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The Shower and Household Water-Use Exposure Model: A Model to Evaluate Residential Exposure to Chemicals Volatilizing From Indoor Water Use

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Editor's Note: **As part of our continued effort to highlight innovative approaches to improve the health and environment of communities, the *Journal* is pleased to publish a bimonthly column from the Agency for Toxic Substances and Disease Registry (ATSDR) at the Centers for Disease Control and Prevention (CDC). ATSDR serves the public by using the best science, taking responsive public health actions, and providing trusted health information to prevent harmful exposures and diseases related to toxic substances. The purpose of this column is to inform readers of ATSDR's activities and initiatives to better understand the relationship between exposure to hazardous substances in the environment, its impact on human health, and how to protect public health.**

The conclusions of this column are those of the author(s) and do not necessarily represent the official position of ATSDR or CDC.

Introduction

When assessing chemical exposure at Superfund sites, the Agency for Toxic Substances and Disease Registry (ATSDR) sometimes encounters volatilization of chemicals from household water, a pathway that might have a significant impact on families. Historically, ATSDR evaluated this pathway using a one-compartment model (Andelman, 1985). The one-compartment model estimates exposure to volatilized chemicals from showering only, however, it does not include exposure from 1) showers by other household members, 2) household appliances that use water, and 3) time spent in the house throughout day. ATSDR needed a better model.

To meet this need, ATSDR developed a three-compartment Shower and Household Water-Use Exposure (SHOWER) model that captures inhalation exposure from not only showering but also being in the bathroom and in the house throughout the day. The model includes contributions from showers and tub baths taken by other family members, as well as the contribution from other water sources in the house such as clothes washers, dishwashers, toilets, and faucets. The model can account for persons being away from home during the day and for using a bathroom fan. The SHOWER model is a more comprehensive model that includes multiple pathways of exposure (i.e., inhalation and dermal) from the most common indoor water sources and usage for households with up to four persons. ATSDR released the SHOWER model in May 2018.

Model Description

The SHOWER model mathematically characterizes volatilization from multiple water sources in each compartment: shower water in the shower stall; the toilet, sink, faucet, and bathtub in the bathroom; and kitchen faucet, clothes washer, and dishwasher in the main house (McKone, 1987). Using air-mixing formulas, the model predicts the indoor air contaminant concentrations in each compartment within the house as a function of time by solving a set of constantly changing mass balance equations (Kim, Little, & Chiu, 2004):

$$V_i \frac{dC_i(t)}{dt} = -\sum Q_{ij} \times C_i(t) + \sum Q_{ji} \times C_j(t) \pm \sum S_{ik}(t)$$

Where:

V_i = volume of compartment i,

$C_i(t)$ = air concentration in compartment i at time t,

Q_{ij} = air exchange rate from compartment i to j,

Q_{ji} = air exchange rate from compartment j to i,

$C_j(t)$ = air concentration in compartment j at time t, and

$S_{ik}(t)$ = contaminant source in compartment from a chemical volatilizing from a water source, removal of contaminated air by the exhaust fan, or migration to outdoor air.

A detailed description of the model is available elsewhere (Agency for Toxic Substances and Disease Registry, 2018). The model has about 40 input parameters that characterize the indoor contaminant sources and human activity patterns (DeOreo, Mayer, Dziegielewski, & Kiefer, 2016; McKone, 1987; U.S. Census Bureau, 2018; U.S. Environmental Protection Agency [U.S. EPA], FIGURE **1**

Calculated Air Concentrations in the Shower, Bathroom, and Main House for a 4-Person Household

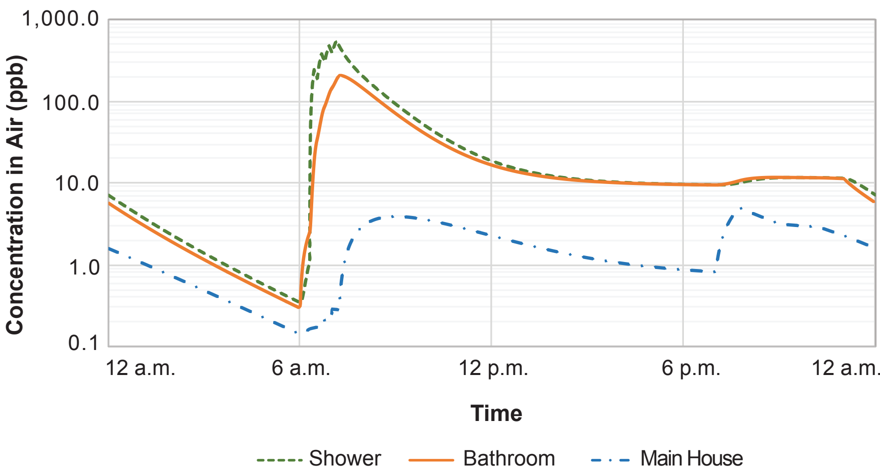


TABLE **1**

Average Daily Exposure Concentrations for All Age Groups That Shower

# of Persons per Household	Average Daily Household Exposure Concentration (µg/m³)*
1	8
2	15
3	20
4	25

*Results shown are based on chlorobenzene at 100 ppb in tap water.

TABLE **2**

Average Daily Inhalation and Dermal Doses for All Age Groups That Shower

Exposure Group	Average Daily Inhalation Dose in Each Household (µg/kg/day)				Average Daily Dermal Dose in Each Household (µg/kg/day)	
	1 Person	2 Persons	3 Persons	4 Persons	1 Person	2, 3, or 4 Persons
Birth to <1 year*	NC	NC	NC	NC	NC	NC
1 to <2 years	NC	16.0	22.0	27.0	NC	0.91
2 to <6 years	NC	11.0	15.0	18.0	NC	0.78
6 to <11 years	NC	6.4	8.7	11.0	NC	0.64
11 to <16 years	NC	4.4	5.9	7.4	NC	0.52
16 to <21 years	NC	3.4	4.7	5.8	NC	0.48
Adult	1.6	3.0	4.1	5.1	0.47	0.47
Pregnant and lactating women	2.4	4.5	6.1	7.5	0.49	0.49

*Children from birth to <1 year were not evaluated for shower scenarios because they do not shower.
NC = not calculated as a 1-person household cannot have a single child younger than 21 years.

2011; Vespa, Lewis, & Kreider, 2013). The model calculates contaminant levels in 1-, 2-, 3-, and 4-person households with members taking consecutive, 8-min morning showers followed by 5-min bathroom stays.

Using chlorobenzene at 100 ppb in tap water, Figure 1 shows contaminant air concentrations as a function of time in each compartment throughout the day. In this example, each morning shower shows a concentration peak in the shower stall followed by a brief decline before the next shower begins. With each shower, the bathroom air concentration rises and then falls after the last shower ends. The main house concentrations rise in the morning following the showers, decline throughout the day, and then rise again in the evening when the dishwasher and clothes washer are used.

Table 1 shows the results for each household as a time-weighted average (TWA) daily human exposure concentration for a target (i.e., the most highly exposed) person. TWA concentration can be compared with ATSDR's inhalation minimal risk levels (MRLs) or U.S. Environmental Protection Agency's (U.S. EPA) reference concentration to evaluate the likelihood of noncancer adverse health effects, or to U.S. EPA's inhalation unit risk to evaluate cancer risk.

The model also calculates doses for both inhalation and dermal exposure (Table 2) using age-specific exposure factors such as breathing rate, body weight, and skin surface area (U.S. EPA, 2011). For contaminants where the target organ is common to all routes of exposure, the inhalation and dermal doses could be added to the oral dose from drinking water to obtain a combined dose. The combined dose can be compared to oral MRLs and reference doses to evaluate the likelihood of noncancerous harmful effects.

The last screen in the model allows the user to select scenarios with different showering and bathing schedules (Figure 2). Users have the option to evaluate exposure in households with morning and evening showers, morning showers and evening baths, and longer shower durations. In addition, users can evaluate the impact of using a bathroom fan or the reduced exposure from the target person's absence from the house for 10 hr during the day.

Model Verification

ATSDR used experimental data to verify the model (U.S. EPA, 2000). The average percent error ± 1 standard deviation was -3% ± 32% for acetone, -18% ± 18% for ethyl acetate, and 32% ± 29% for toluene. Overall, the simulated concentrations are in good agreement with the experimental data considering the complexity of the model and the variation that is expected in experimental data when collecting five 30-s air samples over 8 min in a chamber with rapidly changing air concentrations.

Model Uncertainty

Uncertainty in model results originates from estimating the volatilization factor for various appliances and from subsequent transfer of contaminant to adjacent compartments. Because air–water mass transfer information is unknown for many of the physical processes while showering, the model assumes that the transfer efficiency is constant at the liquid/gas boundary (McKone, 1987). For this reason, radon volatilization data that can be measured very accurately due to its radioactivity were used as a surrogate to estimate the volatilization for other chemicals (Prichard & Gesell, 1981).

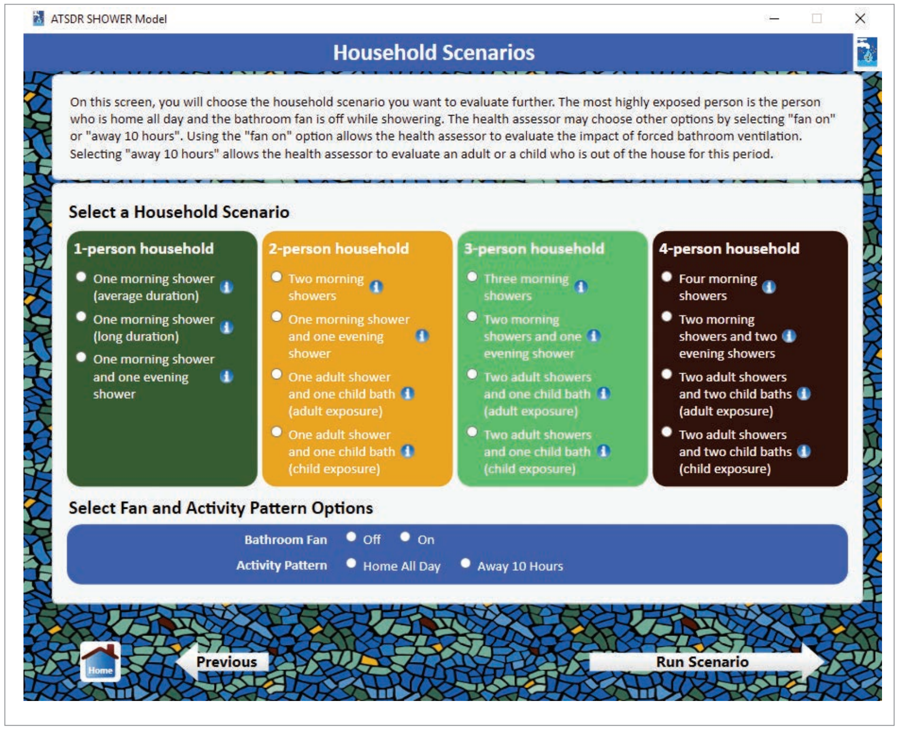
Identifying compartment volumes and the human activity patterns for various scenarios are also uncertain. We have chosen to be health protective by using a small shower stall and bathroom along with an average house size and by assuming consecutive showers. Thus, the results represent that segment of the population that meets these conditions. ATSDR is developing a second version of the SHOWER model that will allow the user to change many parameters and to conduct a sensitivity analysis to determine which parameters have the greatest impact on the results.

Conclusion

ATSDR's three-compartment SHOWER model is a significant improvement over previous one-compartment models. The SHOWER model accounts for inhalation and dermal exposures from the most common indoor water sources, including not only showering and bathing but also contributions from clothes washers and dishwashers. The model predicts exposure for the entire day and for households up to four persons. We anticipate that the ATSDR SHOWER model will be a useful tool in evaluating inhalation and dermal exposure to volatile and semivolatile chemicals, pesticides, and per- and polyfluoroalkyl substances in household water. To request the SHOWER model, send your contact information to showermodel@cdc.gov.

FIGURE **2**

Household Scenarios With Different Showering and Bathing Schedules, Including the Use of a Bathroom Fan and Being Home All Day or Away for 10 Hours



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References

Agency for Toxic Substances and Disease Registry. (2018). *Technical document for the Shower and Household Water-Use Exposure (SHOWER) model.* Atlanta, GA: Author.

Andelman, J.B. (1985). Human exposures to volatile halogenated organic chemicals in indoor and outdoor air. *Environmental Health Perspectives, 62*, 313–318.

DeOreo, W.B., Mayer, P., Dziegielewski, B., & Kiefer, J. (2016). *Residential end uses of water, version 2*. Denver, CO: Water Research Foundation.

Kim, E., Little, J.C., & Chiu, N. (2004). Estimating exposure to chemical contaminants in drinking water. *Environmental Science & Technology*, *38*(6), 1799–1806.

McKone, T.E. (1987). Human exposure to volatile organic compounds in household tap water: The indoor inhalation pathway. *Environmental Science & Technology*, *21*(12), 1194–1201.

Prichard, H.M., & Gesell, T.F. (1981). An estimate of population exposures due to radon in public water supplies in the area of Houston, Texas. *Health Physics*, *41*(4), 599–606.

U.S. Census Bureau. (2018). *American Housing Survey (AHS)*. Retrieved from https://www.census.gov/programs-surveys/ahs/about.html

U.S. Environmental Protection Agency. (2000). *Volatilization rates from water to indoor air: Phase II* (EPA/600/R-00/096). Washington, DC: Author. Retrieved from http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=20677

U.S. Environmental Protection Agency. (2011). *Exposure factors handbook: 2011 edition* (Final Report, EPA/600/R-09/052F) (pp. 16-1–196). Washington, DC: Author. Retrieved from https://cfpub.epa.gov/ncea/risk/recordisplay.cfm?deid=236252

Vespa, J., Lewis, J.M., & Kreider, R.M. (2103). *America's families and living arrangements: 2012*. Washington, DC: Author. Retrieved from https://www.census.gov/prod/2013pubs/p20-570.pdf

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