International Journal of Toxicology, 25:95–107, 2006

ISSN: 1091-5818 print / 1092-874X online
DOI: 10.1080/10915810600605724

Modeling Aggregate Exposures to Glycol Ethers from Use of Commercial Floor Products

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Computer modeling of aggregate exposure provides the capability to estimate the range of doses that can occur from product use and to understand the relative importance of different routes of exposure. This paper presents an assessment of aggregate occupational exposure to two glycol ethers used as solvents in floor maintenance products for industrial and institutional facilities, using a simulation tool named PROMISE. Three commercial floor-care products were assumed to be applied in sequence—a floor stripper, then a floor cleaner, and lastly a protective coating. The glycol ethers modeled were ethylene glycol butyl ether (EGBE) in the floor stripper and in the floor cleaner, and dipropylene glycol methyl ether (DPGME) in the coating. Modeling uncertainty was assessed through a comparison of the PROMISE inhalation exposure estimates with those from an independent model (MCCEM), and parameter uncertainty was investigated using PROMISE software's Monte Carlo simulation capabilities. Modeling results indicated that inhalation is the dominant exposure route. The predicted average air concentration and inhalation dose from PROMISE agreed with the second model (MCCEM) within 10%. Monte Carlo simulation indicated that the upper end of the aggregate-dose distribution for the scenario was more than 50% higher than the value of the point estimate. The modeled 8-h TWA concentrations for EGBE and DPGME were lower than the corresponding permissible exposure limits American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLV) by at least a factor of 20, indicating that under the assumed conditions workplace exposures to glycol ethers are below levels of concern.

Keywords Dose, Exposure, Floor Products, Glycol Ethers, Modeling, Multiroute

Glycol ethers are a group of solvents that, alone or in combination, are used as carriers or active components in a wide range of products (Chinn, Anderson, and Yoneyama 2000). These solvents have different toxicological activity that has been extensively summarized in a number of recent reviews for both the category as a whole and the specific chemicals considered in this paper, ethylene glycol monobutyl ether (EGBE; CAS no. 111-76-2) and dipropylene glycol monomethyl ether (DPGME; CAS no. 34590-94-8) (Boatman and Knaak 2001; Cragg and Boatman 2001; ECETOC 2005).

Risk assessments for applications using these chemicals must take into consideration not only the potential for producing adverse health effects but also the potential to cause exposure by multiple routes (i.e., via inhalation, dermal contact, or hand-to-mouth ingestion). The possibility of multiroute exposure makes the evaluation of the total (i.e., aggregate) exposure essential for the assessment of potential health risks. Monitoring strategies often are limited to one route of exposure (such as inhalation or dermal) and, thus, do not address the issue of risks associated with multiroute exposure.

Computer modeling is an especially useful tool for assessing solvent exposures because the total dose from multiple routes can be determined, as well as the route(s) primarily responsible

Received 26 September 2005; accepted 2 December 2005.

This work was funded by the Ethylene and Propylene Glycol Ether Panel of the American Chemistry Council (see www.pgep.org and www.egep.org for a list of sponsoring corporations). We also wish to thank Dr. David McCready for calculation of mass transfer coefficients.

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for the aggregate exposure. Because models may have errors in structure or programming and frequently require the use of untested assumptions, a comparative assessment of modeling uncertainty is an important part of model application (Hertwich, McKone, and Pease 2000). Uncertainty can be evaluated by comparing results from alternative models to determine how robust the model predictions are with respect to variation in model design. The extent of variability in model predictions that occurs from parameter uncertainty can be assessed through probabilistic approaches such as Monte Carlo simulation (Burmaster 1996; Findley and Paustenbach 1994), whereby key inputs are varied about their central values to obtain a distribution of estimates rather than a point estimate of total/aggregate exposure.

This paper presents an assessment of aggregate occupational exposure to two glycol ethers used as solvents in floor maintenance products for industrial and institutional facilities. The assessment uses a simulation model—PROMISE (Probabilistic Methodology for Improving Scenario-Driven Exposure Assessment)—that models solvent exposures occurring during use of solvent-containing consumer and commercial products. PROMISE determines the absorbed dose received by the worker from three routes of exposure: (1) inhalation of solvent vapor released from the product during and following application; (2) dermal contact with the product; and (3) incidental ingestion of the product. As part of this assessment, PROMISE predicts time-varying airborne concentrations of chemicals during and after product use. A downloadable version of the PROMISE model along with full documentation is available from the American Chemistry Council at www.americanchemistry.com.

The primary goal of this paper is to demonstrate the utility of exposure models to characterize occupational exposures to solvents resulting from sequential use of commercial cleaning products. The scenario was constructed as a reasonable example of an upper-end exposure to a worker using institutional cleaning products containing glycol ether solvents. The goal can be achieved by (1) using the model to assess the product-use scenario and to produce an estimate of the aggregate dose for the worker; (2) comparing the results of the PROMISE prediction of air concentrations to those from a second model, the Multi-Chamber Concentration and Exposure Model (MCCEM) (Nagda and Koontz 1991); and (3) examining the uncertainty in this estimate as a result of variation in selected model inputs. Full documentation of MCCEM including the equations used to estimate evaporation of volatile chemicals from a film can be found on line under the embedded "help tab" of MCCEM. The model itself is downloadable from the U.S. Environmental Protection Agency (USEPA), Office of Pollution Prevention and Toxics (OPPT) web site: http://www.epa.gov/oppt/exposure/docs/updates_mccem_v1.2.htm.

OVERVIEW OF THE PROMISE MODEL

PROMISE models exposure to one or more solvents as a series of mass transfers between "compartments." These compartments are defined as follows:

- The volume of the liquid phase of the solvent containing product(s) used in an application;
- The air volume of the room/location where the product is applied;
- An external compartment of infinite size (essentially ambient air) that receives air from the application room/location and provides make-up air for the room;
- The volume and mass of the product that reaches the worker's skin (applied dose);
- The volume of the worker's lungs; and
- The volume of the worker's body.

The movement of the solvent among these compartments is based on user inputs describing the properties of the solvent and the product containing the solvent, the amount of product applied, and the characteristics of the room/location where the product is used. The processes that drive the movement of the solvent are modeled using thermodynamic models along with models developed by Jayjock (1994) and described in the technical documentation for the ConsExpo model (Van Veen 1996). PROMISE includes a series of equations describing the rate of movement of the solvents and the volume of each compartment (selected equations are presented below). The types of inputs required to model multi-route exposure in PROMISE are summarized in Table 1.

The evaporation of the solvent from a product is modeled based on the properties of the solvent(s) in the product, other components of the product, and Roult's law. The software can model products containing up to four components. The model tracks the mass of the applied product and how it changes as a function of the evaporation of the solvent(s) of interest, the presence of other components in the product, or by the reaction (or irreversible absorption) with a surface. The evaporation rate is driven by (1) the difference between the vapor pressure of the solvent in the mixture and the concentration in the room, and (2) by mass-transfer coefficients. PROMISE allows a default method of estimating the mass-transfer coefficient using the procedure of Jayjock (1994) or the ability to enter a specific value as was done in this study. The airborne concentration of each solvent then is predicted based on the evaporation rate, the volume of the room where the product is applied, and the air exchange rate between the room and outdoors (see Figure 1). The mathematical equations used to estimate the evaporation rate are described in Appendix 1.

For estimation of exposure via inhalation, the model assumes that a fraction of the inhaled chemical mass is absorbed, according to the following equation:

$$U = T \times Q \times C \times A \times R \quad [1]$$

where

U is the uptake or absorbed mass of the chemical (mg);
T is the time (min) the individual is breathing the vapor;

TABLE 1
PROMISE input requirements for multiroute exposure assessment

Air concentrations
- Room volume, m^3
- Ventilation rate, 1/h
- Application start/stop times, min
- Area application rate, cm^2/min
- Applied solution thickness, cm
- Temperature, °C
- Initial room-air concentration per compound
- Outside air concentration per compound
- Solution density, g/cm^3
- Weight fraction in solution per compound
- Molecular weight per compound
- Vapor pressure per compound
- Mass transfer coefficient per compound, cm/min
- Immobilization rate constant per compound, 1/min

Inhalation of vapors
- Inhalation uptake, respirable fraction
- Contact time, min
- Inhalation rate, ml/min
- Inhalation uptake absorbed fraction

Dermal contact
- Product amount, g
- Weight fraction for compound of concern
- Product volume, ml
- Contact volume of product, ml
- Dermal absorbed fraction

Ingestion
- Ingestion absorbed fraction
- Number of swallows per event
- Product amount ingested per swallow, g
- Compound concentration in product, mg/g

Q is the inhalation rate (ml/min);
C is the room-air concentration (mg/ml) of the chemical;
A is the absorbed fraction; and
R is the respirable fraction.

PROMISE provides several alternative algorithms/models for dermal contact. The algorithm used here is based on fixed-volume exposure and fractional uptake, as follows:

$$U = M \times C \times F \times D \quad [2]$$

where

U is the uptake of the chemical (mg);
M is the product mass applied (mg);
C is the chemical weight fraction in the product (mg/mg);
F is the product contact volume relative to applied product volume (ml/ml); and
D is the dermal absorbed fraction.

Incidental ingestion of the chemical of concern is estimated by the model according to the following equation:

$$U = M \times N \times F \times A \quad [3]$$

where

U is the uptake of the chemical (mg);
M is the product mass ingested per swallow (mg);

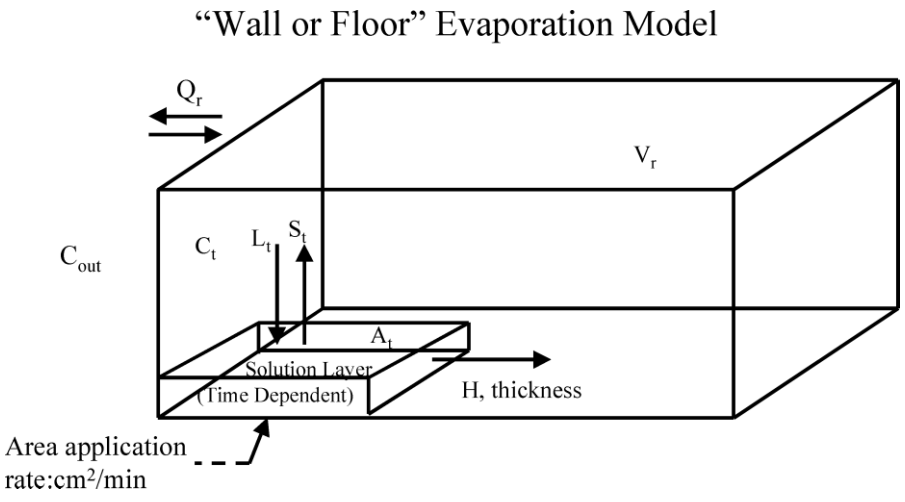


FIGURE 1
PROMISE evaporation model for prediction of airborne concentrations. C(t) = chemical concentration in room air; $M_{soln,net}(t)$ = mass in solution = A(t) × H × D_{soln}; S(t) = evaporation rate from solution (source to air); L(t) = condensation rate from vapor (loss from air); V_r = room volume; Q_r = ventilation rate; C_{out} = chemical concentration in outside air; A(t) = net liquid area (applied − evaporation); t = time.

N is the number times during the exposure period that the chemical of mass M enters the mouth, i.e., is swallowed;
F is the chemical weight fraction in the product (mg/mg); and
A is the absorbed fraction.

The incidental ingestion equation makes no assumptions regarding the anatomical differences in tissue structure that may have different absorptive characteristics.

MODELING APPROACH

Exposure Scenario

When assessing exposures from a product, it is important to first develop an exposure scenario that defines the products used, the environment where the products are used, the interaction of the worker with the products (i.e., the product applications), and the characteristics of the worker. The scenario used in this paper is selected as an example of a common task involving the use of large volumes of multiple products that contain the solvent(s) of interest. Floor-care products typically are used in combination (e.g., products that clean a floor and products that replace the finish). Glycol ethers are used in both types of products. The amount of product used will be a function of the floor area treated. Therefore, the selected scenario is an 8-h exposure that results from application of multiple floor-care products on the floor of a relatively large commercial establishment.

In this scenario, three commercial floor-care products are applied sequentially—a floor stripper, followed by a floor cleaner, and lastly a protective coating. Table 2 summarizes the respective compositions of these products. The solvents modeled are EGBE, in both the floor stripper and the floor cleaner, and DPGME in the protective coating. The stripper and the cleaner were diluted with water 1:4 and 1:256, respectively, whereas the floor finish (protective coating) was not diluted. The weight fraction of EGBE in the applied (diluted) product was considerably higher for the stripper than for the cleaner, reflecting the much lower dilution in the stripper.

The user of the product was assumed to be an adult male. The environment in which the product was applied is assumed to be a large room with a volume of 2834 m^3 (100,000 ft^3), a floor surface area to be treated of 929 m^2 (10,000 ft^2), and an air exchange rate with the outdoors of one air change per hour (ACH). Outdoor-air requirements for buildings have been developed by American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 1989) based on either the number of occupants per building. For office buildings, the 1989 requirement is 15 ft^3/min (25.5 m^3/h) per occupant. Assuming 100 occupants, a building of 5000 m^3 (Robinson and Wiley 1989) yields a requirement for mechanical ventilation of approximately 0.5 ACH. This rate, when added to an air-infiltration component (0.5 ACH), assumed to be similar to residences, see, for example, Koontz and Rector 1995, results in an estimated ACH of 1/h. This estimate is close to the median value of 0.89 ACH reported by Persily (1989), based on measurements of air exchange rates in 14 office buildings.

A structure of these dimensions would correspond to commercial establishment such as a large supermarket, warehouse, or store. It is likely that the ventilation rates in a large commercial structures could be greater than 1 per hour, typical for residential housing; however, this value was used as a conservative estimate as higher ventilation rates would tend to lower air concentrations and decrease exposure.

All activities were assumed to occur on the same day. A crew of workers arrived at the beginning of an 8-h workday and conducted the following activities:

1. Application of stripper (80 min)
2. Application of cleaner and cleaning of floor (66 min)
3. Application of new coating (36 min)
4. Other activities in the room (no additional use of products containing glycol ethers).

Each member of the crew was responsible for a portion of the floor, approximately 100 m^2 (≈1076 ft^2).

Floor strippers are designed to loosen existing floor finishes; to work properly, the stripper and the existing finish must be removed before the stripper evaporates. As a result, stripping the finish from a large floor area was performed as a series of separate stripping tasks. Each task, in turn, consists of (1) application of a stripper, (2) a waiting period during which the solution remains on the floor to soften and loosen the existing floor finish, and (3) removal of the old finish and stripping solution. The size of an area to be stripped was determined by the rate at which the solution dried. Therefore, for this scenario the floor area for each worker was divided into eight smaller areas. The product application for each subarea was modeled as a 5-min period for applying the product followed by 5 min for the stripping solution to soften the finish and 5 min for removal (i.e., a total of 15-min exposure time). This separation of the process into a series of separate events was not required for the other two floor care products, each of which is assumed to be applied in a continuous manner.

Each worker was assumed to wear gloves when dealing with the concentrated products but not when applying or removing the diluted products. Values for the specific model input values and rational for these values are found in Table 3.

TABLE 2
Product composition (by volume)*

Product	EGBE	DPGME	Other ingredients	Water
Floor stripper	5.0%		5.0%	90.0%
Floor cleaner	0.1%		0.2%	99.7%
Floor finish		5.0%	21.0%	74.0%

*Information supplied by manufacturer of floor-cleaning products.

TABLE 3
Specific input values and rationale for modeling institutional floor care scenario

Model input	Values	Reference
Building values		
Room of use volume	2834 m^3	Typical of a large room of a commercial establishment (≈10,000 ft^2 floor space)
Room of use air exchange rate	1 $hour^{-1}$	ASHRAE, 1989 (also see text)
Total floor surface treated	929 m^2	Typical of a large room of a commercial establishment (≈10,000 ft^2 floor space)
Period of application		
Floor stripper	8 sectors ×10 min/sector = 80 min	ISSA 1999
Floor mopping	66 min	ISSA 1999
Floor refinishing	36 min	ISSA 1999
Total exposure period	8 h	Shift length
Chemical specific values (EGBE)		
Molecular weight	118.17	Boatman and Knaak 2001
Specific gravity	0.898 (25°C)	Boatman and Knaak 2001
Vapor pressure	0.88 torr (25°C)	Boatman and Knaak 2001
Chemical specific values (DPGME)		
Molecular weight	148.2	Cragg and Boatman 2001
Specific gravity	0.95 (25°C)	Cragg and Boatman 2001
Vapor pressure	0.41 (25°C)	Cragg and Boatman 2001
Product-specific floor stripper		
Concentration EGBE	5% (aqueous solution)	Based on information from manufacturer
Quantity used (after dilution)	78,900 g	Based on information from manufacturer
Floor cleaner		
Concentration EGBE	0.1%	Based on information from manufacturer
Quantity used (after dilution)	20,200 g	Based on information from manufacturer
Protective coating		
Concentration DPGME	5%	Based on information from manufacturer
Quantity used	15,100 g	Based on information from manufacturer
Physiological factors		
Body weight	71.6 kg	USEPA 1997
Inhalation rate	1 m^3/h	USEPA 1997
Pulmonary absorption	60%	Johanson 1986

Table 4 gives the values for the volumes and mass of the products that are applied and the thickness of the applied products (applied volume divided by floor surface area) to the establishment floor as a whole. The product thickness is about a factor of 4 higher for the stripper than for the cleaner or coating.

TABLE 4
Product application characteristics*

Product	Applied volume (cm^3)	Applied mass (g)	Film thickness (cm)
Floor stripper	78,900	78,900	0.0085
Floor cleaner	20,200	20,200	0.0022
Floor finish	15,100	15,100	0.0016

*Information supplied by manufacturer of floor-cleaning products.

The application rate, in cm^3/min or g/min, is determined by dividing the applied volume/mass by the corresponding duration of application indicated above.

Model Inputs

The types of inputs needed to model multiroute exposure with PROMISE are listed in Table 1. The exposure-scenario description given above supplies the values for a number of the inputs for modeling room-air concentrations—room volume, ventilation or air exchange rate, application start/stop times, application rate, and applied solution thickness. The solution density for each product is assumed to be 1 g/cm^3. The weight fractions of the modeled product constituents are constrained to add to unity. A room-air temperature of 22°C is assumed, and the outdoor-air and initial indoor-air concentrations are assumed to

be 0 for each compound. The mass-transfer coefficients for the modeled constituents are estimated using a method described by Sparks et al. (1996); in a review of alternative methods for estimating mass-transfer coefficients, McCready and Fontaine (2003) recommend this method over others because "it is based on experimental data simulating evaporation inside a room." No sinks are assumed to be present in the room.

For modeling of inhalation to vapor (see Equation 1 in the model overview), the inhalation uptake fraction for each worker is assumed to be 0.6 (Johanson 1986). The modeled time during which the individuals are breathing the vapor is 480 min (8 h) and the assumed inhalation rate was 16,700 ml/min (1 m^3/h). This inhalation rate is believed to be representative of light to moderate activities (USEPA 1997) and the duration time that of an 8-h work shift. The model calculates time-varying air concentrations (mg/ml) for up to four solvents but estimates inhalation dose (mg) only for the compound of concern—in this case, EGBE in the floor stripper and cleaner, and DPGME in the protective coating.

The algorithm used for dermal contact exposure (see Equation 2 in the model overview) is based on fixed-volume exposure and fractional uptake. The uptake is a function of the product mass applied, the chemical weight fraction, the product contact volume relative to applied volume, and the dermal absorption fraction (D). D was estimated using the following equation:

$$D = (FR \times PC \times CT \times HA)/(PC \times HA \times FT) \qquad [4]$$

where

FR is the permeability coefficient (cm/h);
PC is the product concentration (mg/cm^3);
CT is the contact time (h);
HA is the hand area (cm^2); and
FT is the film thickness on the hand (cm).

Equation 4 reduces to (FR × CT)/FT. A skin permeability constant of 0.0002 cm/h (flux rate 0.2 mg/cm^2/ h) (Dugard et al. 1984) and a film thickness of 0.002 cm (Versar, Inc. 1992) are assumed. The flux value reported by Dugard et al. appears to fall within the range anticipated by the structure, and physical and chemical properties, for other glycol ethers studied by this group, and also within the range of values obtained in similar in vitro studies with propylene glycol ethers conducted by Venier et al. (2004). It also appears to be a conservative estimate, bias toward greater penetration of EGBE through skin, based on the much lower values of flux rate for human skin obtained by Wilkinson and Williams (2002) of 0.064 mg/cm^2/h and that calculated form the in vitro studies of Bartnik and coworkers (1987) of 0.0173 mg/cm^2/h. The contact time is assumed to be the duration of product application; 1.33 h for the stripper, 1.1 h for the cleaner, and 0.6 h for the protective coating, resulting in dermal absorption fraction values of 0.13, 0.11, and 0.06 for the respective products. The dermal uptake dose is estimated by assuming that the worker's hands are wet with each product (as applied) during the entire time the product is used. A surface area of 1000 cm^2 is assumed for the hands, corresponding to a central (median) value for adult males (USEPA 1997). A contact volume of 2 ml was assumed for each product.

For modeling the incidental ingestion of the chemical of concern (see Equation 3 in the model overview), a nominal amount (0.05 g) of each product is assumed to be swallowed during each use. We are not aware of any data that provide specific data on hand to mouth transfer of liquids in hard surface cleaning operations. The value is based on USEPA (1997) data for incidental soil ingestion in adults and is believed to be a conservative estimate of the amount of product that could be ingested from incidental hand-to-mouth contact. An absorbed fraction of 100% is assumed for the incidental ingestion.

Model Consistency

PROMISE outputs relating to inhalation exposure were compared with those from MCCEM, which also can model time-varying air concentrations and inhalation exposure for one chemical in as many as four zones (chambers) of a building. MCCEM, available to the public at http://www.epa.gov/opptintr/exposure/docs/mccem.htm, was developed in the late 1980s for estimating inhalation exposure that can occur during use of various consumer products. The development of MCCEM was funded by the USEPA, and the software has undergone peer-review and model-evaluation exercises (see, for example, Koontz et al. 1992).

Unlike the PROMISE model, MCCEM requires repeated runs to model multiple chemicals and, thus, does not consider their interactions (e.g., in terms of their respective vapor pressures). MCCEM includes several empirical models for time-varying emission rates of chemicals released from consumer products. The appropriate source model in this case, called the "incremental model," treats continuous application of a product as a contiguous series of instantaneous applications, or application "strips." The model assumes a constant application rate over time, coupled with an emission rate for each instantaneously applied segment (or "strip") that declines exponentially over time. A mathematical expression (Evans 1994) has been developed for the total emission rate resulting from the combination of continuous application and exponentially declining emission rate. The rate of decline in the emission rate is based on an empirical algorithm for the evaporation time of a "pure film" as a function of the molecular weight and vapor pressure for the modeled chemical.

Parameter Uncertainty Assessment

The purpose of this assessment was to examine the variation in dose received by the defined worker during regular use of the floor-care products described above. The capability of PROMISE to perform Monte Carlo simulation was used to

investigate the variation in daily exposure/dose that would occur on a single workday as a result of differences in various factors relating to the product application and the conditions under which it occurred. Values for parameter distributions, controlled by the user, are assumed by the model to be independent.

The parameter uncertainty analysis is best understood as the range in predicted doses associated with the uncertainty in values of certain input varables (parameters) related to the product application, the individual, and the surrounding environment. These uncertainties in values arise from either lack of information (such as the amount of product ingested) or variation (worker body weight). Three factors relating to product application and the surrounding environment also were varied. The amount of product applied was varied by supplying a distribution for applied solution thickness; the indoor temperature and air exchange rate also were varied. The inhalation rate was varied for inhalation exposure, the contact volume and dermal absorbed fraction were varied for dermal contact, and the amount swallowed was varied for exposure via ingestion. The nature of the exposure scenario and the manner in which PROMISE inputs are supplied imposed some constraints on the factors that could be varied for this exercise. For example, the product constituents are constrained to add to unity, and varying any of these components would violate this constraint. The model also treats the room volume and area of product application as constants.

The parameter distributions applied for the Monte Carlo simulation are summarized in Table 5. Most inputs were varied using a triangular distribution because the limited information prohibited the calculation of a standard deviation, necessary input for a normal distribution. A normal distribution was assumed in the two cases where adequate information was available to calculate a standard deviation. The inputs from the original (point estimate) simulation were used as the mode for the triangular distribution or the mean for the normal distribution. The ventilation rate, contact volume (for dermal exposure), the dermal absorbed fraction, and the amount swallowed were varied by a factor of 4 in either direction from the mode, as these were considered the inputs with the greatest uncertainty. The inhalation rate was varied by 0.5 m/h in either direction from the mode to capture the range of breathing rates for light to heavy work (USEPA 1997). The room temperature was varied with a normal distribution so as to provide a nominal range from 17°C to 27°C. The applied solution thickness was assigned a standard deviation equal to 25% of the mean (the mean thickness for floor finish is shown in Table 5).

Modeling the Use of Floor Stripper

Modeling of the floor stripper required consideration of the method of use described above (application, loosening, and removal). At the end of each stripping event, mopping of the stripper and old finish greatly reduced the amount of stripping solution (and glycol ether) on the floor and, thus, reducing the rate of evaporation of the glycol ether.

In this scenario the floor area was divided into eight subareas, and the product application was modeled as a 5-min process for each of these subareas, with the inhalation exposure truncated 10 min after the application was completed (i.e., total of 15-min exposure time). A separate model run was performed to model the exposure to the glycol ether in the residual left after mop up. As a conservative approach, 10% of the applied product was assumed to remain (accomplished in the model by resetting the film thickness to 1/10th of its original value). The residual product was allowed to emit for the remainder of the total application time (i.e., for the last 65 of the total 80 min). At an elapsed time of 80 min, the floor-cleaning product was assumed to remove any remaining glycol ether from the stripper.

The resulting uptake estimates for one modeled subarea were multiplied by 8 (i.e., to account for eight subareas) to obtain a total uptake estimate for the stripper application. This approach will result in overestimation of exposure, for two reasons: (1) the residual product after mopping, for successive areas after the first, will remain for less than 65 min before the floor cleaning begins; and (2) nonzero air concentrations following the first stripping application will result in some suppression of emissions when the next subarea is stripped, and so on.

TABLE 5
Parameter distributions for Monte Carlo simulation

	Triangular distribution			Normal distribution	
Parameter	Minimum	Mode	Maximum	Mean	*SD*
Ventilation rate, 1/h	0.25	1.0	4.0		
Applied solution thickness, cm				0.0016	0.0004
Temperature, °C				22.0	2.5
Inhalation rate, ml/min	8,300	16,700	25,000		
Contact volume, ml	0.25	2.0	8.0		
Dermal absorbed fraction	0.015	0.06	0.24		
Amount swallowed, g	0.0125	0.05	0.2		

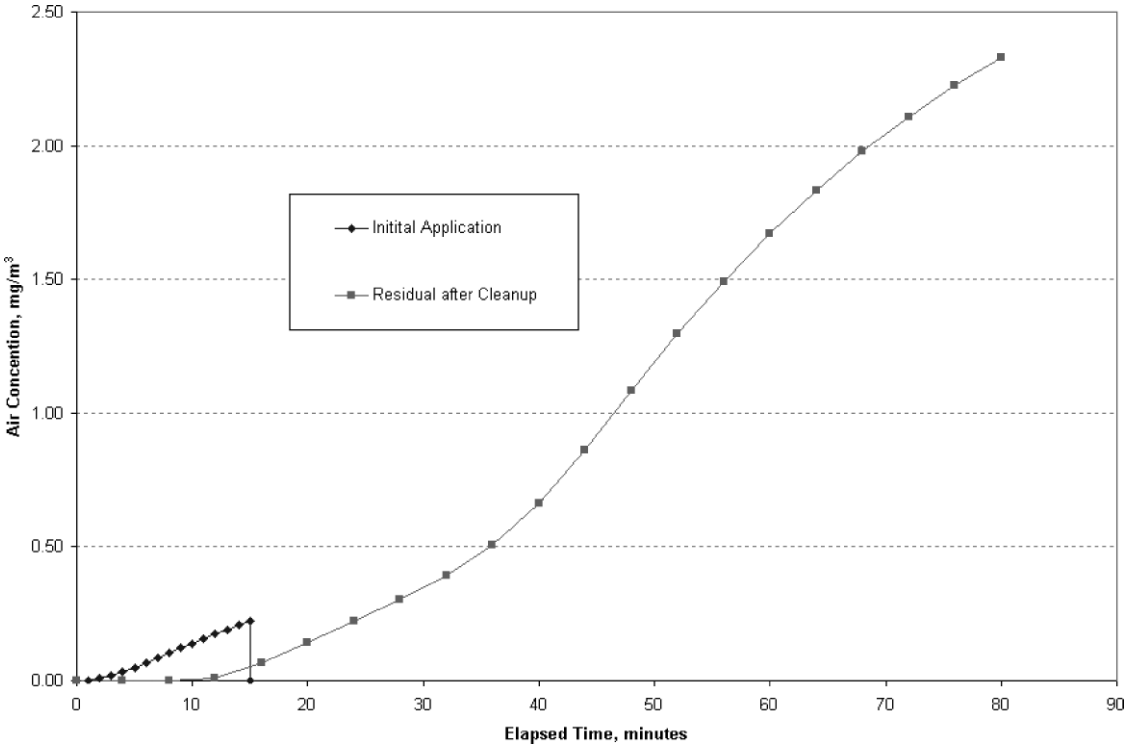


FIGURE 2
Modeled EGBE air concentrations for the stripper application.

RESULTS

Air Concentrations

Figure 2 shows the modeled time-varying concentration in air of EGBE for the two emission components of one subarea for the floor stripper—initial application and residual after cleanup. The residual component essentially begins as the first component is truncated. The peak modeled air concentration, which occurs during the period of residual emissions, was about 2.5 mg/m^3. The peak concentration actually was not yet reached at the end of the 80-min stripper period, but the concentration profile beyond that point would be altered by subsequent application of the floor cleaner.

Figure 3 depicts the modeled time-varying concentrations in air for EGBE emitted from the floor cleaner and DPGME emitted from the floor finish. Even though the cleaner was applied before the finish, the peak concentration of EGBE lagged behind that for DPGME due to the effects of the differing product compositions. Different scales are used on the Y-axis for the two plots in the figure. The peak concentration for EGBE (<1 mg/m^3, see upper plot) was even lower than that for the stripper application with truncated emissions, due the much higher dilution factor in the applied solution. For DPGME the peak concentration was considerably higher (about 75 mg/m^3, see lower plot). The emissions for the cleaner could have been truncated in the model once the finish application was started, but the difference was inconsequential given the relatively low EGBE concentration in the cleaner.

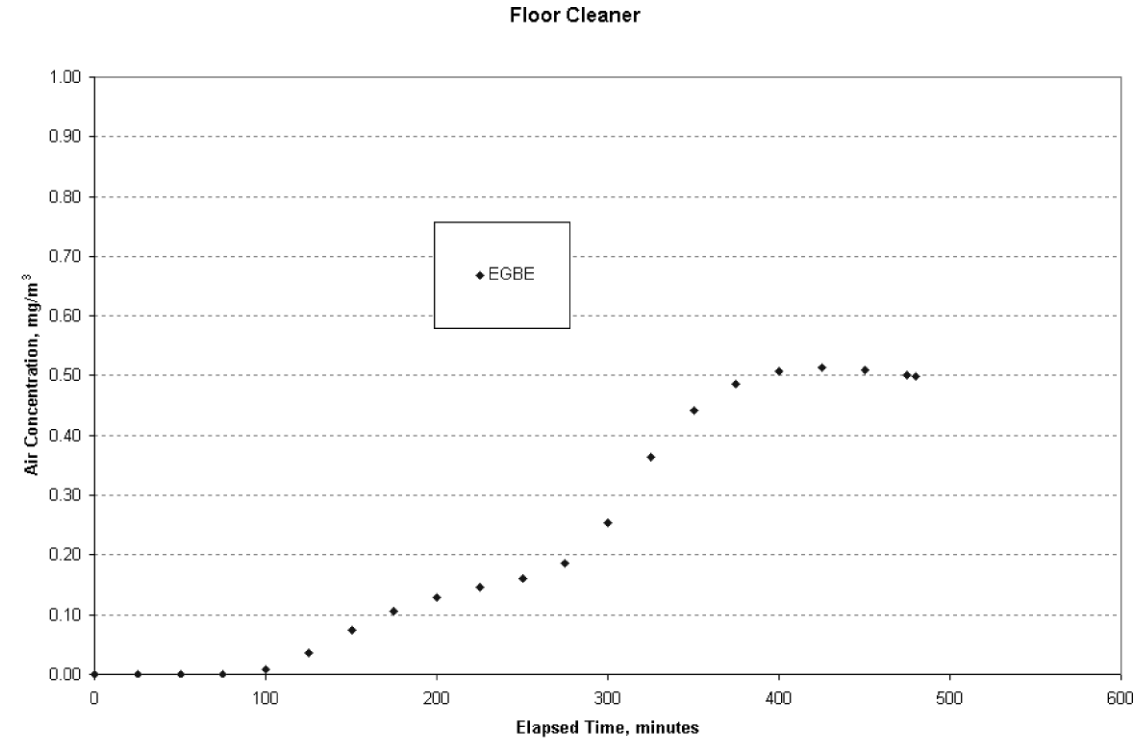
The modeled 8-h TWA air concentrations were 1.2 mg/m^3 (0.25 ppm) for EGBE from the stripper, 0.2 mg/m^3 (0.04 ppm) for EGBE from the cleaner, and 30.1 mg/m^3 (8.2 ppm) for DPGME from the finish. The time weighted average (TWA) concentrations of EGBE for the stripper and cleaner applications could be summed, but the summation made little difference as the total was dominated by the stripper application.

Route-Specific Contributions to Worker's Total Dose

The modeling results are summarized in Table 6 in terms of the worker's absorbed dose by exposure route for each product. Inhalation tended to be the dominant route, accounting more

TABLE 6
Modeled absorbed dose by route for three product applications

		Absorbed dose by route, mg			
Product	Compound	Inhalation	Dermal	Ingestion	Total
Floor stripper	EGBE	5.9	6.7	2.5	15.1
Floor cleaner	EGBE	1.8	0.2	0.1	2.1
Floor finish	DPGME	240.6	6.0	2.5	249.1



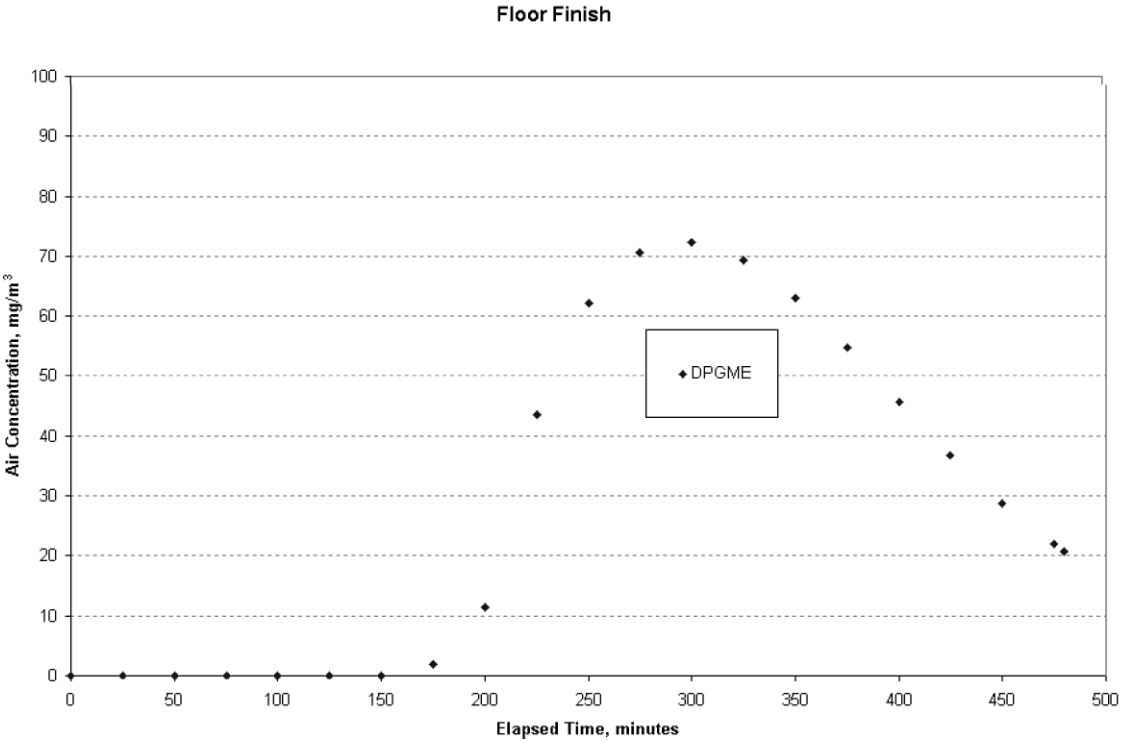


FIGURE 3
Modeled air concentrations for the cleaner and finish applications.

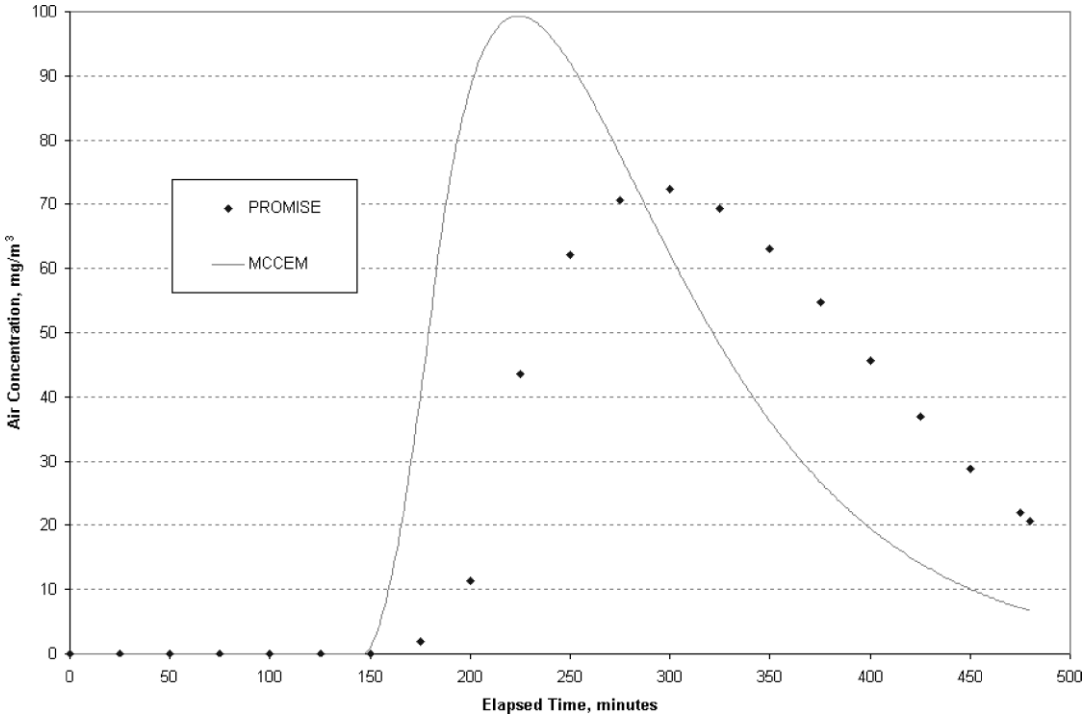


FIGURE 4
DPGME air concentrations modeled by PROMISE and MCCEM.

than 95% of the DPGME dose for the floor-finish application and more than 85% of the EGBE dose for the floor-cleaner application (for the stripper application inhalation accounts for 39% of the dose). The relative contributions were sensitive, in particular, to the assumptions made for the dermal and ingestion routes. If, for example, the assumed product-contact volume had been five times higher and the absorbed fraction had been twice as high, then the absorbed dose via dermal contact would have been higher by an order of magnitude.

Model Consistency

The temporal variation in air concentrations for DPGME released from the floor finish was compared for the PROMISE and MCCEM models in Figure 4. Although there were differences in the shapes of the respective temporal profiles, the TWA results were close. The modeled 8-h TWA concentrations were 30.1 mg/m^3 for PROMISE and 32.3 mg/m^3 for MCCEM, a difference of less than 10%. Similarly, the estimates of inhaled dose were close—241 mg for PROMISE versus 259 mg for MCCEM. The peak concentration modeled with PROMISE occurs later and was lower than that modeled with MCCEM. The difference in the timing and magnitude of the peak estimated by the two models was related to their assumptions concerning time-related emissions—MCCEM has an empirical algorithm for exponentially declining emissions, based on evaporation of a pure film, whereas the time-varying emission rate in PROMISE considers the film thickness of the applied product as well as the other product constituents.

Parameter Uncertainty Assessment

The Monte Carlo simulation was performed on exposures from the application of the floor finish product, for which the dose to the glycol ether (DPGME) was the greatest (see Table 6). The simulation was run for 1000 trials; results are summarized in Table 7. As discussed above, the point estimate of aggregate dose during and after the finish application was based on typical (central) values for the scenario whereas the Monte Carlo simulation reflects a range of input values. The upper end of the dose distribution (95th percentile—391 mg) was about 60% higher than the point estimate and the lower end of the distribution (5th percentile—77 mg) was less than a third of the point estimate.

TABLE 7
Monte Carlo simulation results for floor finish application

Percentile of simulated dose distribution	Aggregate dose for DPGME, mg	Dosage, mg/kg*
5th	77	1.1
10th	92	1.3
25th	122	1.7
50th	172	2.4
75th	246	3.4
90th	318	4.4
95th	391	5.5

*Assuming a 71.6-kg individual.

DISCUSSION

The above exercise illustrates the potential for characterizing aggregate exposures from the use of cleaning products containing glycol ethers with a modeling tool (PROMISE). In this assessment, the model suggests that doses from dermal and ingestion routes for these products generally are small in comparison to doses from inhalation. Inhalation accounted for more than 95% of the aggregate dose for DPGME in the finish and more than 85% of the dose for EGBE in the cleaner. This finding occurs even when the assumptions for dermal and oral exposures are believed to overestimate exposure potential.

The considerably higher air concentrations and therefore estimated absorbed dose for DPGME as compared to EGBE (Table 3 and Figure 3) relate to the fact that the EGBE-containing stripper solution is removed before it is allowed to dry. Because EGBE is miscible in water and has a relatively low vapor pressure, it tends to remain in the water phase and does not evaporate until most of the water has evaporated. Thus, most of the EGBE is discarded in the removal phase of the stripping operation precluding evaporation into air. The DPGME-containing floor finish, on the other hand, remains on the floor until dry, thus all the DPGME in the stripper is evaporated into the air.

The finding that dermal and oral routes of exposure may result in relatively small doses may appear to suggest that there was no need for multiroute exposure modeling in this scenario. However, without the multiroute modeling there would have been no way to rank the relative importance of exposure routes according to estimated dose.

The scripted scenario for this exposure assessment was not based on a specific field study in which air monitoring had been conducted. However, measured air concentration data were available for a somewhat analogous, but not identical, floor stripping operation.[1] In that case the floor of a smaller retail store (floor area = 290 m^2; room volume = 1240 m^3) was stripped with a solution containing 6% EGBE. The application rate was similar to that used in the modeling exercise, 578 versus 658 cm^3/min, and the total time of the stripping procedure was ≈130 versus 80 min in the modeled scenario. The room ventilation rate was described as "normal." Personal air sampling was conducted on two individuals yielding 8-h TWA concentrations of 4.6 and 4.4 mg/m^3 (0.95 and 0.9 ppm, respectively), which is somewhat higher but comparable to that obtained in the modeling exercise of 1.2 mg/m^3 (0.25 ppm). The smaller room size with a similar application rate could well have led to the modestly higher value. Nevertheless, these comparable values demonstrates that the modeled results are clearly within the realm of plausibility. We are not aware of any additional air monitoring or biomonitoring data for this type of application.

Comparisons with MCCEM showed the modeled 8-h TWA concentration and inhalation dose to be consistent across both models. As noted previously, the difference in the timing and magnitude of the peak estimated by the two models is likely related to the difference in the manner in which time-related emissions are estimated by the two models. MCCEM uses an empirical algorithm for exponentially declining emissions, based on evaporation of a pure film, whereas the time-varying emission rate in PROMISE considers the film thickness of the applied product as well as the other product constituents. The Monte Carlo simulation exercise indicated that the upper end of the aggregate dose distribution accounting for uncertainty in the parameters considered in the model is more than 50% higher than the value of the point estimate.

Both of the exposure models used in this exercise produce an estimate of internal dose, mg/kg/day, necessary along with some benchmark dose of hazard for evaluating risk. This dosimetric estimated by these models is conducted in a relatively simplistic manner, i.e., for inhalation, dose is determined by the product of the mean air concentration over time and an estimated respiration rate of an exposed individual of a specific body weight. No provisions are made in these models for processes in which a volatile chemical that has been absorbed into systemic circulation is then exhaled through the lung or uptake as affected by blood concentrations and other physiological factors. Physiologically based pharmacokinetic (PBPK) models exist that take these and other physiological factors into consideration. Corley and coworkers have developed such a PBPK model for EGBE both for inhalation and dermal exposure and Sweeney and coworkers have demonstrated how such models for other glycol ethers (methoxyethanol, ethoxyethanol, and ethoxyethylactetate), coupled with probabilistic approaches, can be used in developing occupational exposure standards (Corley et al. 1994, 1997; Sweeny et al. 2001). However, it was beyond the scope of the present study to couple these exposure models to these more sophisticated PBPK models.

Although the estimates of aggregate dose and the relative contributions from different exposure routes and floor-care products are useful, there are currently no existing toxicology benchmarks (e.g., inhalation reference dose) for the two solvents. There are, however, guidelines for occupational exposure against which the modeled TWA air concentrations can be compared. The modeled 8-h TWA concentration for DPGME (30 mg/m^3) is lower than the corresponding American Conference of Governmental Industrial Hygienists (ACGIH) Threshold Limit Values (TLV) exposure limit of 606 mg/m^3 (100 ppm) by a factor of 20, and the modeled TWA air concentration for EGBE from the stripper (1.2 mg/m^3) is lower than the corresponding ACGIH TLV of 97 mg/m^3 (20 ppm) by a factor of ≈80. Thus, the point estimates from the modeling exercise indicate that levels of potential concern, from the standpoint of occupational exposure, are not being exceeded for these product applications under the scenario conditions

PROMISE provides simulation outputs only for the aggregate dose (i.e., not for the individual routes of inhalation, dermal contact, and accidental ingestion). Thus, it is not possible to directly

[1]Personal communication: D. A. Daggett, Program Manager, Global Product Safety Research, Development & Engineering, Johnson Diversey, Inc., Sturtevant, WI 53177, USA.

determine the range of 8-h TWA air concentrations based on the aggregate dose simulation. However, these values can be estimated by performing a Monte Carlo simulation whereby only the parameters affecting the modeled air concentration—the ventilation rate, the applied solution thickness, and the indoor temperature—are varied. The range of the 8-hour TWA air concentrations (first to 99th percentiles of the distribution) for DPGME from this Monte Carlo simulation is from 6 mg/m^3 to 55 mg/m^3. The upper end of this range still is below the corresponding ACGIH, TLV_8 of 600 mg/m^3 by more than a factor of 10, providing further assurance that exposure levels of potential concern are not being exceeded for this product-use scenario.

REFERENCES

ASHRAE. 1989. Ventilation for acceptable indoor air quality. June 1989. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. Standard, ASHRAE 62-1989.

Bartnik, F. G., A. K. Reddy, G. Klecak, Y. Zimmermann, J. J. Hostynek, and K. Kunstler. 1987. Percutaneous absorption, metabolism, and hemolytic activity of *n*-butoxyethanol. *Fundam. Appl. Toxicol.* 8:59–70.

Boatman, R. J., and J. B. Knaak. 2001. Ethers of ethylene glycol and derivatives. In *Patty's toxicology*, 5th ed., Vol. 7, ed. E. Bingham, B. Cohrssen, and C. H. Powell, 73–270. New York: John Wiley & Sons.

Burmaster, D. E. 1996. Benefits and costs of using probabilistic techniques in human health risk assessments—with an emphasis on site-specific risk assessments. *Hum. Ecol. Risk Assess.* 2:35–43.

Chinn, H., E. Anderson, and M. Yoneyama. 2000. *CEH marketing research report. Glycol ethers.* SRI International, Menlo Park, CA.

Corley, R. A., G. A. Bormett, and B. I. Ghanyem. 1994. Physiologically based pharmacokinetics of 2-butoxyethanol and its major metabolite, 2-butoxyacetic acid, in rats and humans. *Toxicol. Appl. Pharmacol.* 129:61–79.

Corley, R. A., D. A. Markham, C. Banks, P. Delorme, A. Masterman, and J. M. Haul. 1997. Physiologically baseed pharmacokinetics and the dermal absorption of 2,-butoxyethanol vapor by humans. *Fundam. Appl. Toxicol.* 39:120–130.

Cragg, S. T., and R. J. Boatman. 2001. Glycol ethers: Ethers of propylene, butylene glycols, and other glycol derivatives. In *Patty's toxicology*, 5th ed., Vol. 7, ed. E. Bingham, B. Cohrssen, and C. H. Powell, 271–395. New York: John Wiley & Sons.

Dugard, P. H., M. Walker, S. J. Mawdsley, and R. C. Scott . 1984. Absorption of some glycol ethers through human skin in vitro. *Environ. Health Perspect.* 57:193–198.

ECETOC. 2005. *The toxicology of glycol ethers and its relevance to man*, 4th ed., Vol. I. Technical Report No. 95. Brussels: European Centre for Ecotoxicology and Toxicology of Chemicals.

Evans, W. C. 1994. Development of continuous-application source terms and analytical solutions for one- and two-compartment systems. In *characterizing sources of indoor air pollution and related sink effects*, 297–293. ASTM STP 1287. American Society for Testing and Materials, West Conshohocken, PA.

Finley, B., and D. Paustenbach. 1994. The benefits of probabilistic exposure assessment: Three case studies involving contaminated air, water, and soil. *Risk Anal.* 53:54–57.

Hertwich, E., T. E. McKone, and W. S. Pease. 1999. A systematic uncertainty analysis of an evaluative fate and exposure model. *Risk Anal.* 20:439–454.

ISSA. 1999. *358 Cleaning times.* The International Sanitary Supply Association (ISSA), Lincolnwood, IL.

Jayjock, M. 1994. Back pressure modeling of indoor air concentration from volatilizing sources. *Am. Ind. Hyg. Assoc. J.* 5:230–235.

Johanson, G. 1986. Physiologically based pharmacokinetic modeling of inhaled 2-butoxyethanol in man. *Toxicol Lett.* 34:23–31.

Koontz, M. D. 1992. Consumer products exposure guidelines: Evaluation of indoor air quality models. Final report for USEPA Office of Research and Development, Environmental Monitoring Systems Laboratory. Las Vegas: GEOMET Technologies, Inc.

Koontz, M. D., and H. R. Rector. 1995. Estimation of distributions for residential air exchange rates. Final report for USEPA Office of Pollution Prevention and Toxics. Las Vegas: GEOMET Technologies, Inc.

McCready, D., and D. Fontaine. 2003. Estimating volatilization and exposure to constituents in surface coatings; models versus experiments. Paper no. 70369. 96th Annual Meeting of Air & Waste Management Association, San Diego, CA.

Nagda, N., and M. Koontz. 1991. A multichamber model for assessing consumer inhalation exposure. *Indoor Air* 4:593–605.

Persily, A. K. 1989. Ventilation rates in office buildings. IAQ 1989. Atlanta, GA: American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc., pp 128–136.

Robinson, J. P., and J. A. Wiley. 1989. Activity patterns of California residents. Berkeley, CA: Survey Research Center, University of California. ARB Contract No. A6-177-33.

Sparks, L. E., B. A. Tichenor, J. Chang, and Z. Guo. 1996. Gas-phase mass transfer model for predicting volatile organic compound (VOC) emission rates from indoor pollutant sources. *Indoor Air* 6:31–40.

Sweeny, L. M., T. R. Tyler, C. R. Kirman, R. A. Corley, R. H. Reitz, D. J. Paustenbach, J. F. Holson, M. D. Whorton, K. M. Thompson, and M. L. Gargas. 2001. Proposed occupational exposure limits for select ethylene glycol ethers using PBPK models and Monte Carlo simulations. *Toxicol. Sci.* 62:124–139.

USEPA. 1997. *Exposure factors handbook.* EPA/600/P-95/002Fa.

Van Veen, M. 1996. A general model for exposure and uptake from consumer products. *Risk Anal.* 16:331–338.

Venier, M., G. Adami, F. Larese, G. Maina, and N. Remzi. 2004. Percutaneous absorption of 5 glycol ethers through human skin *in vitro*. *Toxicol. In Vitro* 18:665–671.

Versar, Inc. 1992. A laboratory method to determine the retention of liquids on the surface of hands. Washington, DC: U.S. Environmental Protection Agency, Office of Pollution Prevention and Toxics. EPA Contract No. 68-02-4254.

Wilkinson, S. C., and F. M. Williams. 2002. Effects of experimental conditions on the absorption of glycol ethers through human skin *in vitro*. *Int. Arch Occup. Environ. Health* 75:519–527.

APPENDIX 1: DIFFERENTIAL EQUATIONS USED IN THE PROMISE MODEL FOR ESTIMATING THE EVAPORATION OF TWO COMPONENTS FROM A COATINGS APPLICATION

Master equations for the PROMISE "Wall or Floor" Evaporation Module (two components in the solution/mixture): Four first-order, nonlinear, coupled, ordinary differential equations in the unknowns—$C_1(t)$, $M_1(t)$, $C_2(t)$, and $M_2(t)$:
For the liquid mass, $M_1(t)$, of solution component 1:

$$(d/dt)M_1(t) = D_1^{(o)} \times H^{(o)} \times a(t) - K_t1 \times \{M_1(t)/(D_1(t) \times H^{(o)})\} \times \{C_{1,sat}(t) - C_1(t)\}$$

For the vapor concentration, $C_1(t)$, of component 1:

$$V_r \times (d/dt)C_1(t) = K_{t1} \times \{M_1(t)/(D_1(t)XH^{(o)})\}C_{1,sat}(t) - C_1(t) - Q_rX(C_1(t) - C_{1,out})$$

For the liquid mass, $M_2(t)$, of solution component 2:

$$(d/dt)M_2(t) = D_2^{(o)} \times H^{(o)} \times a(t) - K_{t2} \times \{M_2(t)/(D_2(t) \times H^{(o)})\} \times \{C_{2,sat}(t) - C_2(t)\}$$

For the vapor concentration, $C_2(t)$, of component 2:

$$V_r \times (d/dt)C_2(t) = K_{t2} \times \{M_2(t)/(D_2(t) \times H^{(o)})\} \times \{C_{2,sat}(t) - C_2(t)\} - Q_r \times (C_2(t) - C_{2,out})$$

where (d/dt) is the differential operator with respect to time, and the subscripts i = 1 and i = 2 refer to "solute" and "solvent," respectively. For component i, $D_i^{(o)}$ = as-applied concentration, $K_{t,i}$ = mass transfer rate, and $C_{out,i}$ = outside air concentration. a(t) is the area application rate. A(t) = covered area, including both application and evaporation effects. $H^{(o)}$ = applied solution thickness, Q_r = ventilation rate, V_r = room vol.
Theoretically, for the net covered area (applied − evaporated):

$$A(t) = M_1(t)/\{D_1(t) \times H(t)\} = M_2(t)/\{D_2(t) \times H(t)\}$$

The amount of thickness [H(t)] variation compared to area [A(t)] variation is unknown and would depend on surface tension effects, which are beyond the scope of this modeling effort. This is not a model of how "dry areas nucleate on wet surfaces." Instead, we make the approximating assumption that:
Approximation:

$$A(t) = M_1(t)/\{D_1(t) \times H^{(o)}\} = M_2(t)/\{D_2(t) \times H^{(o)}\}$$

where $H^{(o)}$ is the as-applied thickness of the solution.