5	T	3.3	3.3	0.4	2.5	4.5	1	0	0
10...	X	TRANS	4	L	3.3	3	1.5	1.3	8.4	1	0.03	0.01
10...	X	SALE	5	T	2.9	2.7	1	1.2	5.6	0	0	0
10...	X	SERV	5	T	5.2	5.3	1.4	1.6	8.4	1	0	0
10...	X	HSHLD	4	L	3.6	3.5	0.8	2.5	6	1	0.07	0.01
10...	X	PROTECT	5	T	2.9	2.7	1	1.2	5.6	0	0	0
10...	X	PREC	5	T	3.3	3.3	0.4	2.5	4.5	1	0	0
10...	X	MACH	2	U	5.3	5.3	0.7	4	6.5	1	0	0
10...	X	FARM	4	L	7.5	7	3	3.6	17	1	0.04	0.01
10...	X	LABOR	5	T	8.5	8.4	2.1	3.6	13.8	1	0	0
17100	1	X	4	L	5.7	5	3	1.4	16	1	0.01	0.01
17100	2	X	1	N	5	5	2	1	9	1	0.02	0.02
17100	3	X	1	N	4.5	4.5	1.4	1.7	7.3	1	0.02	0.02
17110	1	X	4	L	3.6	3.2	1.9	1.4	10	1	0.05	0.01
17110	2	X	4	L	3.6	3.2	1.9	1.4	10	1	0.05	0.01
17110	3	X	4	L	3.4	3	1.7	1.4	9	1	0.05	0.01
17111	1	X	1	N	5.6	5.6	2.1	1.4	9.8	1	0.02	0.02
17111	2	X	1	N	5.8	5.8	2.4	1	10.6	1	0.02	0.02
17111	3	X	1	N	4.7	4.7	1.8	1.1	8.3	1	0.02	0.02
17112	1	X	2	U	3.8	3.8	1	2	5.5	1	0	0
17112	2	X	2	U	3.8	3.8	1	2	5.5	1	0	0
17112	3	X	2	U	3.5	3.5	0.9	2	5	1	0	0
17120	1	X	4	L	4.2	3.9	1.5	2	9	1	0.03	0.01
17120	2	X	4	L	4.2	3.9	1.5	2	9	1	0.03	0.01
17120	3	X	6	P	3.5	3.5	.	.	.	1	.	.
17121	1	X	4	L	4.2	3.9	1.5	2	9	1	0.03	0.01
17121	2	X	4	L	4.2	3.9	1.5	2	9	1	0.03	0.01
17121	3	X	6	P	3.5	3.5	.	.	.	1	.	.
17130	1	X	4	L	5.8	5.5	1.8	1.8	11.3	1	0	0.01
17130	2	X	1	N	5.7	5.7	1.8	2.1	9.3	1	0.02	0.02
17130	3	X	1	N	4.7	4.7	1.2	2.3	7.1	1	0.02	0.02
17131	1	X	4	L	5.8	5.5	1.8	1.8	11.3	1	0	0.01
17131	2	X	1	N	5.7	5.7	1.8	2.1	9.3	1	0.02	0.02
17131	3	X	1	N	4.7	4.7	1.2	2.3	7.1	1	0.02	0.02
17140	1	X	1	N	5.3	5.3	1.8	1.7	8.9	1	0.02	0.02

17140	2	X	1	N	5.2	5.2	1.7	1.7	8.9	1	0.02	0.01
17140	3	X	1	N	3.8	3.8	1	1.8	5.8	1	0.02	0.02
17144	1	X	1	N	5.3	5.3	1.8	1.7	8.9	1	0.02	0.02
17144	2	X	1	N	5.2	5.2	1.7	1.7	8.9	1	0.02	0.01
17144	3	X	1	N	3.8	3.8	1	1.8	5.8	1	0.02	0.02
17180	1	X	4	L	6.6	5.9	3.2	2	17.4	1	0.01	0.01
17180	2	X	1	N	6	6	2	2	10	1	0.02	0.02
17180	3	X	1	N	4.8	4.8	1.4	2	7.6	1	0.02	0.02
10200	X	X	2	U	1.8	1.8	0.4	1	2.5	0	0	0
10300	X	X	2	U	1.8	1.8	0.4	1	2.5	0	0	0
11000	X	X	5	T	4.7	4.6	1.3	1.5	8	1	0	0
11100	X	X	4	L	2.6	2.5	0.5	2	4	0	0.13	0.01
11110	X	X	3	E	2.8	2.5	0.9	1.9	4	0	0	0.02
11200	X	X	3	E	3.4	3	1.4	2	5	1	0	0.01
11210	X	X	2	U	2.5	2.5	0.1	2.3	2.7	0	0	0
11220	X	X	3	E	4.1	3.5	1.9	2.2	5	1	0	0.01
11300	X	X	1	N	5	5	1	2	7	1	0	0.02
11310	X	X	3	E	5.3	4.5	2.7	2.6	6	1	0	0
11400	X	X	3	E	2.2	2	0.7	1.5	4	0	0	0.02
11410	X	X	6	P	2	2	.	.	.	0	.	.
11500	X	X	6	P	2	2	.	.	.	0	.	.
11600	X	X	1	N	4.5	4.5	1.5	2	8	1	0.05	0.01
11610	X	X	6	P	4.5	4.5	.	.	.	1	.	.
11620	X	X	3	E	4.9	4.5	1.4	3.5	6	1	0	0
11630	X	X	5	T	3.5	3.4	0.4	3	4.5	1	0	0
11640	X	X	3	E	4.7	4.5	0.7	4	6	1	0	0
11650	X	X	2	U	4.5	4.5	1.4	2	7	1	0	0
11700	X	X	2	U	3.5	3.5	0.9	2	5	1	0	0
11800	X	X	2	U	3.3	3.3	0.1	3	3.5	1	0	0
11900	X	X	3	E	6.6	5.5	3.6	3	9	1	0	0
12000	X	X	4	L	3.1	3	0.7	2.5	5	1	0.2	0.01
12100	X	X	2	U	3.3	3.3	0.1	3	3.5	1	0	0
12200	X	X	2	U	3.3	3.3	0.1	3	3.5	1	0	0
12300	X	X	2	U	2.8	2.8	0.1	2.5	3	0	0	0
12400	X	X	2	U	2.8	2.8	0.1	2.5	3	0	0	0
12500	X	X	2	U	2.8	2.8	0.1	2.5	3	0	0	0
12600	X	X	2	U	4.5	4.5	0.3	4	5	1	0	0
12700	X	X	2	U	3.2	3.2	0.1	3	3.3	1	0	0
12800	X	X	2	U	3	3	0.3	2.5	3.5	1	0	0
13000	X	X	5	T	3.8	3.7	0.8	2	6	1	0	0
13100	X	X	2	U	3.3	3.3	0.4	2.5	4	1	0	0
13200	X	X	5	T	3.7	3.6	0.8	2	6	1	0	0
13210	X	X	5	T	3.9	3.8	0.8	2.2	6	1	0	0
13220	X	X	2	U	3.4	3.4	0.6	2.3	4.5	1	0	0
13230	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13300	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13400	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13500	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13600	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13700	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
13800	X	X	2	U	3.5	3.5	0.6	2.5	4.5	1	0	0
14000	X	X	2	U	2	2	0.6	1	3	0	0	0

14100	X	X	1	N	2	2	0.3	1	4	0	0	0
14110	X	X	2	U	3	3	0.6	2	4	1	0	0
14120	X	X	2	U	1.8	1.8	0.4	1	2.5	0	0	0
14200	X	X	2	U	1.8	1.8	0.4	1	2.5	0	0	0
14300	X	X	4	L	3.1	3	0.7	2.5	5	1	0.2	0.01
14400	X	X	2	U	1.8	1.8	0.1	1.5	2	0	0	0
14500	X	X	4	L	0.9	0.9	0.1	0.8	1.1	0	0.09	0.01
14600	X	X	6	P	2.5	2.5	.	.	.	0	.	.
14700	X	X	5	T	2	2	0.4	1	2.9	0	0	0
15000	X	X	4	L	1.9	1.8	0.7	1.4	4	0	0.23	0.01
15100	X	X	2	U	2.1	2.1	0.4	1.4	2.8	0	0	0
15110	X	X	2	U	2.3	2.3	0.4	1.5	3	0	0	0
15120	X	X	2	U	2.1	2.1	0.4	1.4	2.8	0	0	0
15130	X	X	2	U	2	2	0.3	1.4	2.5	0	0	0
15140	X	X	2	U	1.8	1.8	0.2	1.4	2.2	0	0	0
15200	X	X	2	U	2.2	2.2	0.5	1.4	3	0	0	0
15300	X	X	6	P	1.8	1.8	.	.	.	0	.	.
15400	X	X	2	U	2.3	2.3	0.4	1.5	3	0	0	0
15500	X	X	2	U	2.8	2.8	0.7	1.5	4	0	0	0
16000	X	X	4	L	2.2	2	1.1	1	6	0	0.07	0.01
16100	X	X	2	U	2.7	2.7	0.8	1.4	4	0	0	0
16200	X	X	2	U	1.7	1.7	0.2	1.4	2	0	0	0
16210	X	X	2	U	1.7	1.7	0.2	1.4	2	0	0	0
16300	X	X	2	U	1.3	1.3	0.2	1	1.6	0	0	0
16400	X	X	2	U	1.7	1.7	0.4	1	2.3	0	0	0
16500	X	X	2	U	2.5	2.5	0.3	2	2.9	0	0	0
16600	X	X	2	U	1.5	1.5	0.3	1	1.9	0	0	0
16700	X	X	4	L	3.3	3	1.4	1.5	8	1	0.05	0.01
16800	X	X	4	L	3.3	3	1.4	1.5	8	1	0.05	0.01
16900	X	X	2	U	3.8	3.8	1.3	1.5	6	1	0	0
17113	X	X	2	U	3	3	0.6	2	4	1	0	0
17114	X	X	5	T	3.1	3.2	0.6	1.4	4	1	0	0
17122	X	X	2	U	1.5	1.5	0.2	1.2	1.8	0	0	0
17141	X	X	5	T	2.8	2.7	0.8	1.5	5	0	0	0
17142	X	X	5	T	2	1.9	0.4	1.5	3	0	0	0
17143	X	X	2	U	2.5	2.5	0.3	2	3	0	0	0
17150	X	X	5	T	3.3	3.2	0.6	2.4	5	1	0	0
17160	X	X	2	U	1.6	1.6	0.2	1.2	2	0	0	0
17170	X	X	2	U	5	5	1.7	2	8	1	0	0
17200	X	X	4	L	1.3	1.3	0.3	1	2.3	0	0.14	0.01
17210	X	X	2	U	1.5	1.5	0.2	1.2	1.8	0	0	0
17211	X	X	2	U	.	.	.	1.2	.	0	0	.
17212	X	X	2	U	.	.	.	1.2	.	0	0	.
17213	X	X	2	U	.	.	.	1.2	.	0	0	.
17214	X	X	2	U	.	.	.	1.2	.	0	0	.
17215	X	X	2	U	.	.	.	1.2	.	0	0	.
17216	X	X	2	U	2.7	2.7	0.8	1.4	4	0	0	0
17220	X	X	4	L	1.2	1.2	0.4	0.9	2.3	0	0.15	0.01
17221	X	X	2	U	1.2	1.2	0.1	1	1.3	0	0	0
17222	X	X	2	U	1.9	1.9	0.2	1.5	2.3	0	0	0
17223	X	X	6	P	1	1	.	.	.	0	.	.
17230	X	X	2	U	1.3	1.3	0.2	1	1.6	0	0	0

17231	X	X	2	U	1.3	1.3	0.2	1	1.6	0	0	0
17232	X	X	2	U	1.3	1.3	0.2	1	1.6	0	0	0
17233	X	X	2	U	1.3	1.3	0.2	1	1.6	0	0	0
17240	X	X	2	U	1.4	1.4	0.2	1	1.8	0	0	0
17241	X	X	2	U	1.4	1.4	0.2	1	1.8	0	0	0
17242	X	X	2	U	1.4	1.4	0.2	1	1.8	0	0	0
17250	X	X	2	U	1.2	1.2	0.1	1	1.3	0	0	0
17260	X	X	2	U	1.9	1.9	0.2	1.5	2.3	0	0	0
17300	X	X	2	U	1.5	1.5	0.2	1.2	1.8	0	0	0
18000	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18100	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18200	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18300	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18400	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18500	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18600	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18700	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18800	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18900	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18910	X	X	4	L	2.3	2	1.3	1	7	0	0.1	0.01
18920	X	X	4	L	2.3	2	1.3	1.8	7	0	0.42	0.01

CHAD Activity Codes

<10> Work and Other Income Producing Activities
10000: work and other income producing activities, general
10100: work, general
  10110: work, general, for organizational activities
    10111: work for professional/union organizations
    10112: work for special interest identity organizations
    10113: work for political party and civic participation
    10114: work for volunteer/ helping organizations
    10115: work of/ for religious groups
    10116: work for fraternal organizations
    10117: work for child/ youth/ family organizations
    10118: work for other organizations
  10120: work, income-related only
  10130: work, secondary (income-related)
10200: unemployment
10300: breaks

<11> Household Activities
11000: general household activities
11100: prepare food
  11110: prepare and clean-up food
11200: indoor chores
  11210: clean-up food
  11220: clean house
11300: outdoor chores
  11310: clean outdoors
11400: care of clothes
  11410: wash clothes
11500: build a fire
11600: repair, general
  11610: repair of boat
  11620: paint home/ room
  11630: repair/ maintain car
  11640: home repairs
  11650: other repairs
11700: care for plants
11800: care for pets/ animals
11900: other household

<12> Child Care
12000: child care, general
12100: care of baby
12200: care of child
12300: help/teach
12400: talk/read
12500: play indoors

12600: play outdoors
12700: medical care-child
12800: other child care
<13> Obtain Goods and Services
13000: obtain goods and services, general
13100: dry clean
13200: shop/ run errands, general
    13210: shop for food
    13220: shop for clothes or household goods
    13230: run errands
13300: obtain personal care service
13400: obtain medical service
13500: obtain government/ financial services
13600: obtain car service
13700: other repairs
13800: other services
<14> Personal Needs and Care
14000: personal needs and care, general
14100: shower, bathe, personal hygiene
    14110: shower, bathe
    14120: personal hygiene
14200: medical care
14300: help and care
14400: eat
14500: sleep or nap
14600: dress, groom
14700: other personal needs
<15> Education and Professional Training
15000: general education and professional training
15100: attend full-time school
    15110: attend day-care
    15120: attend K-12
    15130: attend college or trade school
    15140: attend adult education and special training
15200: attend other classes
15300: do homework
15400: use library
15500: other education
<16> Entertainment/ Social Activities
16000: general entertainment/ social activities
16100: attend sports events
16200: participate in social, political, or religious activities
    16210: practice religion
16300: view movie
16400: attend theater
16500: visit museums
16600: visit

16700: attend a party
16800: go to bar/ lounge
16900: other entertainment/ social events

<17> Leisure

- 17000: leisure, general
- 17100: participate in sports and active leisure
  - 17110: participate in sports
    - 17111: hunting, fishing, hiking
    - 17112: golf
    - 17113: bowling/ pool/ ping pong/ pinball
    - 17114: yoga
  - 17120: participate in outdoor leisure
    - 17121: play, unspecified
    - 17122: passive, sitting
  - 17130: exercise
    - 17131: walk, bike, or jog (not in transit)
  - 17140: create art, music, participate in hobbies
    - 17141: participate in hobbies
    - 17142: create domestic crafts
    - 17143: create art
    - 17144: perform music/ drama/ dance
  - 17150: play games
  - 17160: use of computer
  - 17170: participate in recess and physical education
  - 17180: other sports and active leisure
- 17200: participate in passive leisure
  - 17210: watch
    - 17211: watch adult at work
    - 17212: watch someone provide childcare
    - 17213: watch personal care
    - 17214: watch education
    - 17215: watch organizational activities
    - 17216: watch recreation
  - 17220: listen to radio/ listen to recorded music/ watch t.v.
    - 17221: listen to radio
    - 17222: listen to recorded music
    - 17223: watch t.v.
  - 17230: read, general
    - 17231: read books
    - 17232: read magazine/ not ascertained
    - 17233: read newspaper
  - 17240: converse/ write
    - 17241: converse
    - 17242: write for leisure/ pleasure/ paperwork
  - 17250: think and relax
  - 17260: other passive leisure
- 17300: other leisure

<18> Travel

- 18000: travel, general
- 18100: travel during work
- 18200: travel to/from work
- 18300: travel for child care
- 18400: travel for goods and services
- 18500: travel for personal care
- 18600: travel for education
- 18700: travel for organizational activity
- 18800: travel for event/ social activity
- 18900: travel for leisure
  - 18910: travel for active leisure
  - 18920: travel for passive leisure

Appendix B

Fixed-Site Monitors in Colorado Reporting CO Data to AIRS for One or More Years Between 1993 and 1997

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1DATE 98/06/25                         EPA AEROMETRIC INFORMATION RETRIEVAL SYSTEM (AIRS)                   PAGE
 AMP450                                               AIR QUALITY SUBSYSTEM
                                                                                                                  1
0          CARBON MONOXIDE (42101)                        COLORADO                      UNITS: 007 PPM
0            P
                                                                              REP        MAX 1-HR     OBS>   MAX 8-HR     OBS>
 SITE ID     C T CITY              COUNTY          ADDRESS                 YR ORG #OBS  1ST      2ND    35   1ST      2ND    9    METH
008-001-3001 1 2                   ADAMS CO        78TH AVE & STEELE ST - W 93 001 8632   9.0      8.2      0   6.6      4.9      0   054
 08-001-3001 1 2                   ADAMS CO        78TH AVE & STEELE ST - W 94 001 8687   9.0      8.8      0   6.4      6.3      0   054
 08-001-3001 1 2                   ADAMS CO        78TH AVE & STEELE ST - W 95 001 8681   8.5      8.1      0   5.7      5.1      0   054
 08-001-3001 1 2                   ADAMS CO        78TH AVE & STEELE ST - W 96 001 8712   6.2      6.2      0   3.9      3.9      0   054
 08-001-3001 1 2                   ADAMS CO        78TH AVE & STEELE ST - W 97 001 8661   8.3      6.6      0   5.0      4.3      0   054
 0 M
 08-001-7015 1 4 COMMERCE CITY     ADAMS CO        ROCKY MOUNTAIN ARSENAL   93 830 7919   7.7      6.6      0   4.3      4.0      0   054
 08-001-7015 1 4 COMMERCE CITY     ADAMS CO        ROCKY MOUNTAIN ARSENAL   94 830 3595   3.2      2.5      0   1.2      1.1      0   054
 08-005-0002 1 2 LITTLETON         ARAPAHOE CO     8100 SO UNIVERSITY BLVD- 93 001 8589   7.0      6.5      0   4.9      3.4      0   054
 08-005-0002 1 2 LITTLETON         ARAPAHOE CO     8100 SO UNIVERSITY BLVD- 94 001 8705   4.6      4.2      0   2.9      2.2      0   054
 08-005-0002 1 2 LITTLETON         ARAPAHOE CO     8100 SO UNIVERSITY BLVD- 95 001 8670   3.6      3.3      0   2.6      2.1      0   054
 08-005-0002 1 2 LITTLETON         ARAPAHOE CO     8100 SO UNIVERSITY BLVD- 96 001 8677   4.3      4.1      0   2.9      2.6      0   054
 08-005-0002 1 2 LITTLETON         ARAPAHOE CO     8100 SO UNIVERSITY BLVD- 97 001 8463   4.3      4.0      0   3.0      2.8      0   054
 08-005-0003 1 2 ENGLEWOOD         ARAPAHOE CO     3300 S. HURON ST.        93 001 8717  11.5     10.9      0   8.4      6.2      0   054
 08-005-0003 1 2 ENGLEWOOD         ARAPAHOE CO     3300 S. HURON ST.        94 001 7126   7.5      7.3      0   4.9      4.0      0   054
 08-013-0009 1 2 LONGMONT          BOULDER CO      440 MAIN ST. LONGMONT    93 001 8701   9.5      9.0      0   7.0      6.4      0   054
 08-013-0009 1 2 LONGMONT          BOULDER CO      440 MAIN ST. LONGMONT    94 001 8557  12.6     12.2      0   6.7      6.2      0   054
 08-013-0009 1 2 LONGMONT          BOULDER CO      440 MAIN ST. LONGMONT    95 001 8690  14.0      8.8      0   5.6      4.7      0   054
 08-013-0009 1 2 LONGMONT          BOULDER CO      440 MAIN ST. LONGMONT    96 001 8735  11.3      9.2      0   5.5      5.5      0   054
 08-013-0009 1 2 LONGMONT          BOULDER CO      440 MAIN ST. LONGMONT    97 001 8617   9.6      9.1      0   5.7      5.4      0   054
 08-013-0010 1 2 BOULDER           BOULDER CO      2150 28TH STREET         93 001  353   7.6      7.6      0   5.1      4.9      0   054
 08-013-0010 1 2 BOULDER           BOULDER CO      2150 28TH STREET         94 001 8639  12.4     10.5      0   6.6      6.0      0   054
 08-013-0010 1 2 BOULDER           BOULDER CO      2150 28TH STREET         95 001 8608  10.6     10.3      0   5.3      5.2      0   054
 08-013-0010 1 2 BOULDER           BOULDER CO      2150 28TH STREET         96 001 8576   8.5      8.4      0   5.6      4.3      0   054
 08-013-0010 1 2 BOULDER           BOULDER CO      2150 28TH STREET         97 001 8697   9.0      8.2      0   5.5      3.9      0   054
 08-013-1001 1 2 BOULDER           BOULDER CO      2320 MARINE ST., BOULDER 93 001 8708  10.2      8.4      0   5.5      4.1      0   054
 08-013-1001 1 2 BOULDER           BOULDER CO      2320 MARINE ST., BOULDER 94 001 8565   7.8      6.0      0   2.8      2.7      0   054
 08-013-1001 1 2 BOULDER           BOULDER CO      2320 MARINE ST., BOULDER 95 001 8651   8.3      8.2      0   4.1      3.7      0   054
 08-013-1001 1 2 BOULDER           BOULDER CO      2320 MARINE ST., BOULDER 96 001 8669   4.5      4.3      0   2.5      2.5      0   054
 08-013-1001 1 2 BOULDER           BOULDER CO      2320 MARINE ST., BOULDER 97 001 8517   7.1      6.9      0   5.1      3.3      0   054
 QUICK LOOK REPORT
 08-031-0002 2 1 DENVER            DENVER CO       2105 BROADWAY - CAMP     93 001 8687  19.4     18.2      0  10.4     10.4      2   054
 08-031-0002 2 1 DENVER            DENVER CO       2105 BROADWAY - CAMP     94 001 8700  20.4     17.1      0   9.9      8.2      1   054
 08-031-0002 2 1 DENVER            DENVER CO       2105 BROADWAY - CAMP     95 001 8697  24.5     16.4      0  11.0      9.5      2   054
 08-031-0002 2 1 DENVER            DENVER CO       2105 BROADWAY - CAMP     96 001 8673  21.6     16.7      0   9.0      7.3      0   054
 08-031-0002 2 1 DENVER            DENVER CO       2105 BROADWAY - CAMP     97 001 8687  11.4     10.0      0   5.7      5.5      0   054
 08-031-0013 1 2 DENVER            DENVER CO       14TH AND ALBION ST. NJH- 93 001 8675  18.1     14.9      0   9.1      7.8      0   054
 08-031-0013 1 2 DENVER            DENVER CO       14TH AND ALBION ST. NJH- 94 001 8665  12.4     12.2      0   8.0      7.6      0   054
 08-031-0013 1 2 DENVER            DENVER CO       14TH AND ALBION ST. NJH- 95 001 8647  14.6     13.6      0   8.5      6.2      0   054
 08-031-0013 1 2 DENVER            DENVER CO       14TH AND ALBION ST. NJH- 96 001 8516  14.6      9.4      0   5.6      5.2      0   054
 08-031-0013 1 2 DENVER            DENVER CO       14TH AND ALBION ST. NJH- 97 001 8690  11.6     10.6      0   4.8      4.7      0   054
 08-031-0014 1 1 DENVER            DENVER CO       23 RD AND JULIAN_(CARRIA 93 001 8676  14.1     12.1      0   8.5      8.2      0   054
 08-031-0014 1 1 DENVER            DENVER CO       23 RD AND JULIAN_(CARRIA 94 001 8543  11.2     10.9      0   9.3      7.3      0   054
 08-031-0014 1 1 DENVER            DENVER CO       23 RD AND JULIAN_(CARRIA 95 001 8701  10.4      9.9      0   7.3      5.9      0   054
 08-031-0014 1 1 DENVER            DENVER CO       23 RD AND JULIAN_(CARRIA 96 001 8736   9.1      8.2      0   7.3      5.7      0   054
 08-031-0014 1 1 DENVER            DENVER CO       23 RD AND JULIAN_(CARRIA 97 001 8677   9.5      8.4      0   7.0      6.2      0   054
1DATE 98/06/25                         EPA AEROMETRIC INFORMATION RETRIEVAL SYSTEM (AIRS)                   PAGE
 AMP450                                               AIR QUALITY SUBSYSTEM
                                                                                                                  2
0          CARBON MONOXIDE (42101)                        COLORADO                      UNITS: 007 PPM
0            P
                                                                              REP        MAX 1-HR     OBS>   MAX 8-HR     OBS>
 SITE ID     C T CITY              COUNTY          ADDRESS                 YR ORG #OBS  1ST      2ND    35   1ST      2ND    9    METH
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O M

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008-031-0018 1 3 DENVER          DENVER CO       BLAKE ST. SIDE OF SPEER  93 001 1021  16.2    15.3       0  10.4     7.7        1   051
 08-031-0018 1 3 DENVER          DENVER CO       BLAKE ST. SIDE OF SPEER  94 001 1591  12.2    11.6       0   7.8     6.5        0   051
 08-031-0019 1 2 DENVER          DENVER CO       SPEER SIDE OF SPEER & AU 93 001  997  16.2    16.1       0  10.4     7.7        1   051
 08-031-0019 1 2 DENVER          DENVER CO       SPEER SIDE OF SPEER & AU 94 001 3049  13.9    13.4       0   9.0     8.2        0   051
 08-031-0019 1 2 DENVER          DENVER CO       SPEER SIDE OF SPEER & AU 95 001 3658  15.0    14.0       0   9.7     7.1        1   000
 08-031-0019 1 2 DENVER          DENVER CO       SPEER SIDE OF SPEER & AU 96 001 8694  15.7    12.5       0   9.2     7.0        0   054
 08-031-0019 1 2 DENVER          DENVER CO       SPEER SIDE OF SPEER & AU 97 001 8354  11.2    11.2       0   6.6     6.4        0   054
 08-031-0020 1 3 DENVER          DENVER CO       935 COLORADO BLVD., UCHS 94 001 1370  12.8    11.7       0   7.6     6.8        0   054
 08-031-0020 1 3 DENVER          DENVER CO       935 COLORADO BLVD., UCHS 95 001 2141  11.9    10.3       0   7.4     6.0        0   054
 08-041-0004 1 2 COLORADO SPRING EL PASO CO      712 S TEJON ST           93 001 8716  11.7    10.7       0   5.6     5.0        0   054
 08-041-0004 1 2 COLORADO SPRING EL PASO CO      712 S TEJON ST           94 001 8716  12.5    10.9       0   4.4     4.2        0   054
 08-041-0004 1 2 COLORADO SPRING EL PASO CO      712 S TEJON ST           95 001 8698  10.4     9.6       0   5.2     4.7        0   054
 08-041-0004 1 2 COLORADO SPRING EL PASO CO      712 S TEJON ST           96 001 8688  10.7     9.1       0   4.7     3.8        0   054
 08-041-0004 1 2 COLORADO SPRING EL PASO CO      712 S TEJON ST           97 001 4658  10.4     8.2       0   4.7     3.9        0   054
 08-041-0006 1 2 COLORADO SPRING EL PASO CO      UINTAH & I-25            93 001 8660  13.6    11.6       0   6.1     5.7        0   054
 08-041-0006 1 2 COLORADO SPRING EL PASO CO      UINTAH & I-25            94 001 8578  11.7    11.4       0   5.4     4.9        0   054
 08-041-0006 1 2 COLORADO SPRING EL PASO CO      UINTAH & I-25            95 001 8716  10.8    10.3       0   7.2     5.5        0   054
 08-041-0006 1 2 COLORADO SPRING EL PASO CO      UINTAH & I-25            96 001 8746  11.3    11.3       0   7.6     5.0        0   054
 08-041-0006 1 2 COLORADO SPRING EL PASO CO      UINTAH & I-25            97 001 8577  13.1    10.6       0   5.9     4.9        0   054
 08-041-6004 1 3 COLORADO SPRING EL PASO CO      6000 PULPIT ROCK DRIVE.  93 026 8341   4.1     3.9       0   2.1     1.8        0   048
 08-041-6004 1 3 COLORADO SPRING EL PASO CO      6000 PULPIT ROCK DRIVE.  94 026 8709   4.0     3.9       0   2.3     2.2        0   000
 08-041-6004 1 3 COLORADO SPRING EL PASO CO      6000 PULPIT ROCK DRIVE.  95 026 8724   4.2     3.8       0   2.3     2.3        0   093
 08-041-6004 1 3 COLORADO SPRING EL PASO CO      6000 PULPIT ROCK DRIVE.  96 026 8544   3.8     3.4       0   2.1     2.0        0   093
 08-041-6005 1 3                 EL PASO CO      4940 S. HIGHWAY 85/87    93 026 8508   7.0     7.0       0   4.5     3.8        0   048
 08-041-6005 1 3                 EL PASO CO      4940 S. HIGHWAY 85/87    94 026 8655   6.8     6.2       0   4.6     4.5        0   000
 08-041-6005 1 3                 EL PASO CO      4940 S. HIGHWAY 85/87    95 026 8515   5.9     5.6       0   3.2     3.1        0   093
 08-041-6005 1 3                 EL PASO CO      4940 S. HIGHWAY 85/87    96 026 3064   6.1     5.6       0   3.0     2.9        0   093
 08-041-6006 1 3                 EL PASO CO      9400 CHIPITA PARK ROAD   93 026 8257   2.0     1.8       0   1.1     1.0        0   048
 08-041-6006 1 3                 EL PASO CO      9400 CHIPITA PARK ROAD   94 026 7620   2.0     1.9       0   1.2      .9        0   000
 08-041-6006 1 3                 EL PASO CO      9400 CHIPITA PARK ROAD   95 026 7793   3.0     2.9       0   2.4     1.9        0   093
 08-041-6006 1 3                 EL PASO CO      9400 CHIPITA PARK ROAD   96 026 4148   2.1     2.1       0   1.8     1.8        0   093
 08-041-6009 1 3                 EL PASO CO      R.D.NIXON POWER PLANT EX 93 026 6003   1.9     1.7       0   1.0      .8        0   048
 08-041-6009 1 3                 EL PASO CO      R.D.NIXON POWER PLANT EX 94 026 8702   2.2     1.9       0   1.3     1.1        0   000
 08-041-6009 1 3                 EL PASO CO      R.D.NIXON POWER PLANT EX 95 026 8707   2.4     2.2       0   1.3     1.1        0   093
 08-041-6009 1 3                 EL PASO CO      R.D.NIXON POWER PLANT EX 96 026 4328   1.5     1.4       0    .8      .8        0   093
 08-041-6011 1 3 COLORADO SPRING EL PASO CO      130 WEST CACHE LA POUDRE 93 026 8584   8.7     7.9       0   4.5     3.9        0   048
 08-041-6011 1 3 COLORADO SPRING EL PASO CO      130 WEST CACHE LA POUDRE 94 026 8318   7.9     6.8       0   3.3     3.2        0   000
 08-041-6011 1 3 COLORADO SPRING EL PASO CO      130 WEST CACHE LA POUDRE 95 026 8500   7.4     7.0       0   4.0     3.7        0   093
 08-041-6011 1 3 COLORADO SPRING EL PASO CO      130 WEST CACHE LA POUDRE 96 026 8469   8.1     8.1       0   4.9     3.7        0   093
 08-041-6013 1 3 COLORADO SPRING EL PASO CO      1699 S. CORONA AVE       93 026 8619  11.0    10.1       0   5.3     4.7        0   054
 08-041-6013 1 3 COLORADO SPRING EL PASO CO      1699 S. CORONA AVE       94 026 8703  10.8     9.3       0   4.6     4.5        0   054
 08-041-6013 1 3 COLORADO SPRING EL PASO CO      1699 S. CORONA AVE       95 026 8429   9.4     8.7       0   5.0     4.0        0   093
 08-041-6013 1 3 COLORADO SPRING EL PASO CO      1699 S. CORONA AVE       96 026 4310  11.9     9.6       0   5.4     3.8        0   093
 08-041-6016 1 3 COLORADO SPRING EL PASO CO      3730 MEADOWLAND BLVD.    93 026 8593  15.1    14.2       0   6.5     5.9        0   054
1DATE 98/06/25                        EPA AEROMETRIC INFORMATION RETRIEVAL SYSTEM (AIRS)                      PAGE
 AMP450                                              AIR QUALITY SUBSYSTEM
                                                                                                                    3
0          CARBON MONOXIDE (42101)                        COLORADO                    UNITS: 007 PPM
0            P
                                                                           REP        MAX 1-HR      OBS>   MAX 8-HR      OBS>
 SITE ID     C T CITY            COUNTY          ADDRESS                  YR ORG #OBS  1ST     2ND      35   1ST     2ND      9    METH
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008-041-6016 1 3 COLORADO SPRING EL PASO CO      3730 MEADOWLAND BLVD.    94 026 8574  16.6    14.5       0   4.9     4.7        0   054
 08-041-6016 1 3 COLORADO SPRING EL PASO CO      3730 MEADOWLAND BLVD.    95 026 8477  15.0    12.4       0   4.9     4.5        0   093
 08-041-6016 1 3 COLORADO SPRING EL PASO CO      3730 MEADOWLAND BLVD.    96 026 8682  11.0    11.0       0   4.6     4.0        0   093
 08-059-0002 1 2 ARVADA          JEFFERSON CO    W 57TH AVENUE AND GARRIS 93 001 8723  11.2    10.4       0   5.1     4.9        0   054
 08-059-0002 1 2 ARVADA          JEFFERSON CO    W 57TH AVENUE AND GARRIS 94 001 8525  10.8    10.0       0   5.2     5.0        0   054
 08-059-0002 1 2 ARVADA          JEFFERSON CO    W 57TH AVENUE AND GARRIS 95 001 8680  11.9     8.9       0   5.1     4.6        0   054
 08-059-0002 1 2 ARVADA          JEFFERSON CO    W 57TH AVENUE AND GARRIS 96 001 8724   7.9     7.2       0   4.3     4.3        0   054
 08-059-0002 1 2 ARVADA          JEFFERSON CO    W 57TH AVENUE AND GARRIS 97 001 8697   9.2     7.7       0   5.1     4.9        0   054
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08-069-1004 1 2 FORT COLLINS    LARIMER CO      708 S. MASON  FT COLLINS 93 001 8698  17.3   13.8      0   7.4    6.6      0  054
08-069-1004 1 2 FORT COLLINS    LARIMER CO      708 S. MASON  FT COLLINS 94 001 8703  13.6   12.1      0   7.3    6.0      0  054
08-069-1004 1 2 FORT COLLINS    LARIMER CO      708 S. MASON  FT COLLINS 95 001 8699  10.6    9.8      0   5.6    5.2      0  054
08-069-1004 1 2 FORT COLLINS    LARIMER CO      708 S. MASON  FT COLLINS 96 001 8597  12.7   10.9      0   5.5    5.1      0  054
08-069-1004 1 2 FORT COLLINS    LARIMER CO      708 S. MASON  FT COLLINS 97 001 8708  10.3    9.2      0   5.3    5.2      0  054
08-077-0014 1 2 GRAND JUNCTION  MESA CO         STOCKER STADIUM (12TH &  93 001 8383  12.0   11.2      0   6.9    6.1      0  054
08-077-0014 1 2 GRAND JUNCTION  MESA CO         STOCKER STADIUM (12TH &  94 001 8367  11.6   11.6      0   7.5    6.0      0  054
08-077-0014 1 2 GRAND JUNCTION  MESA CO         STOCKER STADIUM (12TH &  95 001 8209  10.0    8.7      0   5.4    5.4      0  054
08-077-0014 1 2 GRAND JUNCTION  MESA CO         STOCKER STADIUM (12TH &  96 001 8754  10.5   10.5      0   7.5    5.8      0  054
08-077-0014 1 2 GRAND JUNCTION  MESA CO         STOCKER STADIUM (12TH &  97 001 8550   8.5    7.8      0   6.4    5.4      0  054
08-123-0007 1 2 GREELEY         WELD CO         811 15TH ST - GREELEY    93 001 8688  10.9   10.2      0   6.1    5.8      0  054
08-123-0007 1 2 GREELEY         WELD CO         811 15TH ST - GREELEY    94 001 8707  11.3   11.1      0   6.4    5.2      0  054
08-123-0007 1 2 GREELEY         WELD CO         811 15TH ST - GREELEY    95 001 8703  10.3    9.6      0   5.7    5.3      0  054
08-123-0007 1 2 GREELEY         WELD CO         811 15TH ST - GREELEY    96 001 8739  12.3   10.7      0   7.5    7.0      0  054
08-123-0007 1 2 GREELEY         WELD CO         811 15TH ST - GREELEY    97 001 8717   9.6    8.6      0   5.3    4.8      0  054
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1DATE 98/06/25                            EPA AEROMETRIC INFORMATION RETRIEVAL SYSTEM (AIRS)                             PAGE
 AMP450                                                   AIR QUALITY SUBSYSTEM
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0                                 CARBON MONOXIDE (42101)
-METHODS:            CODE          COLLECTION METHOD                      ANALYSIS METHOD
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0                     000     MULTIPLE METHODS                   MULTIPLE METHODS
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1DATE 98/06/25                            EPA AEROMETRIC INFORMATION RETRIEVAL SYSTEM (AIRS)                             PAGE
 AMP217P                                                 AIR QUALITY SUBSYSTEM
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 QUICK LOOK REPORT








 AQ CLEANUP PROCESSING SUMMARY SHEET
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Appendix C

Distributions and Equations Used in the Ventilation Rate Algorithm

Each table in Appendix C is specific to parameter and gender (e.g., NVO_{2max} values for males). The tables which list distributions include the following data items

Age: age of person in years
Source: source of data (see Table 5-4)
Distr: distribution of data [normal, lognormal (LN), or uniform]
Mean: arithmetic mean for normal distributions SD: arithmetic standard deviation
GM: geometric mean of lognormal distribution
GSD: geometric standard deviation of lognormal distribution
Lower bound: smallest value permitted
Upper bound: largest value permitted
Assumptions: special assumptions used in developing distribution parameters

The tables which provide equations for estimating RMR include the following data items

Age: age of person in years
Source: source of data (see Table 5-9)
DV: dependent variable of regression equation
IV: independent variable of regression equation
Slope: slope of regression equation (estimate of “a” in Equation 5-10)
Interc: intercept of regression equation (estimate of “b” in Equation 5-10)
SE: standard error of regression residuals (estimate of σ_e in Equation 5-10)
Assumptions: special assumptions used in developing equation parameters

The codes listed under “source” are informal identification codes developed by analysts. The following table relates these codes to tables provided in Section 5.

Table C-1. Explanation of Codes Listed Under “Source” in Appendix C Tables.

Code Listed in “Source” Column of Table in Appendix C	Referenced Table in This Report	Original Reference
3a	Table 5-6	Astrand (1960)
3b	Table 5-6	Mercier et al. (1991)
3c	Table 5-6	Katch and Park (1975)
4	Table 5-5	Brainard and Burmaster (1992), Burmaster et al. (1994).
5	Table 5-7	Esmail, Bhambhani, and Brintnell (1995).
R47a - R47l	Table 5-8	Schofield (1985)

NVO2max - Males

Males (last revised 6-11-98)

		NVO2max distribution					
Age	Source	Distr	Mean	SD	Lower	Upper	Assumptions
0	1	Normal	44.0	5.2	33.7	54.3	2-yr-old mean, CV = 6.9/57.9
1	1	Normal	44.0	5.2	33.7	54.3	2-yr-old mean, CV = 6.9/57.9
2	1	Normal	44.0	5.2	33.7	54.3	CV = 6.9/57.9
3	1	Normal	46.0	5.5	35.3	56.7	CV = 6.9/57.9
4	1	Normal	48.0	5.7	36.8	59.2	CV = 6.9/57.9
5	1	Normal	50.0	6.0	38.3	61.7	CV = 6.9/57.9
6	1	Normal	52.0	6.2	39.9	64.1	CV = 6.9/57.9
7	1	Normal	54.0	6.4	41.4	66.6	CV = 6.9/57.9
8	1	Normal	56.0	6.7	42.9	69.1	CV = 6.9/57.9
9	3g	Normal	57.9	6.9	44.4	71.4	
10	3g	Normal	57.9	6.9	44.4	71.4	
11	3b	Normal	45.4	8.1	29.6	61.2	
12	3b	Normal	47.4	8.1	31.5	63.3	
13	3b	Normal	46.0	7.0	32.3	59.7	
14	3b	Normal	45.7	4.3	37.4	54.0	
15	3b	Normal	47.5	4.7	38.3	56.7	
16	1	Normal	55.0	5.4	44.4	65.6	CV = 4.69/47.5
17	1	Normal	53.0	5.2	42.7	63.3	
18	1	Normal	50.0	4.9	40.3	59.7	
19	1	Normal	50.0	4.9	40.3	59.7	
20	3a	Normal	58.6	4.5	49.8	67.4	
21	3c	Normal	54.5	7.6	39.6	69.4	
22	3c	Normal	54.5	7.6	39.6	69.4	
23	3c	Normal	54.5	7.6	39.6	69.4	
24	3c	Normal	54.5	7.6	39.6	69.4	
25	3c	Normal	54.5	7.6	39.6	69.4	
26	3c	Normal	54.5	7.6	39.6	69.4	
27	3c	Normal	54.5	7.6	39.6	69.4	
28	3a	Normal	58.6	4.5	49.8	67.4	
29	3a	Normal	58.6	4.5	49.8	67.4	
30	3a	Normal	39.8	7.3	25.5	54.1	
31	3a	Normal	39.8	7.3	25.5	54.1	
32	3a	Normal	39.8	7.3	25.5	54.1	
33	3a	Normal	39.8	7.3	25.5	54.1	
34	3a	Normal	39.8	7.3	25.5	54.1	
35	3a	Normal	39.8	7.3	25.5	54.1	
36	3a	Normal	39.8	7.3	25.5	54.1	
37	3a	Normal	39.8	7.3	25.5	54.1	
38	3a	Normal	39.8	7.3	25.5	54.1	
39	3a	Normal	39.8	7.3	25.5	54.1	
40	3a	Normal	39.2	5.5	28.4	50.0	
41	3a	Normal	39.2	5.5	28.4	50.0	

42	3a	Normal	39.2	5.5	28.4	50.0	
43	3a	Normal	39.2	5.5	28.4	50.0	
44	3a	Normal	39.2	5.5	28.4	50.0	
45	3a	Normal	39.2	5.5	28.4	50.0	
46	3a	Normal	39.2	5.5	28.4	50.0	
47	3a	Normal	39.2	5.5	28.4	50.0	
48	3a	Normal	39.2	5.5	28.4	50.0	
49	3a	Normal	39.2	5.5	28.4	50.0	
50	3a	Normal	33.1	4.9	23.5	42.7	
51	3a	Normal	33.1	4.9	23.5	42.7	
52	3a	Normal	33.1	4.9	23.5	42.7	
53	3a	Normal	33.1	4.9	23.5	42.7	
54	3a	Normal	33.1	4.9	23.5	42.7	
55	3a	Normal	33.1	4.9	23.5	42.7	
56	3a	Normal	33.1	4.9	23.5	42.7	
57	3a	Normal	33.1	4.9	23.5	42.7	
58	3a	Normal	33.1	4.9	23.5	42.7	
59	3a	Normal	33.1	4.9	23.5	42.7	
60	3a	Normal	31.4	5.3	21.0	41.8	
61	3a	Normal	31.4	5.3	21.0	41.8	
62	3a	Normal	31.4	5.3	21.0	41.8	
63	3a	Normal	31.4	5.3	21.0	41.8	
64	3a	Normal	31.4	5.3	21.0	41.8	
65	3a	Normal	31.4	5.3	21.0	41.8	
66	3a	Normal	31.4	5.3	21.0	41.8	
67	3a	Normal	31.4	5.3	21.0	41.8	
68	3a	Normal	31.4	5.3	21.0	41.8	
69	3a	Normal	31.4	5.3	21.0	41.8	
70	3d	Normal	27.2	5.7	16.1	38.3	
71	3d	Normal	27.2	5.7	16.1	38.3	
72	3d	Normal	27.2	5.7	16.1	38.3	
73	3d	Normal	27.2	5.7	16.1	38.3	
74	3d	Normal	27.2	5.7	16.1	38.3	
75	3d	Normal	27.2	5.7	16.1	38.3	
76	3d	Normal	27.2	5.7	16.1	38.3	
77	3d	Normal	27.2	5.7	16.1	38.3	
78	3d	Normal	27.2	5.7	16.1	38.3	
79	3d	Normal	27.2	5.7	16.1	38.3	
80	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
81	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
82	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
83	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
84	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
85	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
86	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
87	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
88	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
89	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
90	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
91	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
92	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies

93	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
94	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
95	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
96	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
97	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
98	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
99	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
100	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies

Females (last revised 6-11-98)

		NVO2max distribution					
Age	Source	Distr	Mean	SD	Lower	Upper	Assumptions
0	2	Normal	43.0	5.1	33.1	52.9	2-yr-old mean, CV = 4.7/39.9
1	2	Normal	43.0	5.1	33.1	52.9	2-yr-old mean, CV = 4.7/39.9
2	2	Normal	43.0	5.1	33.1	52.9	CV = 4.7/39.9
3	2	Normal	44.0	5.2	33.8	54.2	CV = 4.7/39.9
4	2	Normal	46.0	5.4	35.4	56.6	CV = 4.7/39.9
5	2	Normal	47.0	5.5	36.1	57.9	CV = 4.7/39.9
6	2	Normal	50.0	5.9	38.5	61.5	CV = 4.7/39.9
7	2	Normal	52.0	6.1	40.0	64.0	CV = 4.7/39.9
8	2	Normal	53.0	6.2	40.8	65.2	CV = 4.7/39.9
9	2	Normal	52.0	6.1	40.0	64.0	CV = 4.7/39.9
10	2	Normal	51.0	6.0	39.2	62.8	CV = 4.7/39.9
11	2	Normal	50.0	5.9	38.5	61.5	CV = 4.7/39.9
12	2	Normal	49.0	5.8	37.7	60.3	CV = 4.7/39.9
13	2	Normal	47.0	5.5	36.1	57.9	CV = 4.7/39.9
14	2	Normal	46.0	5.4	35.4	56.6	CV = 4.7/39.9
15	2	Normal	46.0	5.4	35.4	56.6	CV = 4.7/39.9
16	2	Normal	45.0	5.3	34.6	55.4	CV = 4.7/39.9
17	2	Normal	44.0	5.2	33.8	54.2	CV = 4.7/39.9
18	2	Normal	41.0	4.8	31.5	50.5	CV = 4.7/39.9
19	2	Normal	41.0	4.8	31.5	50.5	CV = 4.7/39.9
20	3a	Normal	39.9	4.7	30.7	49.1	
21	3a	Normal	39.9	4.7	30.7	49.1	
22	3a	Normal	39.9	4.7	30.7	49.1	
23	3a	Normal	39.9	4.7	30.7	49.1	
24	3a	Normal	39.9	4.7	30.7	49.1	
25	3a	Normal	39.9	4.7	30.7	49.1	
26	3a	Normal	39.9	4.7	30.7	49.1	
27	3a	Normal	39.9	4.7	30.7	49.1	
28	3a	Normal	39.9	4.7	30.7	49.1	
29	3a	Normal	39.9	4.7	30.7	49.1	
30	3a	Normal	37.3	5.2	27.1	47.5	
31	3a	Normal	37.3	5.2	27.1	47.5	
32	3a	Normal	37.3	5.2	27.1	47.5	
33	3a	Normal	37.3	5.2	27.1	47.5	
34	3a	Normal	37.3	5.2	27.1	47.5	
35	3a	Normal	37.3	5.2	27.1	47.5	
36	3a	Normal	37.3	5.2	27.1	47.5	
37	3a	Normal	37.3	5.2	27.1	47.5	
38	3a	Normal	37.3	5.2	27.1	47.5	
39	3a	Normal	37.3	5.2	27.1	47.5	
40	3a	Normal	32.5	2.7	27.2	37.8	
41	3a	Normal	32.5	2.7	27.2	37.8	
42	3a	Normal	32.5	2.7	27.2	37.8	
43	3a	Normal	32.5	2.7	27.2	37.8	
44	3a	Normal	32.5	2.7	27.2	37.8	
45	3a	Normal	32.5	2.7	27.2	37.8	

46	3a	Normal	32.5	2.7	27.2	37.8	
47	3a	Normal	32.5	2.7	27.2	37.8	
48	3a	Normal	32.5	2.7	27.2	37.8	
49	3a	Normal	32.5	2.7	27.2	37.8	
50	3a	Normal	28.4	2.7	23.1	33.7	
51	3a	Normal	28.4	2.7	23.1	33.7	
52	3a	Normal	28.4	2.7	23.1	33.7	
53	3a	Normal	28.4	2.7	23.1	33.7	
54	3a	Normal	28.4	2.7	23.1	33.7	
55	3a	Normal	28.4	2.7	23.1	33.7	
56	3a	Normal	28.4	2.7	23.1	33.7	
57	3a	Normal	28.4	2.7	23.1	33.7	
58	3a	Normal	28.4	2.7	23.1	33.7	
59	3a	Normal	28.4	2.7	23.1	33.7	
60	3a	Normal	30.7	8.0	15.1	46.3	
61	3a	Normal	30.7	8.0	15.1	46.3	
62	3a	Normal	30.7	8.0	15.1	46.3	
63	3a	Normal	30.7	8.0	15.1	46.3	
64	3a	Normal	30.7	8.0	15.1	46.3	
65	3a	Normal	30.7	8.0	15.1	46.3	
66	3d	Normal	30.7	8.0	15.1	46.3	
67	3d	Normal	30.7	8.0	15.1	46.3	
68	3d	Normal	30.7	8.0	15.1	46.3	
69	3d	Normal	30.7	8.0	15.1	46.3	
70	3d	Normal	27.2	5.7	16.1	38.3	
71	3d	Normal	27.2	5.7	16.1	38.3	
72	3d	Normal	27.2	5.7	16.1	38.3	
73	3d	Normal	27.2	5.7	16.1	38.3	
74	3d	Normal	27.2	5.7	16.1	38.3	
75	3d	Normal	27.2	5.7	16.1	38.3	
76	3d	Normal	27.2	5.7	16.1	38.3	
77	3d	Normal	27.2	5.7	16.1	38.3	
78	3d	Normal	27.2	5.7	16.1	38.3	
79	3d	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
80	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
81	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
82	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
83	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
84	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
85	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
86	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
87	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
88	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
89	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
90	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
91	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
92	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
93	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
94	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
95	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
96	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
97	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies

98	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
99	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies
100	(3d)	Normal	27.2	5.7	16.1	38.3	Assumes data for age 70-79 applies

Body Mass - Males

Males (last revised 6-11-98)

Age	Source	Body mass distribution, kg					Assumptions
		Distr	GM	GSD	Lower	Upper	
0	4	LN	9.3	1.141	7.2	12.0	
1	4	LN	11.7	1.126	9.3	14.8	
2	4	LN	13.5	1.127	10.7	17.1	
3	4	LN	15.6	1.121	12.5	19.5	
4	4	LN	17.6	1.142	13.6	22.8	
5	4	LN	19.9	1.148	15.2	26.1	
6	4	LN	22.9	1.156	17.2	30.4	
7	4	LN	24.8	1.163	18.4	33.3	
8	4	LN	27.9	1.198	19.6	39.8	
9	4	LN	30.9	1.179	22.4	42.7	
10	4	LN	36.2	1.215	24.7	53.0	
11	4	LN	40.0	1.287	24.4	65.6	
12	4	LN	43.8	1.251	28.2	67.9	
13	4	LN	48.4	1.240	31.7	73.8	
14	4	LN	55.7	1.198	39.1	79.4	
15	4	LN	59.7	1.172	43.7	81.5	
16	4	LN	66.7	1.183	48.0	92.7	
17	4	LN	66.0	1.182	47.6	91.6	
18	4	LN	70.1	1.172	51.4	95.7	
19	4	LN	70.8	1.166	52.4	95.7	
20	4	LN	76.7	1.190	54.5	107.9	
21	4	LN	76.7	1.190	54.5	107.9	
22	4	LN	76.7	1.190	54.5	107.9	
23	4	LN	76.7	1.190	54.5	107.9	
24	4	LN	76.7	1.190	54.5	107.9	
25	4	LN	76.7	1.190	54.5	107.9	
26	4	LN	76.7	1.190	54.5	107.9	
27	4	LN	76.7	1.190	54.5	107.9	
28	4	LN	76.7	1.190	54.5	107.9	
29	4	LN	76.7	1.190	54.5	107.9	
30	4	LN	76.7	1.190	54.5	107.9	
31	4	LN	76.7	1.190	54.5	107.9	
32	4	LN	76.7	1.190	54.5	107.9	
33	4	LN	76.7	1.190	54.5	107.9	
34	4	LN	76.7	1.190	54.5	107.9	
35	4	LN	76.7	1.190	54.5	107.9	
36	4	LN	76.7	1.190	54.5	107.9	
37	4	LN	76.7	1.190	54.5	107.9	
38	4	LN	76.7	1.190	54.5	107.9	
39	4	LN	76.7	1.190	54.5	107.9	
40	4	LN	76.7	1.190	54.5	107.9	
41	4	LN	76.7	1.190	54.5	107.9	
42	4	LN	76.7	1.190	54.5	107.9	
43	4	LN	76.7	1.190	54.5	107.9	
44	4	LN	76.7	1.190	54.5	107.9	

45	4	LN	76.7	1.190	54.5	107.9	
46	4	LN	76.7	1.190	54.5	107.9	
47	4	LN	76.7	1.190	54.5	107.9	
48	4	LN	76.7	1.190	54.5	107.9	
49	4	LN	76.7	1.190	54.5	107.9	
50	4	LN	76.7	1.190	54.5	107.9	
51	4	LN	76.7	1.190	54.5	107.9	
52	4	LN	76.7	1.190	54.5	107.9	
53	4	LN	76.7	1.190	54.5	107.9	
54	4	LN	76.7	1.190	54.5	107.9	
55	4	LN	76.7	1.190	54.5	107.9	
56	4	LN	76.7	1.190	54.5	107.9	
57	4	LN	76.7	1.190	54.5	107.9	
58	4	LN	76.7	1.190	54.5	107.9	
59	4	LN	76.7	1.190	54.5	107.9	
60	4	LN	76.7	1.190	54.5	107.9	
61	4	LN	76.7	1.190	54.5	107.9	
62	4	LN	76.7	1.190	54.5	107.9	
63	4	LN	76.7	1.190	54.5	107.9	
64	4	LN	76.7	1.190	54.5	107.9	
65	4	LN	76.7	1.190	54.5	107.9	
66	4	LN	76.7	1.190	54.5	107.9	
67	4	LN	76.7	1.190	54.5	107.9	
68	4	LN	76.7	1.190	54.5	107.9	
69	4	LN	76.7	1.190	54.5	107.9	
70	4	LN	76.7	1.190	54.5	107.9	
71	4	LN	76.7	1.190	54.5	107.9	
72	4	LN	76.7	1.190	54.5	107.9	
73	4	LN	76.7	1.190	54.5	107.9	
74	4	LN	76.7	1.190	54.5	107.9	
75	4	LN	76.7	1.190	54.5	107.9	
76	4	LN	76.7	1.190	54.5	107.9	
77	4	LN	76.7	1.190	54.5	107.9	
78	4	LN	76.7	1.190	54.5	107.9	
79	4	LN	76.7	1.190	54.5	107.9	
80	4	LN	76.7	1.190	54.5	107.9	
81	4	LN	76.7	1.190	54.5	107.9	
82	4	LN	76.7	1.190	54.5	107.9	
83	4	LN	76.7	1.190	54.5	107.9	
84	4	LN	76.7	1.190	54.5	107.9	
85	4	LN	76.7	1.190	54.5	107.9	
86	4	LN	76.7	1.190	54.5	107.9	
87	4	LN	76.7	1.190	54.5	107.9	
88	4	LN	76.7	1.190	54.5	107.9	
89	4	LN	76.7	1.190	54.5	107.9	
90	4	LN	76.7	1.190	54.5	107.9	
91	4	LN	76.7	1.190	54.5	107.9	
92	4	LN	76.7	1.190	54.5	107.9	
93	4	LN	76.7	1.190	54.5	107.9	
94	4	LN	76.7	1.190	54.5	107.9	
95	4	LN	76.7	1.190	54.5	107.9	
96	4	LN	76.7	1.190	54.5	107.9	

97	4	LN	76.7	1.190	54.5	107.9	
98	4	LN	76.7	1.190	54.5	107.9	
99	4	LN	76.7	1.190	54.5	107.9	
100	4	LN	76.7	1.190	54.5	107.9	

Body Mass - Females

Females (last revised 6-11-98)

Age	Source	Body mass distribution, kg					
		Distr	GM	GSD	Lower	Upper	Assumptions
0	4	LN	8.7	1.156	6.5	11.6	
1	4	LN	10.8	1.137	8.4	13.9	
2	4	LN	12.9	1.119	10.3	16.1	
3	4	LN	14.7	1.147	11.2	19.2	
4	4	LN	16.9	1.142	13.0	21.9	
5	4	LN	19.7	1.177	14.3	27.1	
6	4	LN	22.2	1.190	15.8	31.2	
7	4	LN	24.3	1.190	17.3	34.2	
8	4	LN	27.4	1.169	20.2	37.2	
9	4	LN	31.8	1.239	20.9	48.4	
10	4	LN	35.5	1.220	24.0	52.4	
11	4	LN	40.9	1.254	26.2	63.7	
12	4	LN	45.6	1.237	30.1	69.2	
13	4	LN	50.4	1.241	33.0	77.0	
14	4	LN	54.1	1.206	37.5	78.1	
15	4	LN	54.6	1.169	40.2	74.1	
16	4	LN	58.0	1.182	41.8	80.5	
17	4	LN	59.1	1.179	42.8	81.6	
18	4	LN	58.6	1.158	44.0	78.1	
19	4	LN	60.3	1.161	45.0	80.8	
20	4	LN	64.7	1.220	43.8	95.5	
21	4	LN	64.7	1.220	43.8	95.5	
22	4	LN	64.7	1.220	43.8	95.5	
23	4	LN	64.7	1.220	43.8	95.5	
24	4	LN	64.7	1.220	43.8	95.5	
25	4	LN	64.7	1.220	43.8	95.5	
26	4	LN	64.7	1.220	43.8	95.5	
27	4	LN	64.7	1.220	43.8	95.5	
28	4	LN	64.7	1.220	43.8	95.5	
29	4	LN	64.7	1.220	43.8	95.5	
30	4	LN	64.7	1.220	43.8	95.5	
31	4	LN	64.7	1.220	43.8	95.5	
32	4	LN	64.7	1.220	43.8	95.5	
33	4	LN	64.7	1.220	43.8	95.5	
34	4	LN	64.7	1.220	43.8	95.5	
35	4	LN	64.7	1.220	43.8	95.5	

36	4	LN	64.7	1.220	43.8	95.5	
37	4	LN	64.7	1.220	43.8	95.5	
38	4	LN	64.7	1.220	43.8	95.5	
39	4	LN	64.7	1.220	43.8	95.5	
40	4	LN	64.7	1.220	43.8	95.5	
41	4	LN	64.7	1.220	43.8	95.5	
42	4	LN	64.7	1.220	43.8	95.5	
43	4	LN	64.7	1.220	43.8	95.5	
44	4	LN	64.7	1.220	43.8	95.5	
45	4	LN	64.7	1.220	43.8	95.5	
46	4	LN	64.7	1.220	43.8	95.5	
47	4	LN	64.7	1.220	43.8	95.5	
48	4	LN	64.7	1.220	43.8	95.5	
49	4	LN	64.7	1.220	43.8	95.5	
50	4	LN	64.7	1.220	43.8	95.5	
51	4	LN	64.7	1.220	43.8	95.5	
52	4	LN	64.7	1.220	43.8	95.5	
53	4	LN	64.7	1.220	43.8	95.5	
54	4	LN	64.7	1.220	43.8	95.5	
55	4	LN	64.7	1.220	43.8	95.5	
56	4	LN	64.7	1.220	43.8	95.5	
57	4	LN	64.7	1.220	43.8	95.5	
58	4	LN	64.7	1.220	43.8	95.5	
59	4	LN	64.7	1.220	43.8	95.5	
60	4	LN	64.7	1.220	43.8	95.5	
61	4	LN	64.7	1.220	43.8	95.5	
62	4	LN	64.7	1.220	43.8	95.5	
63	4	LN	64.7	1.220	43.8	95.5	
64	4	LN	64.7	1.220	43.8	95.5	
65	4	LN	64.7	1.220	43.8	95.5	
66	4	LN	64.7	1.220	43.8	95.5	
67	4	LN	64.7	1.220	43.8	95.5	
68	4	LN	64.7	1.220	43.8	95.5	
69	4	LN	64.7	1.220	43.8	95.5	
70	4	LN	64.7	1.220	43.8	95.5	
71	4	LN	64.7	1.220	43.8	95.5	
72	4	LN	64.7	1.220	43.8	95.5	
73	4	LN	64.7	1.220	43.8	95.5	
74	4	LN	64.7	1.220	43.8	95.5	
75	4	LN	64.7	1.220	43.8	95.5	
76	4	LN	64.7	1.220	43.8	95.5	
77	4	LN	64.7	1.220	43.8	95.5	
78	4	LN	64.7	1.220	43.8	95.5	
79	4	LN	64.7	1.220	43.8	95.5	

80	4	LN	64.7	1.220	43.8	95.5	
81	4	LN	64.7	1.220	43.8	95.5	
82	4	LN	64.7	1.220	43.8	95.5	
83	4	LN	64.7	1.220	43.8	95.5	
84	4	LN	64.7	1.220	43.8	95.5	
85	4	LN	64.7	1.220	43.8	95.5	
86	4	LN	64.7	1.220	43.8	95.5	
87	4	LN	64.7	1.220	43.8	95.5	
88	4	LN	64.7	1.220	43.8	95.5	
89	4	LN	64.7	1.220	43.8	95.5	
90	4	LN	64.7	1.220	43.8	95.5	
91	4	LN	64.7	1.220	43.8	95.5	
92	4	LN	64.7	1.220	43.8	95.5	
93	4	LN	64.7	1.220	43.8	95.5	
94	4	LN	64.7	1.220	43.8	95.5	
95	4	LN	64.7	1.220	43.8	95.5	
96	4	LN	64.7	1.220	43.8	95.5	
97	4	LN	64.7	1.220	43.8	95.5	
98	4	LN	64.7	1.220	43.8	95.5	
99	4	LN	64.7	1.220	43.8	95.5	
100	4	LN	64.7	1.220	43.8	95.5	

ECF - Males

Males (last revised 6-11-98)

Age	Source	ECF Distr	ECF Lower	ECF Upper	Assumptions
0	5	Uniform	0.20	0.21	
1	5	Uniform	0.20	0.21	
2	5	Uniform	0.20	0.21	
3	5	Uniform	0.20	0.21	
4	5	Uniform	0.20	0.21	
5	5	Uniform	0.20	0.21	
6	5	Uniform	0.20	0.21	
7	5	Uniform	0.20	0.21	
8	5	Uniform	0.20	0.21	
9	5	Uniform	0.20	0.21	
10	5	Uniform	0.20	0.21	
11	5	Uniform	0.20	0.21	
12	5	Uniform	0.20	0.21	
13	5	Uniform	0.20	0.21	
14	5	Uniform	0.20	0.21	
15	5	Uniform	0.20	0.21	
16	5	Uniform	0.20	0.21	
17	5	Uniform	0.20	0.21	
18	5	Uniform	0.20	0.21	
19	5	Uniform	0.20	0.21	
20	5	Uniform	0.20	0.21	
21	5	Uniform	0.20	0.21	
22	5	Uniform	0.20	0.21	
23	5	Uniform	0.20	0.21	
24	5	Uniform	0.20	0.21	
25	5	Uniform	0.20	0.21	
26	5	Uniform	0.20	0.21	
27	5	Uniform	0.20	0.21	
28	5	Uniform	0.20	0.21	
29	5	Uniform	0.20	0.21	
30	5	Uniform	0.20	0.21	
31	5	Uniform	0.20	0.21	
32	5	Uniform	0.20	0.21	
33	5	Uniform	0.20	0.21	
34	5	Uniform	0.20	0.21	
35	5	Uniform	0.20	0.21	
36	5	Uniform	0.20	0.21	
37	5	Uniform	0.20	0.21	
38	5	Uniform	0.20	0.21	

39	5	Uniform	0.20	0.21	
40	5	Uniform	0.20	0.21	
41	5	Uniform	0.20	0.21	
42	5	Uniform	0.20	0.21	
43	5	Uniform	0.20	0.21	
44	5	Uniform	0.20	0.21	
45	5	Uniform	0.20	0.21	
46	5	Uniform	0.20	0.21	
47	5	Uniform	0.20	0.21	
48	5	Uniform	0.20	0.21	
49	5	Uniform	0.20	0.21	
50	5	Uniform	0.20	0.21	
51	5	Uniform	0.20	0.21	
52	5	Uniform	0.20	0.21	
53	5	Uniform	0.20	0.21	
54	5	Uniform	0.20	0.21	
55	5	Uniform	0.20	0.21	
56	5	Uniform	0.20	0.21	
57	5	Uniform	0.20	0.21	
58	5	Uniform	0.20	0.21	
59	5	Uniform	0.20	0.21	
60	5	Uniform	0.20	0.21	
61	5	Uniform	0.20	0.21	
62	5	Uniform	0.20	0.21	
63	5	Uniform	0.20	0.21	
64	5	Uniform	0.20	0.21	
65	5	Uniform	0.20	0.21	
66	5	Uniform	0.20	0.21	
67	5	Uniform	0.20	0.21	
68	5	Uniform	0.20	0.21	
69	5	Uniform	0.20	0.21	
70	5	Uniform	0.20	0.21	
71	5	Uniform	0.20	0.21	
72	5	Uniform	0.20	0.21	
73	5	Uniform	0.20	0.21	
74	5	Uniform	0.20	0.21	
75	5	Uniform	0.20	0.21	
76	5	Uniform	0.20	0.21	
77	5	Uniform	0.20	0.21	
78	5	Uniform	0.20	0.21	
79	5	Uniform	0.20	0.21	
80	5	Uniform	0.20	0.21	
81	5	Uniform	0.20	0.21	
82	5	Uniform	0.20	0.21	

83	5	Uniform	0.20	0.21	
84	5	Uniform	0.20	0.21	
85	5	Uniform	0.20	0.21	
86	5	Uniform	0.20	0.21	
87	5	Uniform	0.20	0.21	
88	5	Uniform	0.20	0.21	
89	5	Uniform	0.20	0.21	
90	5	Uniform	0.20	0.21	
91	5	Uniform	0.20	0.21	
92	5	Uniform	0.20	0.21	
93	5	Uniform	0.20	0.21	
94	5	Uniform	0.20	0.21	
95	5	Uniform	0.20	0.21	
96	5	Uniform	0.20	0.21	
97	5	Uniform	0.20	0.21	
98	5	Uniform	0.20	0.21	
99	5	Uniform	0.20	0.21	
100	5	Uniform	0.20	0.21	

ECF - Females

Females (last revised 6-11-98)

Age	Source	ECF			Assumptions
		Distr	Lower	Upper	
0	5	Uniform	0.20	0.21	
1	5	Uniform	0.20	0.21	
2	5	Uniform	0.20	0.21	
3	5	Uniform	0.20	0.21	
4	5	Uniform	0.20	0.21	
5	5	Uniform	0.20	0.21	
6	5	Uniform	0.20	0.21	
7	5	Uniform	0.20	0.21	
8	5	Uniform	0.20	0.21	
9	5	Uniform	0.20	0.21	
10	5	Uniform	0.20	0.21	
11	5	Uniform	0.20	0.21	
12	5	Uniform	0.20	0.21	
13	5	Uniform	0.20	0.21	
14	5	Uniform	0.20	0.21	
15	5	Uniform	0.20	0.21	
16	5	Uniform	0.20	0.21	
17	5	Uniform	0.20	0.21	
18	5	Uniform	0.20	0.21	
19	5	Uniform	0.20	0.21	
20	5	Uniform	0.20	0.21	
21	5	Uniform	0.20	0.21	
22	5	Uniform	0.20	0.21	
23	5	Uniform	0.20	0.21	
24	5	Uniform	0.20	0.21	
25	5	Uniform	0.20	0.21	
26	5	Uniform	0.20	0.21	
27	5	Uniform	0.20	0.21	
28	5	Uniform	0.20	0.21	
29	5	Uniform	0.20	0.21	
30	5	Uniform	0.20	0.21	
31	5	Uniform	0.20	0.21	
32	5	Uniform	0.20	0.21	
33	5	Uniform	0.20	0.21	
34	5	Uniform	0.20	0.21	
35	5	Uniform	0.20	0.21	
36	5	Uniform	0.20	0.21	
37	5	Uniform	0.20	0.21	
38	5	Uniform	0.20	0.21	

39	5	Uniform	0.20	0.21	
40	5	Uniform	0.20	0.21	
41	5	Uniform	0.20	0.21	
42	5	Uniform	0.20	0.21	
43	5	Uniform	0.20	0.21	
44	5	Uniform	0.20	0.21	
45	5	Uniform	0.20	0.21	
46	5	Uniform	0.20	0.21	
47	5	Uniform	0.20	0.21	
48	5	Uniform	0.20	0.21	
49	5	Uniform	0.20	0.21	
50	5	Uniform	0.20	0.21	
51	5	Uniform	0.20	0.21	
52	5	Uniform	0.20	0.21	
53	5	Uniform	0.20	0.21	
54	5	Uniform	0.20	0.21	
55	5	Uniform	0.20	0.21	
56	5	Uniform	0.20	0.21	
57	5	Uniform	0.20	0.21	
58	5	Uniform	0.20	0.21	
59	5	Uniform	0.20	0.21	
60	5	Uniform	0.20	0.21	
61	5	Uniform	0.20	0.21	
62	5	Uniform	0.20	0.21	
63	5	Uniform	0.20	0.21	
64	5	Uniform	0.20	0.21	
65	5	Uniform	0.20	0.21	
66	5	Uniform	0.20	0.21	
67	5	Uniform	0.20	0.21	
68	5	Uniform	0.20	0.21	
69	5	Uniform	0.20	0.21	
70	5	Uniform	0.20	0.21	
71	5	Uniform	0.20	0.21	
72	5	Uniform	0.20	0.21	
73	5	Uniform	0.20	0.21	
74	5	Uniform	0.20	0.21	
75	5	Uniform	0.20	0.21	
76	5	Uniform	0.20	0.21	
77	5	Uniform	0.20	0.21	
78	5	Uniform	0.20	0.21	
79	5	Uniform	0.20	0.21	
80	5	Uniform	0.20	0.21	
81	5	Uniform	0.20	0.21	
82	5	Uniform	0.20	0.21	

83	5	Uniform	0.20	0.21	
84	5	Uniform	0.20	0.21	
85	5	Uniform	0.20	0.21	
86	5	Uniform	0.20	0.21	
87	5	Uniform	0.20	0.21	
88	5	Uniform	0.20	0.21	
89	5	Uniform	0.20	0.21	
90	5	Uniform	0.20	0.21	
91	5	Uniform	0.20	0.21	
92	5	Uniform	0.20	0.21	
93	5	Uniform	0.20	0.21	
94	5	Uniform	0.20	0.21	
95	5	Uniform	0.20	0.21	
96	5	Uniform	0.20	0.21	
97	5	Uniform	0.20	0.21	
98	5	Uniform	0.20	0.21	
99	5	Uniform	0.20	0.21	
100	5	Uniform	0.20	0.21	

RMR - Males

Males (last revised 6-11-98)

Age	Source	Regression equation						Estimate for median weight	Assumptions
		DV	IV	Slope	Interc	SE	Units		
0	R47g	BMR	BM	0.244	-0.127	0.290	MJ/day	2.1	equation for age = 1 yr applies
1	R47g	BMR	BM	0.244	-0.127	0.290	MJ/day	2.7	
2	R47g	BMR	BM	0.244	-0.127	0.280	MJ/day	3.2	
3	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	3.6	
4	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	3.8	
5	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	4.0	
6	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	4.3	
7	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	4.5	
8	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	4.8	
9	R47h	BMR	BM	0.095	2.110	0.280	MJ/day	5.0	
10	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	5.4	
11	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	5.7	
12	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	6.0	
13	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	6.3	
14	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	6.9	
15	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	7.2	
16	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	7.7	
17	R47i	BMR	BM	0.074	2.754	0.440	MJ/day	7.6	
18	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.3	
19	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.4	
20	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
21	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
22	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
23	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
24	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
25	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
26	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
27	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
28	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
29	R47j	BMR	BM	0.063	2.896	0.640	MJ/day	7.7	
30	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
31	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
32	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
33	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	

34	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
35	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
36	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
37	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
38	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
39	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
40	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
41	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
42	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
43	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
44	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
45	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
46	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
47	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
48	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
49	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
50	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
51	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
52	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
53	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
54	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
55	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
56	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
57	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
58	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
59	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
60	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
61	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
62	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
63	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
64	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
65	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
66	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
67	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
68	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
69	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
70	R47k	BMR	BM	0.048	3.653	0.700	MJ/day	7.3	
71	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
72	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
73	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
74	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
75	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
76	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
77	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	

78	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
79	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
80	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
81	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
82	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
83	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
84	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
85	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
86	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
87	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
88	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
89	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
90	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
91	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
92	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
93	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
94	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
95	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
96	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
97	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
98	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
99	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	
100	R47l	BMR	BM	0.049	2.459	0.690	MJ/day	6.2	

RMR - Females

Females	(last revised 6-11-98)								
		Regression equation						Estimate for median weight	
Age	Source	DV	IV	Slope	Interc	SE	Units		Assumptions
0	R47a	BMR	BM	0.244	-0.130	0.250	MJ/day	2.0	
1	R47a	BMR	BM	0.244	-0.130	0.250	MJ/day	2.5	
2	R47a	BMR	BM	0.244	-0.130	0.250	MJ/day	3.0	
3	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	3.3	
4	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	3.5	
5	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	3.7	
6	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	3.9	
7	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	4.1	
8	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	4.4	
9	R47b	BMR	BM	0.085	2.033	0.290	MJ/day	4.7	
10	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	4.9	
11	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	5.2	
12	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	5.5	
13	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	5.7	
14	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	5.9	
15	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	6.0	
16	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	6.1	
17	R47c	BMR	BM	0.056	2.898	0.470	MJ/day	6.2	
18	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	5.7	
19	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	5.8	
20	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
21	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
22	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
23	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
24	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
25	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
26	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
27	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
28	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
29	R47d	BMR	BM	0.062	2.036	0.500	MJ/day	6.0	
30	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
31	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
32	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
33	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
34	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
35	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	

36	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
37	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
38	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
39	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
40	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
41	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
42	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
43	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
44	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
45	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
46	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
47	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
48	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
49	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
50	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
51	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
52	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
53	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
54	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
55	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
56	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
57	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
58	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
59	R47e	BMR	BM	0.034	3.538	0.470	MJ/day	5.7	
60	R47e	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
61	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
62	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
63	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
64	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
65	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
66	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
67	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
68	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
69	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
70	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
71	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
72	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
73	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
74	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
75	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
76	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
77	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
78	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
79	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	

80	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
81	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
82	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
83	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
84	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
85	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
86	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
87	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
88	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
89	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
90	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
91	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
92	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
93	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
94	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
95	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
96	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
97	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
98	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
99	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	
100	R47f	BMR	BM	0.038	2.755	0.450	MJ/day	5.2	

Appendix D

Analysis of Clinical Data Provided by Dr. William Adams

Two alternative models were considered for the relationship between ventilation rate (VE, liters air per minute) and oxygen uptake rate (VO_2, liters oxygen per minute). The "RAW" model assumes that the ventilation rate to body mass ratio is a linear function of the oxygen uptake rate to body mass ratio. The "LOG" model assumes that the logarithm of the ventilation rate to body mass ratio is a linear function of the logarithm of the oxygen uptake rate to body mass ratio. Let BM be the body mass. The model equations are

RAW MODEL: $VE/BM = a + b\ VO_2/BM + \text{error(person)} + \text{error(test)}$

LOG MODEL: $\log(VE/BM) = a + b \log(VO_2/BM) + \text{error(person)} + \text{error(test)}$

In this statistical mixed model, there are assumed to be two independent sources of error, representing the variability between persons and the variability between different activities by the same person. Each person has a value of error(person) independently drawn from a normal distribution with mean zero and variance σ^2(person); the same error(person) value applies to every activity for that person. Each combination of person and activity has a value of error(test) independently drawn from a normal distribution with mean zero and variance σ^2(test); each new activity has a different error(test) value. A major advantage of this formulation is that it accounts for the correlations between different measurements on the same person. The intercept (a), slope (b), and error variances (σ^2(person) and σ^2(test)) depend on the gender and age group (18-44, 45-64, or 65+). All logarithms are natural logarithms (base e).

These two models were fitted to data supplied by Dr. Adams compiling the results of 32 clinical studies, where VE and VO_2 were measured during the last minute of each step of a test sequence on either a cycle ergometer or a treadmill (up to 14 steps per study subject). If the same person was tested in two or more studies, then the value of error(person) randomly assigned to that person was assumed to be the same for all studies. Before fitting the more complicated, but more realistic, mixed model formulations, we first used simple linear regression to fit the special case where the error(person) terms are ignored, so that all test results are assumed to be independent, even if they are measured on the same person. The two regression models were compared using standard goodness-of-fit measures and regression diagnostics, as summarized below. The regression model comparison showed the LOG model fitted better, as expected from Tom McCurdy's preliminary analysis, and so the mixed model version of the LOG model was used in the pNEM/CO simulation model. Rewriting the LOG model as a function of VE, we get

$$VE = e^{a}\,(VO_2)^{b}\,(BM)^{1-b}\,e^{\text{error(person)}}\,e^{\text{error(test)}}.$$

For each simulated person-day in PNEM/CO, the value of error(person) is randomly drawn from a normal distribution with mean zero and variance σ^2(person); the values of error(person) and BM are assumed to be the same throughout the simulated day. For each activity, the value of error(test) is randomly drawn from a normal distribution with mean zero and variance σ^2(test). For each activity, VE is computed from the simulated value of VO_2 using the above equation. The values of a, b, σ^2(person), and σ^2(test), estimated from the LOG model, are given in Table 1.

The two regression models are defined by the above models RAW and LOG, with error(person) = 0. These regression models were compared using standard goodness-of-fit measures and regression diagnostics, summarized as follows. Conditioning on the observed values of BM,

VO_2, age group, and gender, the overall log-likelihood is defined as the logarithm of the fitted probability density function for VE (assumed to be normal for the RAW model and log-normal for the LOG model). The overall log-likelihood was 9536.36 for the RAW model and 10927.67 for the LOG model, showing a much better fit for the LOG model. The log-likelihoods by age group and gender showed that the LOG model fit better for five of the six age group and gender combinations; the RAW model fit just slightly better for the females aged 65 and older. Scatter plots of the standardized deletion residuals against the VO_2/BM ratio showed some patterns incompatible with the assumed statistical models (the residuals and explanatory variables should show no obvious associations) and there were some very high residuals for both models. However, these scatter plots showed a much better fit for the LOG model formulation. Furthermore, although the standardized residuals should be approximately normally distributed, a normality test was failed for five of the six strata using the RAW model, but was passed for five of the six strata using the LOG model. For five of the six strata, refitting the two models after removing points with extremely high residuals and/or points expected to strongly influence the fitted model coefficients did not significantly improve the fit or change the estimated coefficients. For the females aged 65 and older stratum, there were only 45 pairs, and one pair had unusually high values of both VE (39.97 l/min) and VO_2 (1.41 l/min). Although removal of this unusual pair changed the fitted parameters by about 10 percent (e.g., for the LOG model the intercept in this stratum was 2.69 before removal and 2.38 after removal), these changes were within the standard errors of the fitted parameters. Therefore it was decided to use the statistical model fitted to all the points for the pNEM/CO model.

Since the regression model is a special case of the mixed model (with σ^2(person) = 0), the mixed models will have higher values of the log-likelihood. Based on the detailed regression diagnostics for the regression case, the final statistical model was the mixed model version of the LOG model, which was fitted by the maximum likelihood method.

Table 1. Mixed model parameters for LOG model: $\log(VE/BM) = a + b \log(VO_2/BM) + \text{error(person)} + \text{error(test)}$.

Age Group	**Gender**	**Intercept (a)**	**Slope (b)**	**Variance Between Persons (σ^2(person))**	**Variance Between Activities (σ^2(test))**
18 - 44	Female	4.3568	1.2756	0.01825	0.01397
	Male	3.9908	1.1969	0.01509	0.01945
45 - 64	Female	3.4543	1.0208	0.01224	0.00591
	Male	4.0183	1.1646	0.01225	0.01237
65 -	Female	2.9562	0.9077	0.00785	0.00114
	Male	3.7304	1.0709	0.01170	0.00399

Appendix E

Algorithm for Estimating Carboxyhemoglobin Levels

COHB MODULE FOR pNEM/CO

H. M. Richmond and T. R. Johnson

February 1999

This appendix describes the probabilistic COHb module and discusses its basis. The approach described here is based primarily on the COHb module described by Biller and Richmond in an Appendix to the 1992 version of pNEM/CO (Johnson et al., 1992).

I. THE BASE PHYSIOLOGICAL MODEL FOR COMPUTING COHb LEVELS

The COHB module in the original CO-NEM (Johnson and Paul, 1983) used as its basic model the differential equation derived by Coburn, Forster, and Kane (1965) which described the dynamic relationship between instantaneous blood levels of COHb, inspired CO, and other physiological variables. This model, which will be referred to here as the CFK model, continues to be the most widely-used method for estimating COHb and is the basic model for COHb computations in pNEM/CO. The CFK model is described in Section II.

The CFK model describes the rate of change of COHb blood levels as a function of the following quantities:

1. Inspired CO pressure
2. COHb level
3. Oxyhemoglobin (O_2Hb) level
4. Hemoglobin (Hb) content of blood
5. Blood volume
6. Alveolar ventilation rate
7. Endogenous CO production rate
8. Mean pulmonary capillary oxygen pressure
9. Pulmonary diffusion rate of CO
10. Haldane coefficient (M)
11. Barometric pressure
12. Vapor pressure of water at body temperature (47 torr)

If all of the listed quantities except COHb level are constant over some time interval, the CFK equation has a linear form over the interval and is readily integrated. The solution to the linear form gives reasonably accurate results for lower levels of COHb. However, CO and oxygen compete for the available hemoglobin and are, therefore, not independent of each other. If this dependency is taken into account, the resulting differential equation is no longer linear. Peterson and Stewart (1975) proposed a heuristic approach to account for with this dependency which assumed the linear form and then adjusted the O_2Hb level iteratively based on the assumption of a linear relationship between COHB and O_2Hb. This approach was used in the COHb module of the original CO-NEM. Alternatively, it is possible to determine COHb at any time by numerical integration of the nonlinear CFK equation (e.g. by use of the Runge-Kutta method) if one assumes a particular relationship between COHb and O_2Hb. Muller and Barton (1987) demonstrated that assuming a linear relationship between COHb and O_2Hb leads to a form of the CFK equation equivalent to the Michaelis-Menton kinetic model which is analytically integrable. However, the analytical solution in this case cannot be solved explicitly for COHb. Muller and Barton demonstrated a binary search method for determining the COHb value.

The COHb module for pNEM/CO employs a linear relationship between COHb and O_2Hb which is consistent with the basic assumptions of the CFK model but differs from the linear forms used by other modelers. The Muller and Barton (1987) solution is employed. However, instead of the simple binary search described in the Muller and Barton paper, a combination of the binary search and Newton-Raphson root finding methods was used to solve for COHb (Press et al., 1986). Using the Muller and Barton solution increased computation time compared to the Peterson-Stewart method but was shown to be faster than fourth order Runge-Kutta numerical integration.

II. The CFK Model For Estimation Of Carboxyhemoglobin

Table 1 defines the variables which appear in the equations of this section. Coburn, Forster, and Kane (1965) derived the following differential equation governing COHb levels in the blood upon exposure to CO.

(Eq. 1)
$$\frac{d[COHb]}{dt} = \frac{\dot{\mathrm{V}}_{\mathrm{CO}}}{\mathrm{V}_{\mathrm{b}}} + \frac{P_{I_{CO}}}{BV_b} - \frac{\overline{P}_{CO_2}[COHb]}{MBV_b[O_2Hb]}$$

where

(Eq. 2)
$$B = \frac{1}{D_{L_{CO}}} + \frac{\left(P_B - P_{H_2O}\right)}{\dot{V}_A}$$

If the only quantity in this equation that can vary with time is [COHb], the CFK equation is linear and can be readily integrated. However, since oxygen (O_2) and CO compete for the available HB, [COHb] and [O_2Hb] must be related. Increasing [COHb] will result in decreasing [O_2Hb]. Thus the CFK equation is not linear and requires the relationship between the two quantities to be known if it is to be accurately integrated over a wide range of COHb levels.

Various linear relationships between [COHb] and [O_2Hb] have been used (See Marcus, 1980; McCartney, 1990; Muller and Barton, 1987; and Tikuisis et al., 1987). A relationship not previously used follows directly from the basic assumptions of the CFK model. The CFK model employs the Haldane coefficient, which is the equilibrium constant associated with the following reaction representing the replacement of O_2 in O_2Hb by CO:

(Eq. 3)
$$CO + O_2Hb = O_2 + COHb$$

Table 1. Definitions Of CFK Model Variables

Variable	Definition
t	Time from start of an exposure event, min
[COHb]	Concentration of carboxyhemoglobin (COHb) in blood at time, t, ml CO per ml blood at STPD
$[O_2Hb]$	Concentration of oxyhemoglobin (O_2Hb) in blood at time t, ml O_2 per ml blood at STPD
[RHb]	Concentration of reduced hemoglobin in blood as equivalent ml CO per ml of blood at STPD
$[COHb]_o$	[COHb] at t = 0
$[THb]_0$	[RHb] + [COHb] + $[O_2Hb]$
%[COHb]	[COHb] expressed as percent of $[RHb]_0$
$\%[O_2Hb]$	$[O_2Hb]$ expressed as percent of $[RHb]_0$
$\%[COHb]_0$	%[COHb] at t = 0
$\%[COHB]_\infty$	%[COHb] at t = ∞
P_{Ico}	Pressure of inspired CO in air saturated with water vapor at body temperature, torr
$\overline{P}C_{CO}$	Mean pulmonary capillary CO pressure, torr
$\overline{P}C_{O_2}$	Mean pulmonary capillary O2 pressure, torr
P_B	Barometric pressure, torr
P_{H_2O}	Vapor pressure of water at body temperature, torr (47 torr)
$\dot{V}_A$	Alveolar ventilation rate, ml/min STPD
$\dot{V}_{CO}$	Endogenous CO production rate, ml/min STPD

Table 1. Definitions Of CFK Model Variables (Continued)

Variable	Definition
$D_{L_{CO}}$	Pulmonary CO diffusion rate, ml/min/torr STPD
M	Haldane coefficient
k	Equilibrium constant for reaction O_2 + RHb = O_2Hb
V_b	Blood volume, ml
Hb	Total hemoglobin in blood, g/100ml
%MetHb	Methemoglobin as weight percent of Hb

The following equation, the Haldane relationship, applies approximately at equilibrium conditions.

(Eq. 4)
$$\frac{\bar{P}_{CO_2}[COHb]}{\bar{P}_{CO}[O_2Hb]} = M$$

The Haldane coefficient, M, is the chemical equilibrium constant for reaction (3)

The above reaction can also be viewed as the difference between two competing chemical reactions:

(Eq. 5) $CO + RHb = COHb$

(Eq. 6) $O_2 + RHb = O_2Hb$

Subtracting (6) from (5) yields (3). If (3) is in equilibrium, then (5) and (6) are in equilibrium. If k is the equilibrium constant for (6) then:

(Eq. 7)
$$\frac{[O_2Hb]}{\bar{P}_{CO_2}[RHb]} = k$$

It is known that an individual breathing air free of CO for an extended period will have about 97% of the reactive hemoglobin tied up as O_2Hb and the rest (3%) as RHb. It is also known that at one atmosphere barometric pressure the mean pulmonary capillary oxygen pressure is approximately 100 torr. Substituting into (7) yields 0.32 as the approximate value of k at body temperature. From mass balance considerations:

(Eq. 8) $[O_2Hb] + [COHb] + [RHb] = [THb]_o$

Eliminating [RHb] between (7) and (8) and solving for $[O_2Hb]$ yields:

(Eq. 9)
$$[O_2Hb] = \frac{k\bar{P}_{CO_2}}{1 + k\bar{P}_{CO_2}}\left([THb]_0 - [COHb]\right)$$

This equation is the desired linear relationship. It has the same form as a relationship given without explanation by McCartney (1990), but replaces the constant in the McCartney equation by the term in (9) involving the mean pulmonary capillary oxygen pressure and the equilibrium constant k. Substituting (9) into (1) yields a CFK equation free of $[O_2Hb]$ and <u>fully consistent</u> with Coburn, Forster, and Kane's original derivation.

(Eq. 10)
$$\frac{d[COHb]}{dt} = \frac{\dot{V}_{CO}}{\dot{V}_b} + \frac{P_{I_{CO}}}{BV_b} - \frac{[COHb]}{[THb]_o - [COHb]}\,\frac{1 + k\bar{P}_{C_{O_2}}}{kMBV_b}$$

In working with the CFK model it is convenient to express COHb as a percent of $[RHb]_0$. Multiplying (10) by 100 and dividing by $[RHb]_0$:

(Eq.11)
$$\frac{d\%[COHb]}{dt} = \frac{100}{[THb]_o}\left(\frac{\dot{V}_{CO}}{V_b} + \frac{P_{I_{CO}}}{BV_b}\right) - \frac{\%[COHb]}{100 - \%[COHb]}\,\frac{100\left(1 + k\bar{P}_{C_{O_2}}\right)}{k[RHb]_o\, MBV_b}$$

Equation (11) can be written in the form suggested by Muller and Barton (1987):

(Eq.12)
$$\frac{d\%[COHb]}{dt} = C_o - C_1\frac{\%[COHb]}{100 - \%[COHb]}$$

where

(Eq.13)
$$C_o = \frac{100}{[THb]_o}\left(\frac{\dot{V}_{CO}}{V_b} + \frac{P_{I_{CO}}}{BV_b}\right)$$

(Eq.14)
$$C_1 = \frac{100\left(1 + k\bar{P}_{c_{O_2}}\right)}{k[THb]_o\, MBV_b}$$

Given values for the atmospheric pressure and the physiological variables in equations (12) - (14), the value of %[COHb] at time t can be found by numerical integration using such techniques as the fourth order Runge-Kutta method (Press et al., 1986).

Muller and Barton (1987) demonstrated that an equation of the form of (12) is equivalent to a Michaelis-Menton kinetics model which is integrable. Integration yields:

(Eq.15)
$$-(C_0 + C_1)t + \%[COHb] - \%[COHb]_0 - \left(100 - \%[COHb]_\infty\right)\ln\frac{\left(\%[COHb]_\infty - \%[COHb]\right)}{\%[COHb]_\infty - \%[COHb]_0} = 0$$

The equation for $\%[COHb]_\infty$ is obtained by setting equation (12) equal to zero and solving for %[COHb] which is now equal to $\%[COHb]_\infty$:

(Eq.16)
$$\%[COHb]_\infty = \frac{100C_0}{(C_0 + C_1)}$$

Equation (15) cannot be solved explicitly for %[COHb]. The Muller and Barton paper suggests the binary search method as one way to find the value of %[COHb]. Press and coauthors (1986) contend a combination of the binary search and Newton-Raphson methods is faster on average.

III. Application of the Basic COHb Model in pNEM/CO

Description of pNEM/CO

pNEM/CO follows the daily activities over an extended period of a finite set of cohorts residing within a given geographic area. The period may be a single season or a calendar year. Each cohort is defined as a group of people with similar demographic and physiological characteristics who are likely to follow similar activity patterns. (Smokers are typically omitted from the cohorts included in pNEM/CO assessments, as cigarette smoking dominates their exposure to CO.) The exposure of each cohort is represented by a continuous sequence of exposure events which span the time period of interest. Each exposure event represents a time interval of 60 minutes or less during which the individual resides in a single environment and engages in a single activity. To permit calculation of hourly average exposures, exposure events are not permitted to fall in more than one clock hour. Consequently, the passage from one exposure event to the next is indicated by a change in microenvironment, activity, or clock hour. Algorithms within pNEM/CO calculates an average CO concentration for each exposure event according to the time, district, and microenvironment specified for the event. As the exposure events for a cohort are contiguous, the model can combine these concentrations to output distributions of one-hour and running eight-hour exposures for each cohort. The exposures calculated for individual cohorts can then be weighted according to their estimated populations to produce exposure distributions for larger population groups of particular interest.

To treat the daily behavior of cohorts probabilistically, each cohort is identified according to home district, work district, demographic group, and the use of cooking fuel in the residence. Currently seven demographic groups are used to distinguish cohorts by sex and age. A set of pools of 24-hour activity patterns is used based on activity data drawn from the Consolidated Human Activity Data Base (CHAD) which is described in Section 2.3 of this report. These patterns are twenty-four hour samplings of the behavior of real people. The patterns in each pool represent the same demographic cohort group, day type (weekday, weekend day), and ambient temperature range. Each pattern consists of a 24-hour set of contiguous exposure events defined by event start time, duration, microenvironment, and activity. For a given cohort a daily pattern is randomly sampled from the appropriate pool each day during the period of the computation.

From the description in the preceding paragraph, it is apparent that while the cohort represents a single demographic group, the activity pattern selected to represent each 24-hour period is obtained from a different member of the group. This feature has an impact on the design of the COHb module.

The COHb Module

The COHb module of pNEM/CO employs the Muller and Barton (1987) integration of the CFK model as represented by equations (12)-(14) to compute the COHb level of a cohort at the end of each exposure event. To perform this computation, the COHb module requires information on each of the quantities listed in the section describing the CFK model. In addition, the COHb level at the beginning of the exposure event must be known. This latter quantity is usually the COHb level computed at the end of the previous contiguous exposure event. To obtain the initial COHb at the start of the exposure period, the computation is started one day before the beginning of the period. The effect of the initial COHb value on the end value is negligible after about 15 hours. The program stores the COHb levels at the end of each clock hour and outputs distributions of COHb levels for the sensitive population.

Assignment of CFK Model Input Data for an Exposure Event

Section IV describes the equations and procedures used by the pNEM/CO COHb module to obtain the values of the input variables for equations (2) and (13) through (16). A brief overview is given here.

The actual inspired CO level can change significantly during an exposure event. The model supplies an average exposure concentration for the event, which is used as the CO input. The time constant for the change in COHb is sufficiently large that the use of concentrations based on averaging times up to one hour can be used in place of the instantaneous concentrations over the averaging time period with little loss of accuracy in estimating the COHb level at the end of the exposure event. Furthermore, applying the average concentrations to a contiguous sequence of exposure events does not cause an accumulation of error.

The COHb model presently used in pNEM/CO does not account for changing barometric pressure. It uses a constant barometric pressure which is a function of the average elevation of an area above sea level. The pressure at sea level is taken to be 760 torr.

The remaining input variables to the CFK model are all physiological parameters. While the Haldane coefficient, the equilibrium constant k, and average pulmonary capillary oxygen pressure are treated as having the same constant values for all cohorts, the remaining physiological input variables will vary among individuals. The next section describes the methods used to generate the various physiological input variables for each combination of cohort and calendar day processed by pNEM/CO.

IV. Computation of Input Data for the COHb Module

As discussed in the previous section and in Sections 2.43 and 2.44 of the main body of this report, the algorithms used to estimate V_E and COHb require values for various physiological parameters such as body mass, blood volume, and pulmonary diffusion rate. Table 2 provides a complete list of these parameters. A special algorithm within pNEM probabilistically generates a value for each parameter on the list (collectively referred to as a "physiological profile") for each combination of cohort and calender day processed by pNEM/CO. Figure 1 is a flow diagram showing the process by which each physiological profile was generated. Each of the generated physiological profiles is internally consistent, in that the functional relationships among the various parameters are maintained. For example, blood volume is determined as a function of weight and height, where height is estimated as a function of weight. Weight in turn is selected from a distribution specific to gender and age. Table 2 provides a brief summary of the method used to estimate values for each parameter in the application of pNEM/CO to Denver.

For each cohort, as defined above, pNEM/CO computes exposure for a contiguous sequence of exposure events spanning the total time period of the computation. This multi-day sequence of exposure events is determined by random sampling day-long event sequences from a set of pools of 24-hour activity patterns. An individual 24-hour pattern in one of these pools is referred to as a unit exposure sequence (UES). Each pool consists of a collection of UESs which are specific to the cohort demographic group, day type, and average daily temperature.

A UES is a contiguous set of exposure events spanning 24 hours. Each event is characterized by start time, duration in minutes, home/work status, microenvironment, and activity. All exposure events are constrained to occur entirely within a clock hour. The UESs start at 7:00 p.m. and end at 7:00 p.m. the following day.

The CFK model within the COHb module is called for each exposure event. For each event it requires the following data.

Time duration of event, min
Inspired CO partial pressure averaged over the event, torr
Percent COHb at the start of the event
Alveolar ventilation rate, ml/min STPD
Average pulmonary capillary oxygen pressure, torr
Haldane Coefficient
Equilibrium constant for the reaction of O_2
Atmospheric pressure, torr
Blood volume, ml
Total potential reduced hemoglobin content of blood, ml CO/ml STPD
Pulmonary CO diffusion rate, ml/min/torr STPD
Endogenous CO production rate, ml/min STPD

Given these data as inputs, the module computes the percent COHb at the end of the exposure event. This value is used by the module as the initial percent COHb for the next contiguous exposure event. The main program retains only those COHb values at the end of each clock hour.

Some of the above data do not change during a pNEM/CO computer run and, therefore, need to be supplied to the computer program only once at the start. Some of the data vary with the cohort and therefore need to be supplied at the beginning of each activity day. Other data tend to change with the exposure event and therefore need to be supplied for each new exposure event.

Table 2. Parameters Included in Physiological Profile for Adults in Version 2.0 of pNEM/CO.

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Age	COHb Ventilation rate	Demographic group	Randomly selected from population-weighted distribution specific to demographic group
Gender	COHb Ventilation rate	Demographic group	Randomly selected from population-weighted distribution specific to demographic group
Weight (body mass)	COHb Ventilation rate	Gender Age	Randomly selected from population-weighted distribution specific to age and gender based on Brainard and Burmaster (1992).
Height	COHb	Weight Gender	Estimated by the following equations: males: height = 34.43 inches + (6.67)[ln(weight)] + (2.38 inches)(z) females: height = 48.07 inches + (3.07)[ln(weight)] + (2.48 inches)(z) The z term was randomly selected from a unit normal [N(0,1)] distribution. Units: height (inches), weight (lbs). The estimation equations are based on the results of a statistical analysis by Johnson (1998) of height and weight data provided by Brainard and Burmaster (1992).
Menstrual phase	COHb	Gender Age	If gender = female, menstrual phase was randomly assigned according to the following age-specific probabilities. Age < 65: 50% premenstrual, 50% postmenstrual. Age 65+: 100% premenstrual.

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Blood volume	COHb	Gender Weight Height	Blood volume (V_b) was determined according to gender by the following equations which are based on work by Allen et al. (1956) which was modified to accept the units used for height and weight. Men: $V_b = (20.4)(\text{weight}) + (0.00683)(H^3) - 30$ Women: $V_b = (14.6)(\text{weight}) + (0.00678)(H^3) - 30$ Units: blood volume (ml), weight (lbs), height (inches).
Hemoglobin content of the blood, Hb	COHb	Gender Age	Randomly selected from normal distribution with arithmetic mean (AM) and arithmetic standard deviation (ASD) determined by gender and age based on data obtained from the 1976-1980 NHANES study (USDHHS, 1982) as follows. Males, 18 - 44: AM = 15.3, ASD = 1.0 Males, 45 - 64: AM = 15.1, ASD = 1.2 Males, 65+: AM = 14.8, ASD = 1.4 Females, 18 - 44: AM = 13.3, ASD = 1.1 Females, 45 - 64: AM = 13.6, ASD = 1.2 Females, 65+: AM = 13.7, ASD = 1.2 Units: grams of Hb per deciliter of blood
Pulmonary CO diffusion rate, DL_{CO}	COHb	Gender Height Age	Pulmonary CO diffusion rate (DL) was determined according to gender, height, and age according to the following equations obtained from a paper by Salorinne (1976) and modified to conform to the units used in the COHb module. Males: $DL_{CO} = (0.361)(\text{height}) - (0.232)(\text{age}) + 16.3$ ml/min/torr Females: $DL_{CO} = (0.556)(\text{height}) - (0.115)(\text{age}) - 5.97$ ml/min/torr Units: DL_{CO} (ml/min/torr), height (inches), age (years).

Parameter	Algorithm(s) Containing Parameter	Other Parameters Required for Calculating Parameter	Method Used to Estimate Parameter Value
Endogenous CO production rate	COHb	Gender Age Menstrual phase	Endogenous CO production rate was randomly selected from a lognormal distribution with geometric mean (GM) and geometric standard deviation (GSD) determined according to the following equations specific to age, gender, and menstrual phase. Males, 18 - 64: GM = 0.473, GSD = 1.316 Males, 65+: GM = 0.473, GSD = 1.316 Females, 18 - 64, premenstrual: GM = 0.497, GSD = 1.459 Females, 18 - 64, postmenstrual: GM = 0.311, GSD = 1.457 Females, 65+: GM = 0.497, GSD = 1.459 Units: GM (ml/hr), GSD (dimensionless).
Resting metabolic rate (RMR)	Ventilation rate	Gender Age Weight (body mass)	See Section 5.4 of the main body of this report.
Energy conversion factor (ECF)	Ventilation rate	Gender	See Section 5.4 of the main body of this report.
Ventilatory Equivalence Ratio (VER)	Ventilation rate	Gender Age Height	See Section 5.4 of the main body of this report.
NVO_{2max}	Ventilation rate	Gender Age	See Section 5.4 of the main body of this report.
VO_{2max}	Ventilation rate	NVO_{2max} Weight (body mass)	See Section 5.4 of the main body of this report.

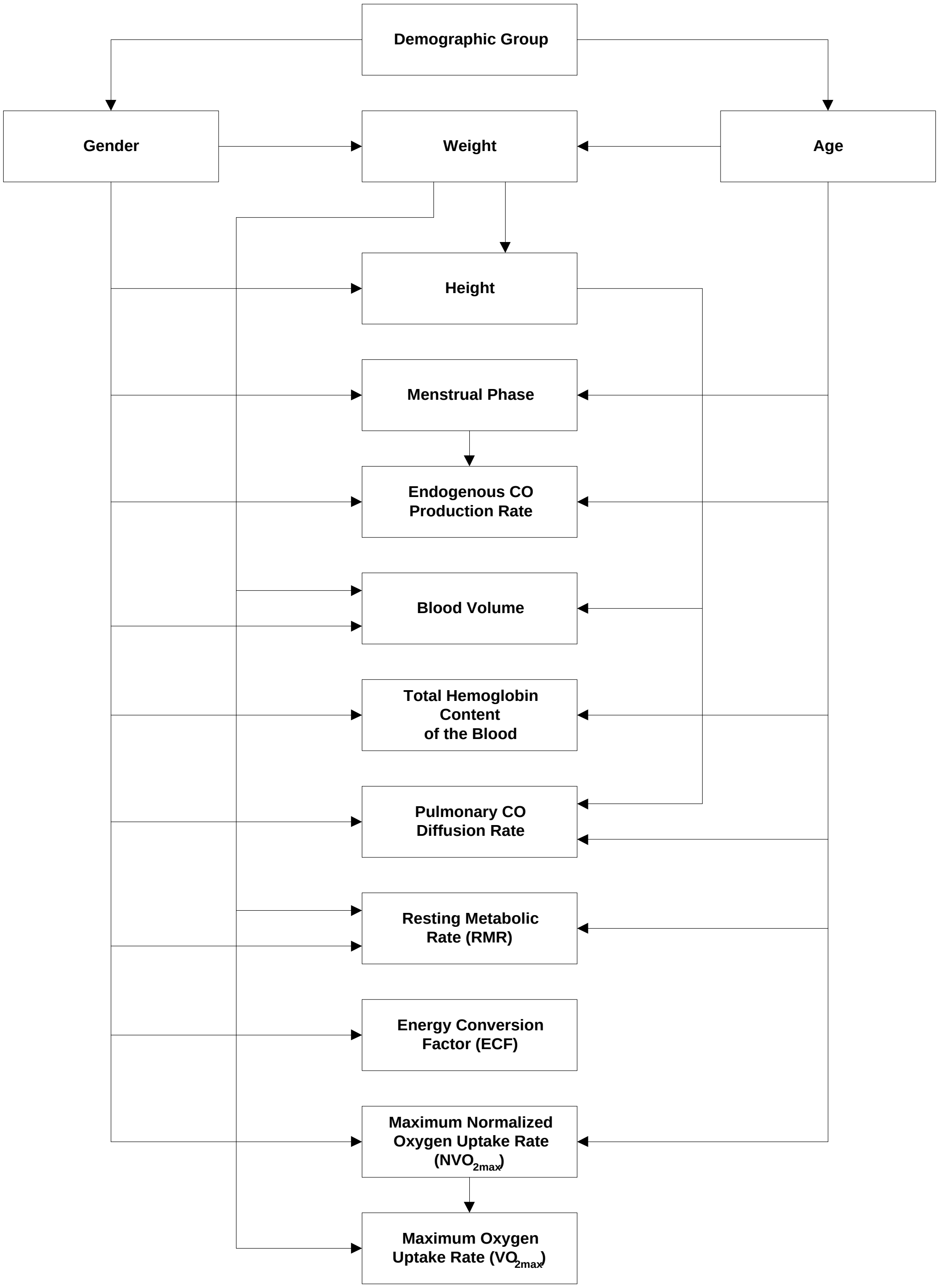

Figure 1. Flow Diagram for Physiological Profile Generator.
Input Data Supplied at Start of the pNEM/CO Computation

Barometric Pressure

A constant barometric pressure is assumed for the study area based on the average height above sea level:

(Eq. 17) $$P_B = 760 * \exp(-0.0000386 * Altitude)$$

where altitude is the average height (in feet) of the study area above sea level (USEPA, 1978).

Average Pulmonary Capillary Oxygen Pressure

The equation employed is based on an approximation used by Peterson and Stewart (1975) in which the 49 torr is subtracted from the partial pressure of inspired oxygen. This leads to the following approximate relationship:

(Eq.18) $$\overline{P}C_{O_2} = 0.209(P_B - 47) - 49$$

The constant 0.209 is the mole fraction of O_2 in dry air. The constant 47 is the vapor pressure of water at body temperature. This expression was used in an investigation of the CFK equation by Tikuisis et al. (1987). Modelers have tended to use the value 100 torr. Equation (18) gives the value 100 torr for a barometric pressure of 760 torr.

Haldane Coefficient

The value of 218 has been used for the Haldane coefficient. Measured values in the range 210 to 270 have been reported in the literature. Modelers have tended to use values in the range 210 to 240. In the early 1980's, the Clean Air Scientific Advisory Committee (CASAC) expressed the opinion to EPA (Friedlander, 1982) that the most careful work done in this area was that by Rodkey (1969), who determined a value of 218. This value was used in the COHb module of the earlier CO NEM version. Other modelers using values in the range 218 to 220 are Peterson and Stewart, 1970; Marcus, 1980; Collier and Goldsmith, 1983; Muller and Barton, 1987. As the value 218 falls within the range currently used by modelers, EPA analysts have decided to continue using value in pNEM/CO.

Equilibrium Constant for the Reaction of O_2 and RHb

This quantity was estimated in Section II to have the value 0.32 based on the observation that %[RHb] is about 3% in individuals breathing air which is free of CO and a value of 100 torr for $\overline{P}C_{O_2}$.

Total Reduced Hemoglobin in the Absence of O_2 and CO

The quantity $[THb]_0$ is expressed as equivalent milliliters of O_2 or CO at STPD per milliliter of blood. Total Hb blood levels are customarily expressed as grams per deciliter of blood. The total Hb level in the absence of COHb and O_2Hb would consist principally of RHb which can react with O_2 or CO and MetHb which cannot. Total Hb blood levels also tend to be higher in people living at higher altitudes. To relate $[THb]_0$ to Hb, it is therefore necessary to correct for the MetHb present, adjust for the effect of altitude, and convert to equivalent milliliters of CO at STPD. The later conversion is based on the observation that a gram of reduced Hb can react with a maximum of 1.39 ml of O_2 or CO at STPD. The application of these three factors yields the equation:

(Eq. 23) $$[THb]_0 = 1.39 * Hb(100 - \% MetHb) * \frac{(1 + HbAlt * Altitude)}{100}$$

where HbAlt is a regression constant. Hb in equation (23) is a sea level value. Hb level in a human population is normally distributed with the mean Hb and standard deviation both dependent on gender and age class (see entry in Table 2 for the distributions of Hb by age and gender). Given the hemoglobin content of the blood based on the distributions listed in Table 2, $[THb]_0$ is calculated using equation (23). The weight percent MetHB, %MetHB, is taken to be 0.5% of the weight of Hb (Muller and Barton, 1987).

The altitude correction factor, HbAlt, was developed by application of simple regression analyses to Hb data obtained in 17 U.S. cities (USEPA, 1973).

Men:	0.000161	S.E. = 0.000064
Women:	0.000115	S.E. = 0.000043

Two cities (Phoenix and Houston) were eliminated in the regression analysis because the measured Hb levels were substantially below that of the other cities. The altitude factor is small. It predicts about a 5% increase in Hb for residents of Denver over that for people living at sea level.

Determination of Weight

Body mass or weight (in kg) was determined by fitting lognormal distributions to data organized by age and gender based on work by Brainard and Burmaster (1992) and Burmaster et al. (1994). Table 5-5 in the main body of this report summarizes the parameters for the lognormal distributions obtained.

Determination of Height

The following equations were used to estimate height as a function of gender and weight.

(Eq. 24) males: height = 34.43 inches + (6.67)[ln(weight)] + (2.38 inches)(z)

(Eq. 25) females: height = 48.07 inches + (3.07)[ln(weight)] + (2.48 inches)(z)

The z term was randomly selected from a unit normal [N(0,1)] distribution.

Equations 24 and 25 are based on the results of a statistical analysis by Johnson (1998) of height and weight data provided by Brainard and Burmaster (1992).

Base Pulmonary Diffusion Rate of CO

A base lung diffusivity of CO for the cohort is calculated as follows:

(Eq. 26) Men: $$D_{L_{CO}} = 0.361 * height - 0.232 * age = 16.3$$

(Eq. 27) Women: $$D_{L_{CO}} = 0.556 * height - 0.115 * age - 5.97$$

where height is in inches and age is in years.

The regression equations were obtained from a paper by Salorinne (1976) and modified to conform to the units used in the COHb module. The Salorinne data were obtained for non-exercising individuals. Tikuisis et al. (1992), working with eleven male subjects at various exercise levels, showed significant increase in lung diffusivity of CO with increasing alveolar ventilation rate. Regression analyses of data provided by Tikuisis for the individual subjects in the study showed the relationship to be linear. From this relationship and the heights and ages of the subjects in the Tikuisis et al. study, it was determined that the Salorinne equations for male subjects correspond to an alveolar ventilation rate of 6.69 l/min STPD. In the absence of other data it is assumed that this same value applies to women. Thus, for each twenty-four hour period equations (26) and (27) are used to compute lung diffusion rates of CO for a base case alveolar ventilation rate of 6.69 1/min STPD. As will be seen, this value is adjusted to account for the actual ventilation rate experienced by the cohort during each individual exposure event.

INPUT DATA SUPPLIED AT START OF EACH 24-HOUR PERIOD

Endogenous Rate of CO Production

The endogenous CO production rates taken from a number of sources show the rate to be distributed lognormally in the population (see Appendix for data and sources). The distribution is different for men and women. For a woman there is a further difference depending on whether she is in her premenstrual or postmenstrual phase. The parameters of the lognormal distribution are given in Table 2 above.

The calculation is as follows: If the cohort is female, a random number is sampled from a uniform distribution of real numbers in the range 0-1. If the number is less than 0.5, the cohort is considered to be in the premenstrual half of the month. Otherwise she is considered to be in the postmenstrual period. If the woman is in the 65+ age category she is treated as premenstrual. The appropriate combination of geometric mean and geometric standard deviation are obtained from the above table depending on the age class, sex, and menstrual phase. As in the previous cases a random number, z, is sampled from the standardized normal distribution, N(0,1). The appropriate endogenous CO production rate is then obtained from:

(Eq. 28) $$\dot{V}_{CO} = 0.01667 * \left(geom.mean\right) * \left(geom.S.D.\right)^{z}$$

The constant term converts ml/hr to ml/min.

INPUT DATA SUPPLIED WITH EACH EXPOSURE EVENT

Duration of Exposure Event

The duration of the exposure event in minutes is supplied by the main program to the COHb module.

Partial Pressure of Inspired Carbon Monoxide

The main program supplies the inspired CO concentration averaged over the duration of the exposure expressed as ppm. This quantity is converted to pressure via:

(Eq. 29) $$P_{I_{CO}} = (CO) * \left(P_b - 47\right) * 10^{-6}$$

Initial Percent COHb Level at Start of Exposure Event

The program retains the percent COHb computed at the end of the previous exposure event and uses this value as the initial percent COHb for the present event. The starting COHb at the beginning of an activity day is the final COHb level at the end of the preceding activity day. This latter procedure is used for the first activity day of the overall computation since the program starts the day before the overall period covered by the pNEM/CO computation.

Alveolar Ventilation Rate

The main program supplies the COHb module with ventilation rate derived from the algorithm discussed in Section 2.4.3 in the main body of this report.

Adjusted Pulmonary Diffusion Rate of CO

Given the alveolar ventilation rate for the exposure event the associated adjusted pulmonary diffusion rate can be calculated from:

(Eq. 30) $$D_{L_{CO}}\left(Adjusted\right) = D_{L_{CO}}\left(Base\right) + 0.000845\dot{V}_A - 5.65$$

(See discussion of base pulmonary diffusion rate.)

V. REFERENCES

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Table 3. Literature Data Used to Derive Geometric Mean and Standard Deviation Lognormal Distribution of Endogenous Co Production Rate

ENDOGENOUS CO PRODUCTION RATE FOR MEN	
V_{co} (ml/hr)	REFERENCE
0.35	Coburn et al., 1963
0.35	“
0.4	“
0.39	“
0.43	“
0.35	“
0.51	“
0.42	“
0.57	“
0.45	“
0.4	Lynch and Moede, 1972
0.81	“
0.26	“
0.65	“
0.51	“
0.62	“
0.44	“
0.43	Berk et al., 1974
0.58	“
0.52	“
0.59	“
0.8	“
0.72	“
0.54	“

ENDOGENOUS CO PRODUCTION RATE FOR MEN	
V_{co} (ml/hr)	REFERENCE
0.45	Delivoria-Papadopoules et al., 1974
0.26	“
0.6	“
0.45	“
0.39	“
0.4	“
0.81	Brouillard et al., 1975
0.57	“
0.33	“
0.7	“
0.58	“
0.38	“
0.51	“
0.55	“
0.37	“
0.49	“
0.45	“
0.5	“
0.33	“
0.45	“
0.36	“
0.54	Werner and Lindahl, 1980
0.76	“
0.48	“
0.31	“
0.7	“

ENDOGENOUS CO PRODUCTION RATE FOR MEN	
V_{co} (ml/hr)	REFERENCE
0.36	“
0.65	“
0.38	Luomanmaki and Coburn, 1969
0.42	“
0.41	“
0.54	“
0.38	“
0.72	Lynch and Moede, 1972
0.37	“
0.23	“
0.33	“
0.42	“
0.44	“
0.29	“
0.48	“
0.57	Delivoria-Papadopoulos et al., 1974
0.54	“
0.72	“
0.99	“
0.48	“
0.53	“
0.43	“
0.64	Merke et al., 1975
0.86	“
0.35	“
0.52	“

ENDOGENOUS CO PRODUCTION RATE FOR MEN	
V_{co} (ml/hr)	REFERENCE
0.8	“
0.54	“
0.68	“
0.28	“
0.48	Lynch and Moede, 1972
0.23	“
0.25	“
0.2	“
0.22	“
0.15	“
0.21	“
0.23	Delivoria-Papadopoulos et al., 1974
0.51	“
0.34	“
0.41	“
0.26	“
0.16	“
0.3	“
0.4	Merke et al., 1975
0.47	“
0.23	“
0.24	“
0.55	“
0.32	“
0.43	“
0.35	“