

Chapter 11 Estimating Inhalation Exposure

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11.1 Introduction

The previous three chapters discussed how to quantify exposure and release rates and estimate chemical fate and transport. This chapter discusses the final step of estimating exposure. This chapter will discuss inhalation exposure only. Unless persistent bioaccumulative hazardous air pollutants (PB-HAPs) are present in source emissions, most air toxics risk assessments will only estimate inhalation **exposure concentrations**. Limiting the exposure assessment this way is possible because the dose-response values that characterize inhalation risk (e.g., reference concentrations, inhalation cancer unit risk estimates – see Chapter 12) take into consideration the complex physical and pharmacokinetic processes that influence how the chemical reaches the target organ, which may be a region of the respiratory tract or a remote site (see Chapter 12 for a more detailed discussion). Specifically, other than exposure modeling to account for things like time in different microenvironments and microenvironment concentrations, no adjustment for other exposure parameters (e.g., body weight and inhalation rate) are warranted. For multipathway risk assessments, however, where ingestion intake rate is the exposure parameter, it will be necessary to consider parameters such as body weight and contact rate (e.g., amount of soil ingested, fish eaten) for the indirect exposure pathway metrics of exposure (see Chapter 19).

Assessors determine human exposure to an environmental pollutant via inhalation by estimating the concentration of that pollutant in the ambient air and the contact of an individual with that air (along with the characteristics of the contact). Because concentrations in the air vary over space and time, it is important to know where and how long people spend their time in relation to the contaminated air under study. Through air quality modeling and monitoring, the ambient concentrations of pollutants in air can be estimated geographically and temporally. Through the use of exposure modeling, estimates of exposure via the inhalation route can be adjusted from modeling data to take into account the demographics of people in the study area and the time they may spend in various microenvironments.

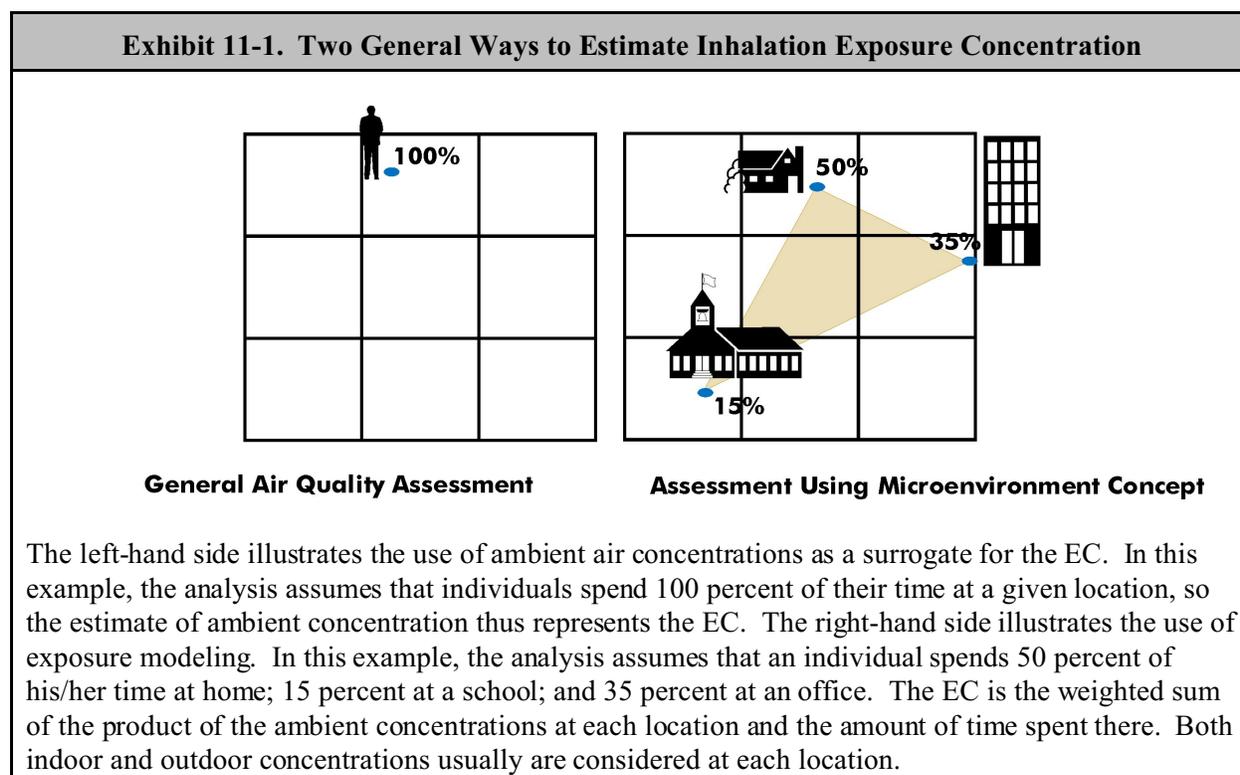
The remainder of this chapter discusses how to estimate inhalation exposure concentrations for the risk assessment (Section 11.2); exposure modeling (Section 11.3); personal monitoring (Section 11.4); common descriptors (Section 11.5); evaluating uncertainty (Section 11.6); and presenting the results of an exposure assessment (Section 11.7).

11.2 Estimating Inhalation Exposure Concentrations

The ambient air exposure concentrations (ECs) can be estimated using either (or both of) two general methods: air quality modeling and air quality monitoring. As discussed in Chapter 9, air quality modeling involves defining the pollutant sources and release characteristics and modeling pollutant fate and transport (how the air toxic is transported, dispersed, and transformed over the area of interest). As Chapter 10 discussed, monitoring involves measuring ambient concentrations of chemicals. Because of the time/expense and other limitations associated with monitoring (most notably, questions about representativeness), modeling is the most common approach for estimating ambient air concentrations to be used in the air toxics risk assessment. Monitoring is often used, instead, as a secondary tool to provide input data to the models and validate the model results and to look for important gaps in the emissions inventory used to run the model.

11.2.1 General Approaches for Deriving Exposure Concentrations

There are two general ways to derive the EC for a given risk assessment (see Exhibit 11-1). Both may incorporate the results of air quality modeling and/or monitoring efforts.



- **Ambient Air Concentrations as a Surrogate.** For screening-level evaluations, assessors use the concentrations of air toxics generated at each modeling node (or interpolated nodes) or the concentrations determined by a monitor (if modeling is not performed) as surrogates of the inhalation exposure concentrations for the populations in the study locations. The default assumption in such a screening assessment is that the population of interest is breathing outdoor air continuously at the modeled or monitor location. This is believed to be a conservative assumption since indoor air concentrations of air toxics are expected to be the same or lower than the outdoor concentrations (when the indoor concentrations are produced solely by inflow from outside air).
- **Exposure modeling.** More comprehensive inhalation exposure assessments combine estimates of ambient pollutant concentrations (e.g., from air quality models) with information about the population of interest, including the types of people present (e.g., ethnicity, age, sex), time spent in different microenvironments, and microenvironment concentrations. The assessment objective is to identify a representative estimate of the pollutant concentration in the inhaled air in each microenvironment and combine it with an estimate of the time spent in different microenvironments (and the activities within these microenvironments) throughout the daily routine of different groups of people with similar attributes (called **cohorts**).

11.2.2 Common Ways to Estimate Exposure Concentrations

Risk assessors commonly use several different ways to estimate exposure concentrations. Some ways are used primarily for screening-level (Tier 1) assessments; others are used primarily for more refined assessments. Exhibit 11-2 illustrates several different ways to estimate exposure concentrations when ambient air concentrations are used as surrogates.

- **Monitoring locations.** Sites where air monitors are located provide a direct measure of ambient air concentrations at those locations. However, these locations may or may not be representative of ambient air concentrations in other parts of the study area. If monitors are not located where people live, the monitoring results may not be of much value for the risk assessment other than to check the accuracy of modeling. Monitoring results may be used as inputs to exposure modeling.
- **Point of maximum modeled concentration.** This is the modeling node where the maximum modeled ambient air concentration occurs, regardless of whether there is a person there or not. This generally provides a conservative estimate of exposure and could be used as the EC in a screening-level evaluation (for example, using the SCREEN3 model). This point can be used to provide an estimate of “high-end” exposure to the risk manager because, although no one may actually be living there at the present, someone might move there in the future. This point may be referred to as the point of the **“maximum exposed individual (MEI).”**
- **Point of maximum modeled concentration at an actual receptor location.** This is the modeling node where the maximum ambient air concentration occurs to an actual person in the area of impact, usually at an actual residence (or, if the residence falls between modeling nodes, an interpolated value). To identify this point precisely, it is necessary to know detailed information about the location of actual people in the study area. As with the point of maximum modeled concentration above, this point can be used to provide an estimate of “high-end” exposure to the risk manager (in this case, based on current actual exposures). This point may be referred to as the point of the **“maximum individual risk (MIR).”**
- **Census tract/block internal point.** The U.S. Census Bureau provides information about populations in geographic units called census tracts, which are subdivided into block groups/enumeration districts and blocks. In cases where there is only limited information about the census tract (e.g., nothing is known other than the number of people living within the tract), the Census Bureau’s “internal point” (sometimes referred to as a centroid) for the tract typically is used as the point of exposure for all the population in the tract. The internal point is a set of geographic coordinates that generally represents the approximate geographic center of a geographic subdivision (see box on next page). The Census Bureau provides an internal point for each of its geographic subdivisions (i.e., tracts, blocks, and block groups). Note that the internal point **is not population weighted** (i.e., it is not located “in the direction of where the people are”).

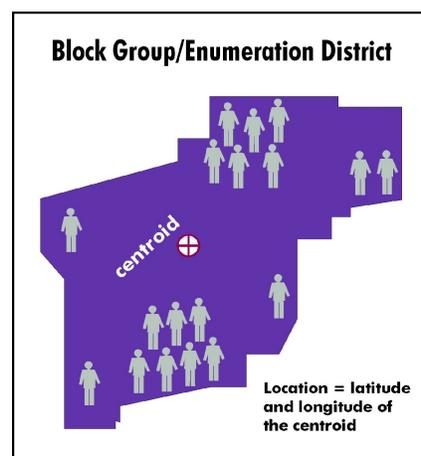
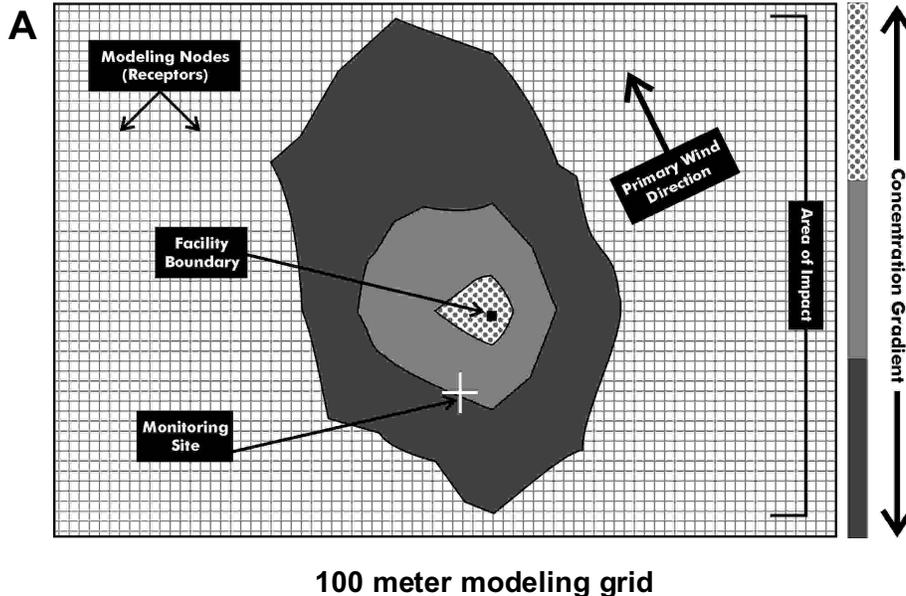


Exhibit 11-2. Illustration of Common Ways to Estimate Exposure Using Ambient Air Concentrations as Surrogates for Exposure Concentration



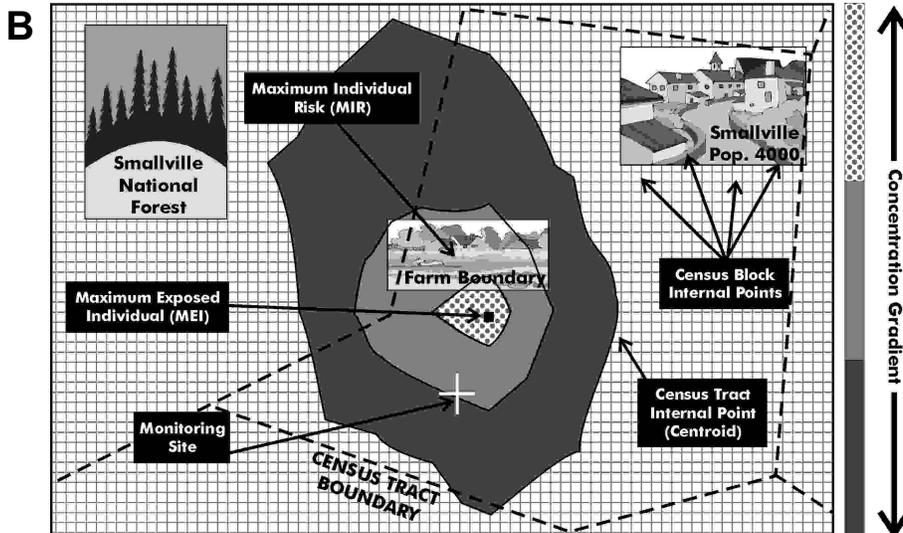
In this hypothetical example, the risk assessors have modeled a release of a volatile organic HAP from a facility using a computerized air quality model, and the ambient air concentration is used as a surrogate for the exposure concentration (EC). The area of impact surrounds the facility and is generally greater in the direction of the primary wind flow (and decreases in concentration with distance from the source). The model was set to make estimates of annual concentration at 100-meter distances from the source in a rectangular grid pattern. The points where the model makes estimates are called “modeling nodes” or “receptors.” Note, however, that modeling receptors do not necessarily coincide with actual people (who are also sometimes referred to as receptors) – that is, there may or may not be a person at any given modeling node. There also is one monitoring site.

Knowing only the information displayed in the first version of the map (A), it is difficult to say much about exposure since we do not know where the people are in relation to the facility or the area of impact. To remedy this, our next step is to obtain demographic data (usually from the Census Bureau) and overlay it on the above map. We may also have first-hand knowledge of exactly where people live in the vicinity of the facility which we can also include on the map. Performing this analysis and redrawing the map gives picture B (next page).

In the second version of the map (B), we have included the census tract boundaries (dotted lines) and we also know from study area reconnaissance that there is an uninhabited national forest to the west of the facility, a farmer (Mr. MacDonald) directly to the north, and a small town in the northeast. (Note that the town, Smallville, actually can be further subdivided into smaller census blocks; however, they are not shown here to keep the picture simple.) Now that we have a better idea of where people are in relation to the facility (and the area of impact caused by the VOC release), we are in a better position to start making some statements about how people are exposed. Some of the more common ways to characterize the exposures that may be occurring include:

1. **Monitoring Site.** The monitoring site is located in one of the higher parts of the area of impact, but it is southwest of the facility and far from most of the area’s populations. This monitoring site would not be appropriate for describing exposure for the people of Smallville, but it could be used for people in the immediate vicinity of the facility and to check the accuracy of the modeling.

Exhibit 11-2 (continued)



2. **Point of Maximum Modeled Concentration.** In this example, this point is located on the facility boundary, where no one currently lives. This point is called the Maximum Exposed Individual or MEI which is defined as the highest estimated risk to a hypothetical exposed individual, regardless of whether people are expected to occupy that area.
3. **Point of Maximum Concentration at a Location Occupied by People.** In this example, this point occurs at Mr. MacDonald's farm. This point is called the Maximum Individual Risk, or MIR, which is defined as the highest estimated risk to an exposed individual in areas that people are believed to occupy. Actually, the concentration used to represent Mr. MacDonald could be described using either an estimate of exposure at a point (e.g., his house) or some other estimate of exposure for the larger farm if there were a good justification for doing so (e.g., an average of all the farm's modeled points, since Mr. MacDonald spends much of his time working around the farm).
4. **Census Tract Internal Point.** In this example, we could simply use the census tract internal point to represent exposure for all people living in the census tract. This is sometimes used, especially when you do not have any first-hand knowledge of the area (i.e., you only have general demographic data from the Census Bureau). However, in this example the census track internal point would not be a very good estimate of exposure concentration because it is higher in concentration than that experienced by most of the population (i.e., the people of Smallville) and it is lower in concentration than that of the highest exposed person (i.e., Mr. MacDonald).
5. **Census Block Internal Points.** So far, this example has focused on characterizing an individual person's exposure living at defined points within the study area (either a real person like Mr. MacDonald, or a hypothetical person like the MIR). What if we wanted to know something more about *how many* people in the study area are living at different levels of exposure? One way to do this is to develop a frequency diagram that displays the exposure concentration at each of the census block internal points and identifies the number of people living in that block (see below). This kind of representation is very helpful to the risk managers because it gives them a sense of the range of exposures and the numbers of people living at different levels of exposure. (In addition, the assessor may also choose to represent the exposure with isopleths of risk (as in the above graphic) and by listing the approximate number people living within each isopleth.)

The internal point with the highest impact in the study area may also be referred to as the point of maximum concentration at a receptor location, although it may not be as precise as the example above where more local knowledge is applied to locate this point.

- **Population-based approaches.** Exposures may be evaluated by tracking individual members of a population and their inhalation through time and space. Such analyses may incorporate a user-specified number of **simulated individuals** or population groups (**cohorts**) to represent the population in the study area. A cohort is defined here as a group of people within a population with the same demographic variables who are assumed to have similar exposures. In this approach, the exposure analysis process consists of relating chemical concentrations in air (outdoor and/or indoor) and tracking the movement of a population cohort through locations where chemical exposure can occur according to a specific activity pattern. Population-based analysis is generally accomplished using exposure models (as described in Section 11.3 below).
- **Personal monitoring.** Exposures may be estimated directly by placing monitors on individuals, which allows collection of more detailed information specific to the exposure pattern for that individual. Such monitors are referred to as **personal monitors** because they provide information on exposure to that individual, rather than to the general area in which an individual might be moving. Personal monitoring is discussed in Section 11.4 below.

Note that the units for the EC estimates are typically expressed in terms of micrograms (or milligrams) of pollutant per cubic meter of air. For pollutants adsorbed to particles, inhalation exposure estimates should be provided as the concentration of these pollutants *on the particles*, not the concentration of the particles themselves.

11.3 Exposure Modeling

This section discusses exposure modeling, which uses the ambient air concentration estimates along with information about the population of interest and information on how the pollutant concentration can vary in different microenvironments to derive estimates of exposure concentration over the period of exposure. Information on human exposure modeling for air toxics can be found on EPA's Fate, Exposure, and Risk Assessment (FERA) website at <http://www.epa.gov/ttn/fera/>.

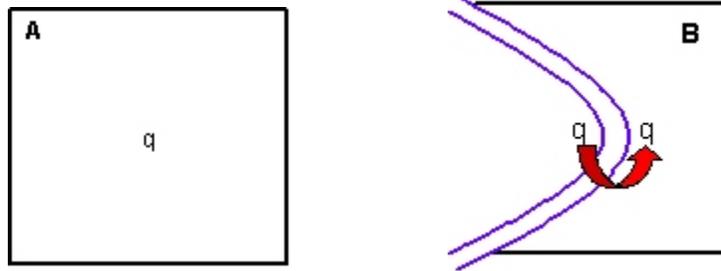
For example, suppose an analyst uses the air quality model, ISCLT3, to estimate the annual average concentration of benzene from a petroleum refinery at each census tract internal point for every census tract within 50 km of the source (for illustration, assume this is 25 census tracts). In a screening level analysis, the analyst may simply use the predicted ambient air concentration as a surrogate for the population chronic exposure concentration of benzene at each of the 25 internal points.

Internal Point or Centroid: Which is Correct?

When evaluating exposure to people in a given place, the modeled air quality at the “internal point” of a geographic entity (such as a census tract or census block) is often used as a starting point to represent exposure for the people in that geographic entity. According to the U.S. Census Bureau:

An internal point is a set of geographic coordinates (latitude and longitude) that is located within a specified geographic entity. A single point is identified for each entity; for many entities, this point represents the approximate geographic center of that entity. If the shape of the entity causes this point to be located outside the boundary of the entity or in a water body, it is relocated to land area within the entity. In computer-readable products, internal points are shown to six decimal places; the decimal point is implied. The first character of the latitude or longitude is a plus (+) or a minus (-) sign. A plus sign in the latitude identifies the point as being in the Northern Hemisphere, while a minus sign identifies a location in the Southern Hemisphere. For longitude, a plus sign identifies the point as being in the Eastern Hemisphere, while a minus sign identifies a location in the Western Hemisphere.

To illustrate how internal points are established, consider the following two examples. In census tract A, the internal point (q) is simply the geographic center of the square. In census tract B, a river flows along the western edge of the tract and makes a sharp bend towards the tract’s eastern edge. In this case, the “geographic center” of census tract B is actually outside the tract itself. Since the Census Bureau requires that the internal point be within the physical boundaries of the geographic entity, the Bureau physically moves the point into the tract, as shown (to a point that is no longer the geographic center).



Note that the internal point is generally set to reflect the geographic center of the entity in question, regardless of where people actually live in that entity. In other words, the point is not “population weighted” (the Census Bureau does not provide population weighted internal points for census tracts or block groups). Without population weighting, an exposure concentration estimated at the internal point might not be representative of the concentrations to which persons living in the census entity might be exposed. Analysts routinely modify the Census Bureau internal points for census tracts and census block groups (using census block data) to locate them to a spot more representative of where people are actually located within the geographic entity (e.g., a “population weighted” internal point).

Source: U.S. Department of Commerce, U.S. Census Bureau. 2000. *Geographic Glossary (Census 2000)*. Available at: <http://www.census.gov/geo/www/tiger/glossry2.pdf>.

However, a limitation of this is that each person in a census tract is not breathing air at the ambient concentration continuously. There are a variety of reasons why this is so. For example:

- People come and go from the census tract for work, play, or travel. They may go to another census tract in the vicinity with either a higher or lower concentration of benzene.
- People do not spend all their time outdoors (which is what our analyst has presumed in our hypothetical example). In fact, most people spend most of their time (with some estimates of about 90 percent) indoors. The chemical concentration of benzene may be higher or lower indoors than outdoors.
- The benzene concentration throughout the census tract, in our example, is probably not always the same as that at the internal point we selected (we have just assumed it was for computational ease).

Exposure modeling was developed to try and help move an analysis into considering these details. Thus, air quality modeling estimates how contaminated the air is in the different locations within a study area. Exposure modeling simulates how different types of people interact differently with that contaminated air to derive integrated (e.g., time weighted) estimates of their exposure for the duration of interest.

This section focuses on exposure models to evaluate inhalation exposures. Exposure models are also available for other routes of exposure as well (e.g., a model may be employed to track patterns of food and drinking water consumption across a population). These indirect pathway exposure models are discussed in Chapter 18.

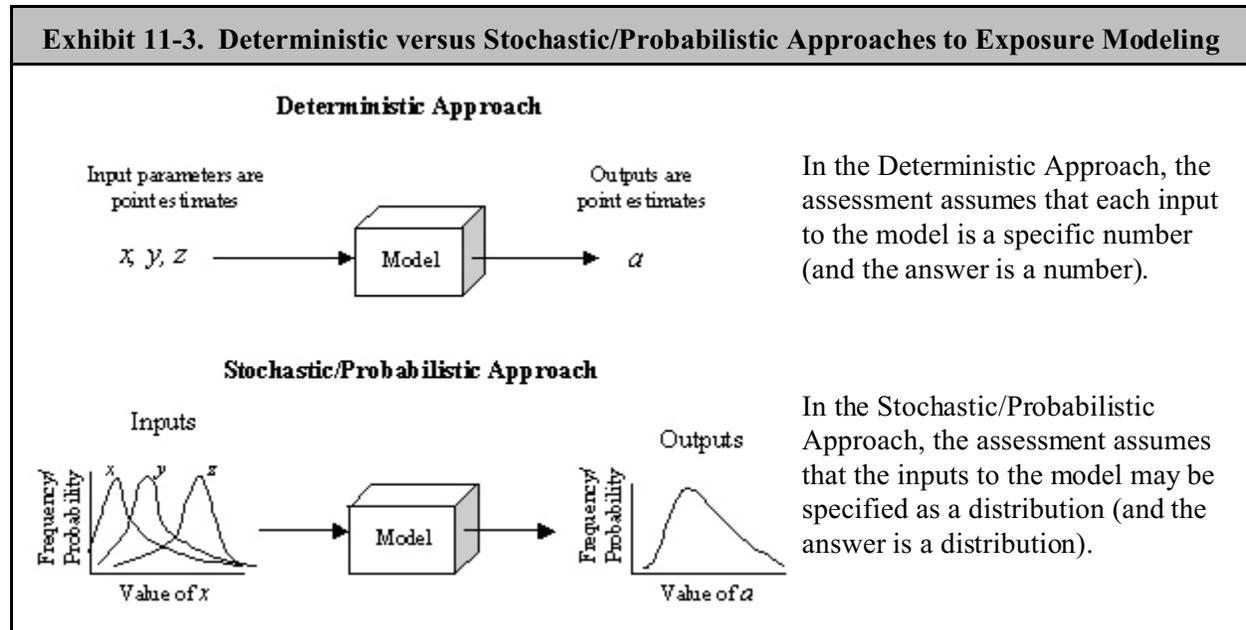
The estimation of population exposure is a very difficult task because it requires information on the activity patterns of the population as well as information on the air toxics concentrations (indoor and outdoor) to which that population is exposed. Although several databases have been developed to characterize activity patterns (see Section 11.3.3), various sources of variability (e.g., among individuals and geographical regions) introduce uncertainty. Three main factors affect the overall accuracy of exposure modeling:

- Uncertainties associated with indoor air toxics concentrations (note that most people spend the majority of their time indoors);
- How well the subgroups (or cohorts) selected for analysis provide a realistic description of the population composition in a given area; and
- Uncertainty and variability associated with the inputs and parameters of exposure models.

Exposure models can be formulated in a **deterministic** framework, where the value for each input and output variable is characterized by a point estimate (i.e., a single value assumed to apply uniformly). Alternatively, the framework may be **stochastic** or **probabilistic**, with one or more input variables characterized by a frequency or probability distribution^(a) (see Exhibit 11-3).

^aThese terms are introduced and defined in Part VI of this Reference Library.

If the input distributions represent variability^(a) across the population, the resulting output distribution correspondingly represents the variability of exposures across the population. On the other hand, if the input distributions represent uncertainty^(a) about input parameters, the output distributions will represent uncertainty about exposure levels. Some of the newer exposure models address both variability and uncertainty separately (see Section 11.3.4).



11.3.1 Inhalation Exposure Modeling

Inhalation exposure is characterized by the pollutant concentration in the air (i.e., the exposure concentration) reaching an individual's nostrils and/or mouth (in units of $\mu\text{g}/\text{m}^3$). Estimates of air concentrations from modeling or monitoring can be used in inhalation exposure modeling. When derived from monitoring measurements, exposure concentrations are an **aggregate** of the contributions from all emissions sources impacting the monitor. When derived from modeling studies, the estimated exposure concentrations reflect only the sources that were included in the modeling exercise. Models have an added benefit of allowing the analyst to determine the contribution of a source to the estimated exposure concentration for any of the exposed population groups. (Trying to determine "what source" contributed "how much" to a monitoring result can be a challenging and perhaps impossible task, depending on the chemical and number of sources in the study area).

Lead Exposure Modeling

Lead (Pb) poisoning presents potentially significant risks to the health and welfare of children all over the world today. The Integrated Exposure Uptake Biokinetic Model for Lead in Children (IEUBK) attempts to predict blood-lead concentrations (PbBs) for children exposed to lead in their environment. The model allows the user to input relevant absorption parameters (e.g., the fraction of lead absorbed from water) as well as intake and exposure rates. Using these inputs, the IEUBK model rapidly calculates and recalculates a complex set of equations to estimate the potential concentration of lead in the blood for a hypothetical child or population of children (6 months to 7 years of age). Measured or estimated blood-lead concentration is not only an indication of exposure, but also a widely-used index for discerning future health problems. For additional information see <http://www.epa.gov/superfund/programs/lead/ieubk.htm>.

Because air pollutant concentrations vary over time and space, inhalation exposure models combine information on human activity patterns and microenvironmental concentrations to estimate exposure concentrations. **Activity patterns** are defined by an individual's or cohort's allocation of time spent in different activities in various microenvironments and various geographic locations. A **microenvironment** is a defined space that can be treated as a well-characterized, relatively homogeneous location with respect to pollutant concentration for a specified time period (e.g., rooms in homes, restaurants, schools, offices; inside vehicles; outdoors).

A common exposure model for inhalation that combines information on microenvironment concentrations and activity patterns calculates a **time-weighted average of all exposures** from the different microenvironments in which a person spends time during the period of interest:

$$EC_A = \frac{1}{T} \left(\sum_j C_j \times t_j \right) \quad \text{(Equation 11-1)}$$

where:

- EC_A = the adjusted average inhalation exposure concentration ($\mu\text{g}/\text{m}^3$),
- T = total averaging time ($T = \sum t_j$; years),
- C_j = the average concentration for microenvironment j ($\mu\text{g}/\text{m}^3$), and
- t_j = time spent in the microenvironment j (years).

Note that the two critical parameters that need to be evaluated in this equation are the concentration of a chemical in a microenvironment and the amount of time spent in that microenvironment. Exhibit 11-4 presents a simple example. General information on how assessors go about obtaining such data is provided below. As a practical matter, most air toxics risk assessments will not actually gather such activity pattern data for study-specific exposure assessments. Rather, available exposure models have already incorporated much of this information for use by the general risk assessment community. However, every model is different and the data input requirements vary from model to model. Usually, assessors carefully review each model's documentation before deciding to use it to determine if it will answer the

question that needs to be answered and what resources would be needed to develop the required inputs.

Exhibit 11-4. Simple Example of How to Estimate Exposure Concentration (EC) for Exposure Modeling

EC. The following exposure profile has been developed for one year (which represents, for example, the 30 years of “work”) for a representative individual within the population of interest:

Duration Spent in Each Microenvironment (% year)	Average Concentration of Pollutant A in Each Microenvironment (µg/m³)
10 = outside	80
50 = at work	20
40 = inside house	10

The EC for that individual is calculated as:

$$EC = (0.1 \times 80) + (0.5 \times 20) + (0.4 \times 10) = 22 \mu\text{g}/\text{m}^3$$

Lifetime EC. To derive a lifetime exposure concentration for that individual, annual estimates are combined as follows:

Duration Exposed to Each Annual Concentration (no. years)	Annual Average Concentration of Pollutant A (µg/m³)
1 = newborn	10
4 = pre-school	40
12 = school	30
4 = college	30
30 = work	22
19 = retirement	40

The Lifetime EC is calculated as:

$$\text{Lifetime EC} = \frac{(1 \times 10) + (4 \times 40) + (12 \times 30) + (4 \times 30) + (30 \times 22) + (19 \times 40)}{70} = 30 \mu\text{g}/\text{m}^3$$

Screening exposure estimate. One way to perform a screening level assessment using these data is to set the EC equal to the highest air concentration modeled (e.g., 80 µg/m³ for annual adjusted or 40 µg/m³ for lifetime adjusted – see examples above) for all microenvironments. If the hazard and risk, respectively, prove to be below acceptable risk values, the risk manager may conclude that no further evaluation is necessary.

11.3.2 Microenvironment Concentration: How is it Developed?

Microenvironments can be indoors (e.g., school, office, car, bus) or outdoors (e.g., filling station, roadway). Indoor microenvironment concentrations are comprised of contributions from a chemical in outdoor air penetrating the indoor environment and from indoor emission sources of that same chemical (if indoor sources are within the scope of the analysis). They may be derived from direct measurements or estimated from modeling.

There are two common approaches to modeling indoor microenvironment concentrations. One is the **microenvironment factors method**, where the outdoor contribution is estimated from the outdoor concentration and a microenvironment factor that represents the ratio of the microenvironment concentration to the outdoor concentration. Microenvironment factors are typically derived from concurrent measurements of concentrations in the microenvironment (containing no indoor emission sources) and outdoors. The indoor contribution is then added to estimate the overall microenvironment concentration (when indoor sources are included in the scope of the assessment). A general equation for the microenvironment factors method is:

$$C_j = M_j C_o + C_s \quad (\text{Equation 11-2})$$

where:

- C_j = concentration in microenvironment j
- M_j = microenvironment factor for microenvironment j
- C_o = concurrent outdoor concentration
- C_s = concentration contribution to the microenvironment j concentration from an indoor emission source

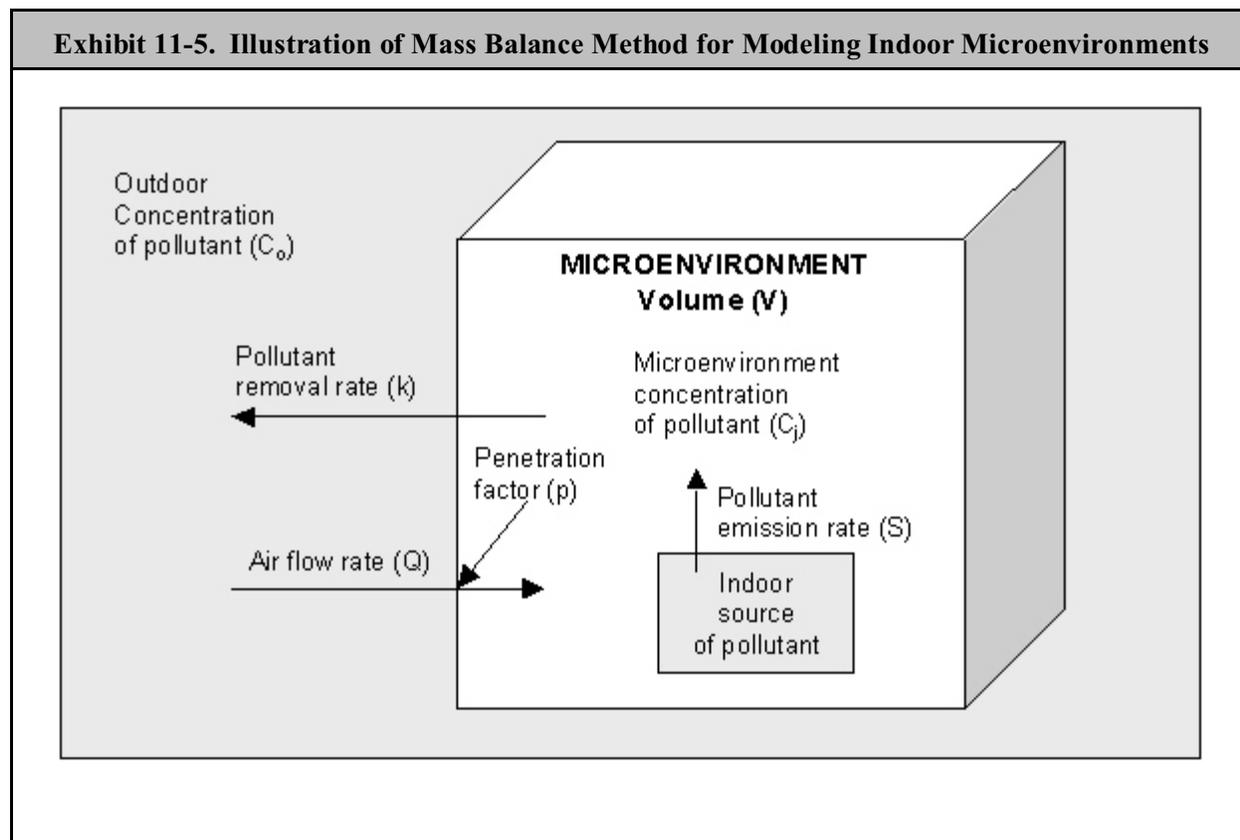
The second approach is the **mass-balance method**. The mass balance method typically assumes that an enclosed microenvironment is a single well-mixed “box,” although multi-chamber configurations are possible. The time-varying concentration of an air pollutant in such a microenvironment is estimated from several variables (see Exhibit 11-5). A general formulation for the change in concentration in an enclosed microenvironment over time is:

$$V \frac{d}{dt} C_j = pQC_o + S - kC_j - QC_j \quad (\text{Equation 11-3})$$

where:

- V = volume of microenvironment enclosure
- C_j = concentration in microenvironment j
- p = penetration factor (only applies to incoming air)
- Q = air flow rate
- k = pollutant removal rate (includes all types of removal, including atmospheric decay, surface reactivity, surface adsorption, wall deposition, etc.)
- C_o = concurrent outdoor concentration
- S = indoor source emission rate

The solution to this differential equation can be used to predict a time sequence of microenvironment j concentrations.



11.3.3 Sources of Data for Human Activity for Inhalation (and other) Exposure Assessments

Numerous EPA and related databases provide information useful for conducting exposure assessments, including information on activity pattern and demographic information useful for inhalation exposure modeling. Types of information included are human activity surveys, standard values for physiological processes and consumption of food and water, measured exposure data, health status surveys and measurements, nutrition surveys, and data on the spatial distribution of populations. This section provides several of the more notable information sources, some of which are important for inhalation exposure modeling, and some of which are important for modeling exposures through pathways other than inhalation (e.g., ingestion of contaminated fish, soil, and groundwater). Because they are so important for an understanding of exposure, we introduce them here (even though the focus of this Chapter is on inhalation). We will revisit many of these sources in Part III (Multipathway Exposure Assessment).

Indoor vs. Outdoor Concentrations

Indoor air concentrations may be an important consideration in an air toxics risk assessment. Depending on the pollutant and the sources being assessed, concentration levels may be substantially higher outdoors, in one or more indoor microenvironments, or inside vehicles. In general, pollutants that have important indoor emission sources will have higher concentrations indoors than outdoors. Important indoor emission sources include combustion sources, building materials, consumer products, and occupant activities like cigarette smoking. Similarly, pollutants that are primarily emitted by motor vehicles would be expected to have higher in-vehicle concentrations than at outdoor locations distant from roadways.

Information that may be useful to the various methods used to estimate microenvironment concentrations is available from studies involving measurements of indoor and personal exposure concentrations. These include the following EPA studies:

- The Building Assessment, Survey and Evaluation (BASE) study, which was a cross-sectional study of 100 buildings. Information relating to BASE is currently being updated to include basic summary results from the 100 buildings studied. The raw data collected for the 100 buildings is scheduled for release soon.⁽¹⁾
 - The Longitudinal Temporal Indoor Monitoring and Evaluation (TIME) Study in federal buildings.⁽¹⁾
 - The Los Angeles Total Exposure Assessment Methodology (TEAM) study,⁽²⁾ which collected concurrent indoor and outdoor samples of 18 VOCs for two consecutive 12-hour periods in 1987, around 45 homes in February and 40 homes in July.
-
- **EPA Consolidated Human Activity Database (CHAD).** CHAD contains data obtained from human activity studies that were performed at city, state, and national levels. CHAD is intended to provide input data for exposure/intake dose modeling and/or statistical analysis.⁽³⁾ CHAD is a master database providing access to other human activity databases using a consistent format. This facilitates access and retrieval of activity and questionnaire information from those databases.

The studies contained in CHAD cover a range of geographic areas. In addition to the National Human Activity Pattern Study (NHAPS) with information about residents from 48 states, there are studies targeting residents of Baltimore, Cincinnati, Denver, Los Angeles, Valdez, Washington DC, and the states of California and Michigan. Because the individual studies differed based on what information was collected, not all fields in the CHAD database are populated for all the records.

Each CHAD diary record consists of a 24-hour sequence of activities. Specified for each activity is a start time, end time, duration, one of 113 location codes, and one of 145 activity codes. Each diary record is tagged with a CHAD ID, which relates it to a record in the demographic database identifying information about the subject of the diary. Demographic fields include personal characteristics (age, gender, ethnicity, weight), social characteristics (education, occupation, income), residential location (state, county, zipcode) and housing characteristics (heating fuel, cooking fuel). In addition, CHAD has the capability to estimate

the relative metabolic rate for each activity in a record using random sampling from distributions derived from clinical studies.

- **EPA Exposure Factors Handbook.** The Exposure Factors Handbook provides a statistical summary of the available data on various parameters and variables used in assessing human exposure. This Handbook is used by risk assessors who need to obtain data on standard factors to calculate human exposure to toxic chemicals. These factors include human activity factors and residential characteristics. Recommended values are for the general population and also for various segments of the population who may have characteristics different from the general population. Included are full discussions of the issues that assessors may want to consider in deciding how to use these data and exposure parameter recommendations. (The Exposure Factors Handbook is in final form, but as new data become available updates will be posted).⁽⁴⁾
- **EPA Human Exposure Database System (HEDS).** HEDS is a web-enabled data repository for human exposure studies.⁽⁵⁾ Its mission is to provide data sets, documents, and metadata for human exposure studies that can be easily accessed and understood by a diverse set of users. HEDS provides only data and accompanying documentation from research studies; it does not provide interpretations. It allows a user to download documents for review or data sets for analysis on their own computer system. Currently contained in HEDS are various components of the National Human Exposure Assessment Survey (NHEXAS).
- **National Human Exposure Assessment Survey (NHEXAS).** The National Human Exposure Assessment Survey was developed by US EPA's Office of Research and Development (ORD) in the 1990's to provide information about multimedia and multipathway population exposure to chemicals of various types. Phase I consists of demonstration/scoping studies using probability-based sampling designs. Volunteer participants were randomly selected from several areas of the U.S. These studies included personal exposure, residential concentrations, and biomarker measurements. The Arizona study measured metals, pesticides, and VOCs. The Maryland study measured metals, pesticides, and polycyclic aromatic hydrocarbons (PAHs). The Region 5 study, conducted in Ohio, Michigan, Illinois, Indiana, Wisconsin, and Minnesota, measured metals and VOCs. Researchers worked with the participants to measure the level of chemicals in the air they breathed, in the foods and beverages they consumed (including drinking water), in the soil and dust around their homes, and in their blood and urine. Participants completed questionnaires to help identify possible sources of chemical exposure. Sample collection occurred between 1995 and 1997. The confidentiality of participants is strictly protected. Information about the studies can be found in the related study entries in EIMS and in the *Journal of Exposure Analysis and Environmental Epidemiology*.⁽⁶⁾
- **CDC National Health and Nutrition Examination Survey (NHANES).** NHANES is a survey conducted by the National Center for Health Statistics (NCHS), Centers for Disease Control and Prevention.⁽⁷⁾ This survey has been designed to collect information about the health and diet of people in the United States. NHANES is unique in that it combines a home interview with health tests that are done in a Mobile Examination Center. The current NHANES is eighth in a series of national examination studies conducted since 1960. The results of these surveys are compiled in databases and summarized in a variety of tables and reports. Data from direct examination, testing, and measurement of national samples of the

civilian noninstitutionalized population provide the basis for (1) estimates of medically-defined prevalence in the US and the distribution of the population with respect to physical, physiological, and psychological characteristics, and (2) analysis of relationships among various measurements without reference to an explicit finite universe of persons. Reports also present information about dietary patterns in various segments of the US population.

- **U.S. Census Data.** The U.S. Census provides data on the spatial distribution of population and population subgroups at several geographic levels: national, state, county, tract, block group and block. (For detailed analysis, Summary File 3 is most useful.) Examples of useful spatially-resolved data for exposure assessment include: population by age, gender, and ethnic group; house heating fuel use; estimated travel time to work by various modes of transportation; and levels of employment in various industries. Associated geographic data specifying boundaries of the various geographic entities for mapping are also available in Topologically Integrated Geographic Encoding and Referencing (TIGER) files.⁽⁸⁾
- **LandScan USA.** LandScan is a high resolution population distribution database for the continental U.S. currently under development, following the methodology used to create a similar global database called LandScan1998 (updated in 2000).⁽⁹⁾ LandScan uses satellite imagery in population distribution modeling to produce population distribution data at a much finer resolution than previously available. LandScan 1998 and 2000 have a grid cell size of 30 seconds (<1 kilometer) and use census data in combination with many other geospatial data, such as land use/cover, topography, slope, roads, and nighttime lights, in order to improve the estimation and prediction of the spatial distribution of residential populations. Future LandScan updates will use a much smaller grid cell size of 3 seconds (<100 meters). Currently, a pilot study in a 29 county area in southeast Texas (around Houston and Port Neches) is being conducted. LandScan will be very useful for exposure modeling, environmental justice studies, and other types of risk assessments.

11.3.4 Examples of Inhalation Exposure Models

Several exposure models have been or are being developed by EPA and others for a variety of purposes. Some of the important characteristics that vary among the models include:

- Ambient concentrations
 - Modeling or monitoring estimates
 - Time scales (e.g., averaging time)
- Exposure concentration time scale
 - Time increment for calculations (e.g., by minute, hourly, seasonally, annually)
 - Averaging time for reporting (e.g., hourly, annually)
- Spatial scale
 - Geographic resolution of predictions (e.g., Census tracts, Census blocks, grids)
 - Potential size of modeling domain (e.g., neighborhood, county, nation)
- Population activity data
 - Type (e.g., time in microenvironments, commuting locations, food and water ingestion rates)

- Temporal resolution (e.g., by minute, hourly, seasonally, annually)
 - Area specific resolution (e.g., national or regional)
 - Demographic resolution (e.g., by age, gender, or ethnic group)
- Framework
 - Deterministic: inputs and outputs are characterized as point estimates
 - Stochastic or probabilistic: inputs and outputs are characterized as distributions representing variability and/or uncertainty; Monte Carlo techniques are used to randomly select input values from the distributions for repeated simulations

The remainder of this section provides brief descriptions of some of the most recently developed inhalation exposure models. The features of each model described are summarized in Exhibit 11-6.

Exhibit 11-6. Comparison of Inhalation Exposure Model Features				
Model	Population Activity Data	Source of Ambient Concentrations	Spatial Resolution	Framework
HEM-3	none (screening model)	ISCST3	census blocks (additional points can be specified)	deterministic
HAPEM	micro-environment time/sequence, commuting	external model or monitoring data	census tract	stochastic
TRIM.Expo (a.k.a. APEX)	micro-environment time/sequence, commuting	external model or monitoring data	depends on resolution of air quality and demographic inputs	stochastic
CPIEM	micro-environment time/sequence, commuting	external model or monitoring data	user-specified for the selection of activity patterns (e.g., state, region)	stochastic

Human Exposure Model (HEM)

The Human Exposure Model (http://www.epa.gov/ttn/fera/human_hem.html) was designed to screen major stationary sources of air pollutant emissions efficiently, ranking the sources according to the potential cancer risks and noncancer hazard associated with long-term (annual) average exposure concentrations.⁽¹⁰⁾ The current version, Version 3 (HEM-3), is implemented on a Windows platform for ease of use. HEM-3 contains a version of the Gaussian atmospheric dispersion model ISCLT2 (with included meteorological data), and U.S. Census Bureau population data (2000) at the Census block level. A limited amount of source data are required as model inputs (e.g., pollutant emission rates, facility location, height of the emission release, stack gas exit velocity, stack diameter, temperature of the off-gases, pollutant properties, and source location). HEM-3 estimates the magnitude and distribution of ambient air concentrations of pollutant in the vicinity of each source. The model usually estimates these concentrations

within a radial distance of 50 kilometers (30.8 miles) from the source. Exposure concentrations for the residents of each Census block are assumed to be the outdoor concentration at the Census block “internal point.” This actually represents a surrogate for exposure, as important exposure variables (e.g., indoor-outdoor concentration differences, human mobility patterns, residential occupancy period, breathing rates) are not explicitly addressed. Multiple facilities (including clusters of facilities, each having multiple emission points) can be addressed by HEM-3. Variability and uncertainty in input data and parameters are not considered.

The Hazardous Air Pollutant Exposure Model (HAPEM5)

The latest version of EPA’s Hazardous Air Pollutant Exposure Model (HAPEM5) is a stochastic screening-level inhalation exposure model appropriate for assessing average long-term (annual) exposures of the general population, or a specific sub-population, over spatial scales ranging from urban to national (http://www.epa.gov/ttn/fera/human_hapem.html). This application requires a moderate level of computer modeling skills.

HAPEM5 uses the general approach of tracking representatives of specified demographic groups as they move among 37 indoor, in-vehicle, and outdoor microenvironments and among geographic locations. The estimated pollutant concentrations in each microenvironment visited are combined into a time-weighted average concentration, which is assigned to members of the demographic group (the cohorts). Microenvironment concentrations are estimated from outdoor concentrations with the factors method. HAPEM5 uses five primary sources of information: population data from the U.S. Census; population activity data from CHAD commuting data developed by the Bureau of the Census; user supplied air quality data either from measurements or an air dispersion model; and microenvironmental factors data.

The previous version of HAPEM5, namely HAPEM4, was used in the NATA national scale assessment of the 1996 NEI to develop estimates of risk, by census tract, for each of the 33 HAPs (<http://www.epa.gov/ttn/amtic/netamap.html>). Specifically, HAPEM4 was used to predict population exposure for each of 10 demographic groups in each tract.

Total Risk Integrated Methodology Exposure Event Model (TRIM.Expo_{Inhalation}), also known as Air Pollutants Exposure Model (APEX)

The Air Pollutants Exposure Model (APEX) comprises the inhalation portion of the TRIM exposure module, TRIM.Expo (http://www.epa.gov/ttn/fera/human_apex.html).^(b)

TRIM.Expo (a.k.a. APEX) uses a personal profile approach rather than a cohort simulation approach. That is, individuals are selected for simulation by selecting combinations of demographic characteristics and finding an activity pattern to match it, rather than directly selecting an activity pattern. If the selection probabilities for the demographic characteristics are the same as within the population to be simulated, this approach will provide a representative sample of that population’s activity patterns without the need for post-simulation weighting of results.

^bEPA has developed the Total Risk Integrated Methodology (TRIM) for use in the assessment of air pollutants (both hazardous and criteria). APEX comprises the inhalation exposure component of TRIM.

The current version (APEX3, available on the web) includes a number of useful features including automatic site selection from large (e.g., national) databases, a series of new output tables providing summary statistics, and a thoroughly reorganized method of describing microenvironments and their parameters. The model has the capability to estimate microenvironment concentration from the mass-balance method, but also provides the option of using the factors method. Most of the spatial and temporal constraints were removed or relaxed in APEX3. The model's spatial resolution is flexible enough to allow for the use of finely resolved modeled air quality values, as well as sparser measured values. Averaging times for exposure concentrations are equally flexible. Like HAPEM5, the user must supply the air quality data (from modeling or monitoring) to the model.

California Population Indoor Exposure Model (CPIEM)

The CPIEM⁽¹¹⁾ is a stochastic inhalation exposure model developed for the California Air Resources Board's (ARB's) Indoor Program to evaluate indoor exposures for the general California population as well as certain sub-populations. CPIEM combines indoor air concentration distributions with Californians' location and activity information to produce exposure and dose distributions for different types of indoor environments.

The temporal resolution and averaging time are user-selected from the options of 1-hour, 8-hour, 12-hour, and 24-hour. The spatial resolution and modeling domain similarly are specified by the user according to county, state region, or the entire state. Although outdoor concentrations may be included in the application, the focus is on indoor exposures and indoor emission sources. The model is implemented on a Windows-based platform for ease of use.

The model uses location/activity profiles that were collected in ARB studies. Microenvironment concentrations are derived from measurement studies for up to nine microenvironments. Concentration distributions from measurement studies for many pollutants and microenvironments are included in the CPIEM database. However, for pollutants and microenvironments not included in the database, the CPIEM presents two alternatives. The first is to estimate indoor air concentration distributions based on distributional information for mass balance parameters with a mass-balance module. The second is for the user to directly specify concentration distributions.

11.3.5 Exposure Modeling Examples

The following applications of air quality modeling and exposure modeling at real-world sites provide useful insights into air toxics modeling. The TRIM.Expo (a.k.a. APEX) inhalation exposure model has also been used with the ISCST3 air quality model to predict human inhalation exposures. A report documenting this aspect of the case study will be available at: http://www.epa.gov/ttn/fera/human_apex.html.

National-scale Air Toxics Assessment (NATA). EPA's NATA is designed to provide a comprehensive evaluation of air toxics exposure and risk across the U.S. Activities include expansion of air toxics monitoring, improving and periodically updating emission inventories, improving national- and local-scale modeling, continued research on health effects and exposures to both ambient and indoor air, and improvement of assessment tools. As noted previously, one component of NATA is a National Scale Assessment conducted with the ASPEN and the

HAPEM4 to estimate annual average exposure concentrations of the 33 urban air toxic pollutants in every US Census tract. Specific examples of the results of the National Scale Assessment and additional information on NATA activities can be found on-line.⁽¹²⁾

Houston Case Study. This study was carried out by EPA's Office of Air Quality Planning & Standards (OAQPS) and the Office of Transportation and Air Quality (OTAQ) as a component of the Integrated Urban Strategy.⁽¹³⁾ For the Houston metropolitan area, ISCST3 modeling was applied, using emissions data for point, non-point, and mobile sources from EPA's 1996 National Toxics Inventory. Ambient air concentrations for numerous air toxics were predicted at the census tract level with ISCST3 and HAPEM, which were then employed to obtain estimates of population exposures. Modeling results were compared to the results obtained through studies of this area carried out as part of the NATA National Scale Assessment. The study demonstrated that modeling using ISCST3 and an improved emissions inventory provides more realistic patterns and better agreement with monitoring data. In addition, elevated concentrations (hot spots) were found that were not detected in the national scale analysis.

11.4 Personal Monitoring

Thus far, we have focused on monitoring devices that generally are located in a secure compound (and sometimes on roof tops) that measure air quality that is representative of some specific geographic scale. An alternative to such an approach is to place monitors directly on individuals, which allows collection of more detailed information specific to the exposure pattern for that individual. Such monitors are referred to as **personal monitors** because they provide information on exposure to that individual, rather than to the general area in which an individual might be moving. An advantage is that personal monitors reflect the time-varying concentrations (unless they are integrating monitors) an individual experiences as he or she moves about through various activities. Personal monitors have seen increasing use in recent years due to two factors: they are more readily available, reliable, and cheaper than in the past, and there is growing evidence that personal exposures may at times be correlated poorly with average values derived for larger geographic areas (see Exhibit 11-7).

Two modes of personal monitoring have been developed. One relies on direct measurements of air concentration for toxics in the breathing zone or otherwise on/near the body of an individual (these are called direct measurement methods). The other relies on changes in biological properties such as blood level of an air toxic (or metabolite). The latter is not considered here because it does not strictly measure ambient air concentrations or estimate exposure. Personal monitors, as with area or fixed monitors described previously in this chapter, are available in two types:

- **Active monitors** use a small air pump to draw air through a filter, packed tube, or similar device. They can be both continuous and integrated. Such a personal exposure monitor is available to measure PM_{10} and $PM_{2.5}$ in air using a 37 mm Teflon filter and a 4 L/min flow rate. The pump and battery pack are worn in a bag, while the filter can be located essentially anywhere on the body. In addition, cyclone personal samplers are available for measuring particulates in air (the term "cyclone" refers to the fact that the sampler measures the particulates by "spinning" the particles in an air stream, which then collect on the sides of the device for collection and analysis). Combinations of impactor and denuder filter packs are

available to sample both aerosols and gases such as SO₂, NH₃, and HNO₃. Different coating materials on the diffuser tube can be used to collect different gases.

Exhibit 11-7. Examples of the Use of Personal Monitoring

- **Relationship of Indoor, Outdoor and Personal Air (RIOPA) study.**⁽¹⁴⁾ Indoor and outdoor concentrations of 30 polycyclic aromatic hydrocarbons (PAHs) were measured in 55 homes in Los Angeles, CA, Houston, TX, and Elizabeth, NJ. The study focused on areas in each city characterized by worst-case conditions in the outdoor air, generally located close to major sources. Integrating MSP samplers, polyurethane foam cartridges, and quartz fiber filters were used for the field sampling, and the samples were analyzed subsequently in the lab. Among many results, the study showed that indoor air was dominated by outdoor sources for these compounds, with reasonably strong correlations between the indoor and outdoor air concentrations.
- **National Human Exposure Assessment Survey (NHEXAS).**⁽¹⁵⁾ The NHEXAS program was designed to “describe the distribution of human exposure to multiple chemicals from multiple routes on a community and regional scale, and its association with environmental concentrations and personal activities.” It is being conducted in three stages: (1) design, field evaluation and demonstration projects; (2) exposure field studies; and (3) special studies to examine issues such as highly exposed populations and long-term exposures. Extensive statistical analyses of the data have been performed, including characterizations of background levels of exposure to selected chemicals, as well as correlations among environmental concentrations, individual exposures, biomarkers, and survey data on personal activities.
- **EPA’s Total Exposure Assessment Methodology (TEAM) studies**⁽¹⁶⁾ estimated exposures of about 800 persons to 25 VOCs; about 300 persons to 32 pesticides; and 1,200 persons to carbon monoxide. The general approach in all four of the main TEAM studies was the same: a probability-based selection of respondents, so that they would represent a much larger population (e.g., the 800 persons in the TEAM VOC studies actually represented about 800,000 persons in 8 cities); the use of personal monitors as well as outdoor monitors to estimate actual personal exposure; and the use of an Office of Management and Budget (OMB)-approved questionnaire and activity diary to try to pinpoint local sources. In two of the TEAM Studies for VOCs and carbon monoxide, an effort was made to measure body burden, by collecting a breath sample from each of the 2,000 persons involved. This was important in identifying active smoking as the main source of exposure to benzene and styrene, for example. Also, the breath measurements identified a “dirty dozen” pollutants that were prevalent in almost every person. The Centers for Disease Control later collected blood samples from 800 different persons and found essentially the same dozen pollutants prevalent in blood.

- **Passive monitors** rely on sorption, entrapment, etc., driven largely by diffusion. They are primarily integrated sampling devices, giving a estimate of average exposure over the sampling period. Examples include diffusion tubes, badges, and detector tubes. Diffusion badges currently are available for measurement of NO₂, O₃, SO₂, CO and formaldehyde. Organic vapors can be measured in passive devices using activated charcoal badges, although the range of compounds, aside from organics, that can be sampled in this way is small.

Reviews of such methods of personal sampling can be found in Bower et al. (1997).⁽¹⁷⁾ However, many of the same limitations as ambient methods exist, and in some cases additional quantitation limit and precision problems are present.

In general, air toxics risk assessments that rely on monitoring to characterize exposure will generally not rely on personal monitoring because of the highly complex and resource intensive nature of this technique, and because personal monitoring and its findings are currently more geared toward basic research.

11.5 Exposure to a Population: Common Descriptors

There are a wide variety of ways to describe exposure to a population, some of which may be legally required, others which may be chosen based on the requirements of the risk manager. No matter what specific measure is chosen, the risk assessment needs a clear and scientifically supportable rationale for the approach taken; risk assessors generally describe that approach clearly and thoroughly in the exposure assessment portion of the risk assessment documentation. Risk assessors aim for there to be no ambiguity about what was done in the exposure assessment.

EPA policy and guidance recommend that exposure to a population be described using several different ways to give the risk manager a sense of the range and magnitude of the exposures. For example, a “high end” exposure estimate might describe the exposure experienced by actual people in the most highly concentrated part of the area of impact, while a “central tendency” exposure estimate might describe the exposure experienced by people in the study area who experience more modest concentrations.

A variety of statistical values are used to describe high-end and central tendency exposures, including 95th percentile exposures (for high-end) and 50th percentile values for central tendency. Risk assessors will want to obtain and become familiar with EPA’s *Risk Characterization Handbook* to better understand various ways exposure and risk can be adequately characterized.⁽¹⁸⁾ EPA’s *Guidelines for Exposure Assessment*⁽¹⁹⁾ is also invaluable in this regard. Some of the alternative approaches for characterizing air toxics exposures are illustrated in Exhibit 11-2 above.

11.6 Evaluating Uncertainty

Uncertainty includes the assumptions and unknown factors inherent in the exposure assessment. Discussing uncertainty places the risk estimates in proper perspective. Specific uncertainties associated with the chemical monitoring data, fate and transport models, and the input data (especially emissions inventory data) that assessors use to estimate exposure concentrations usually account for the bulk of uncertainty within the assessment. Exposure models also contribute to the overall uncertainty in exposure assessment. The assessor needs to understand the extent to which variability and uncertainty are considered in all the fate and transport and exposure models that are used. HAPEM and other exposure models can accept input data on the distributions of time spent in different micro-environments and produce time-average exposure estimates for defined populations.

The assessor should be familiar with the extent to which the various components of the exposure assessment can and do accommodate uncertainty and variability analyses. In addition, it is important to consider the compatibility of models in the various steps in the exposure assessment (emissions, transport, etc.) with regard to addressing important sources of uncertainty. Once the capabilities and data requirements of the various models are known, the assessor should consider

the appropriate level of detail for addressing uncertainty in specific variables, and approaches for integrating uncertainty analyses across the models.

11.7 Presenting the Results of an Exposure Assessment

The summary of exposure assessment for air toxics consists of presenting the ECs for each chemical of potential concern (COPC) with the duration of exposure for the populations of interest, as well as characterizing salient features of the study population(s), particularly those that may be influencing their exposure and resultant risk (e.g., size and proximity to sources and/or locations of highest ambient concentrations). The assumptions used to develop these estimates should also be presented and discussed. In addition to the summary tables, it is useful to show sample calculations for each pathway to aid in the review of the calculations. (If exposure modeling is used, a thorough discussion with sample calculations is usually also provided.)

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