



## Source apportionment of benzene downwind of a major point source

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### ABSTRACT

In the United States, the Emergency Planning and Community Right-to-Know Act requires sources that emit more than their Threshold Planning Quantity (TPQ) must publically report their total annual emissions. Because these values are aggregated over an entire year, high total emissions are often reported in the toxic release inventory. The Akwesasne Mohawk Reservation in rural Northern New York State lies downwind of an industrial source that reported annual benzene emissions of approximately 29 000 pounds. To assess if these emissions contributed significantly to the ambient concentrations, 24 hour canister samples were collected every 6<sup>th</sup> day from May 30 2007 to July 12 2008 at 9 locations on the Reservation. The samples were analyzed for benzene, toluene, ethyl benzene, and xylenes (BTEX) by GC/FID/MS using EPA Method TO15 procedures. In addition, gasoline samples (6 regular unleaded, 2 midgrade unleaded and 2 super unleaded) were collected in December 2007, May 2008 and July 2008 from five gas stations. The concentrations of BTEX in each gasoline sample were determined by headspace analysis. Vehicle tailpipe sampling was conducted by directly collecting samples from the tailpipe into Tedlar bags on 5 days: March 26, 2008, April 24, 2008, May 8, 2008, May 29, 2008 and June 12, 2008. Three samples were collected from each of the 22 vehicles that were fueled with unleaded regular gasoline from the reservation. Using these measured source profiles and ambient concentrations, the Chemical Mass Balance model was applied to each sample to assess the source contributions of BTEX. The results show that the predominant benzene source is vehicular exhaust with a small contribution from gasoline volatilization. The industrial plant has little or no impact on the ambient benzene concentrations in this community.

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### 1. Introduction

In the United States, the Emergency Planning and Community Right-to-Know Act (EPCRA) enacted in 1986 requires companies to report the emissions of any of 650 chemical species with reporting thresholds dependent on the estimated toxicity of the emitted constituents. Because the total annual aggregated emissions are reported, the local community can perceive that they are being exposed to a significant quantity of hazardous material. However, large reported total annual emissions may not necessarily lead to significant exposures.

The Eisenhower Lock and Dam on the St. Lawrence Seaway near Massena, NY provides power for two large aluminum smelters (Figure 1). The ALCOA St Lawrence Reduction Plant is immediately to the west of the border of the St. Regis Mohawk community on the Akwesasne Mohawk Reservation. According to the 2006 Toxic Release Inventory, this plant released 29 140 pounds per year of benzene and similar emissions have been reported in prior years.

It is generally accepted that benzene is a risk factor for acute myeloid leukemia in humans (Infante et al., 1977; Rinsky et al., 1987; International Agency for Research on Cancer, 1989; Paustenbach et al., 1992; Crump, 1994; Utterback and Rinsky, 1995; Rinsky et al., 2002). A recent study further found that decreased white blood cell counts, platelet counts, and other hematological values could be observed in persons exposed to 1 ppm benzene (Lan et al., 2004).

Benzene is also emitted by motor vehicles and through volatilization losses from vehicle filling operations. Mobile sources are generally the most significant benzene emission sources and, according to historic emissions estimates, motor vehicles accounted for 60% of benzene air emissions in 1992 while off-road vehicles contributed about 25% (USEPA, 1993). Based on the 1999 National Air Toxics Assessment (NATA), mobile sources accounted for a total of 68% of the national benzene inventory with 49% from on-road sources and 19% from off-road sources (USEPA 2007). The 2002 NATA shows a continuing reduction in the impact of mobile sources with 41% of the benzene emissions from on-road vehicles and 17% from off-road vehicles (USEPA, 2009).

About 12 000 vehicles pass the Canadian-American border per day and there are 15 gasoline stations in this area. The emissions from spark-ignition vehicles also results in the emissions of toluene, ethyl benzene, and xylenes which together with benzene are collectively known as BTEX. BTEX are important atmospheric non-methane hydrocarbons and contributors to ozone formation in the troposphere (Monod et al., 2001). Since BTEX can be emitted from a number of sources including vehicles, gas stations, and industrial facilities (Fujita et al., 1995a; Fujita et al., 1995b; Derwent et al., 1995; Srivastava et al., 2005; Srivastava et al., 2006), identification of the BTEX sources is important to determine control strategies.

## 2. Experimental Methods

### 2.1. Monitoring sites

Nine sampling locations are shown in Figure 1 (1A, 1B, 1C, 2A, 2B, 2C, 3A, 3B, and 3C). Sites 1B, 2B, 3B and 3C are located less than 1.6 km from Route 37. Site 1B is located at the Akwesasne Business Center on the Frog town road intersection approximately 0.5 km away from Route 37 adjacent to the Mohawk Bingo Palace, less than 0.8 km away from the Mohawk International Speedway and Jacobs Tobacco facility. The monitoring site is approximately 9 m away from the road intersection. Site 2B is in a heavily wooded area and is located less than 0.8 km away from the Akwesasne Mohawk Casino and 0.5 km away from Speedway Plaza that houses a gas station, restaurant, laundromat, carwash, and quick lube. Site 3B is located less than 70 m from Route 37 in a residential area that houses a local body repair shop. The remaining sampling sites are located in residential areas with relatively low traffic on the adjacent roads. Site 1A is on the banks of the St. Lawrence River downwind of the ALCOA facility. Sites 1C and 2C are in a heavily wooded area. Site 3A is approximately 61 m away from Drum St. Land owners in this area reported that during the summer, the grass is mowed twice a week. Site 2A is on the St. Regis Road, a frequently used entry into the Quebec portion of the reservation opposite a local cigarette factory.

### 2.2. Chemical analysis

Twenty-four hour integrated canister samples were collected every six days from June, 2007 to June, 2008 at these sampling sites. In total, about 400 ambient samples were obtained. Concentrations of five species including benzene, toluene, ethyl benzene, *m,p*-xylene, *o*-xylene were determined by a Trace Ultra GC (Thermo Fisher Scientific, US) using a Thermo Polaris Q mass spectrometer (Thermo Fisher Scientific, US) and a Thermo flame ionization detector (Thermo Fisher Scientific, US) GC/FID/MS through procedures defined in the US EPA TO15 equipped with CS 1200 ES flow controllers (Entech Inc, Simi Valley CA) were set out for sampling in each run: one field blank, nine canisters at nine different locations and one canister collocated. The collocation site was rotated in all nine positions throughout the sampling period. The flow controllers were calibrated to  $3.4 \pm 1.0$  mL/min to allow for 24 hour sampling into the canister. Each sampler was placed on a 1.83 m high stand. The samplers were cleaned and prepared for

sampling as per the procedures in the EPA TO15 (USEPA, 1999). The canisters were cleaned and tested for cleanliness after analysis before the next sampling scheduled.

### 2.3. Chemical mass balance (CMB) model

The CMB receptor model (Friedlander, 1973; Watson et al., 1984; Gordon, 1988; Watson et al., 1990) consists of a solution to linear equations that express each receptor chemical concentration as a linear sum of products of source profile abundances and source contributions. For each run of CMB, the model fits chemically speciated data from a source or set of sources to each individual sample composition. The source profiles and ambient concentrations as well as their measured uncertainties serve as input data to CMB. The output consists of the amount contributed by each source type represented by a profile to the total mass as well as to each chemical species. CMB calculates values for the contributions from each source and the uncertainties of those values.

$$x_{ij} = \sum_{k=1}^p f_{ik} g_{kj} + e_{ij} \quad (1)$$

where  $x_{ij}$  is the concentration of the species  $i$  for sample  $j$ ,  $g_{kj}$  is the mass contribution from the  $k_{th}$  source to sample  $j$ ,  $f_{ik}$  is the fraction of species  $i$  in emissions from source  $k$ ,  $e_{ij}$  is the residual indicating the difference between the predicted and observed value. The CMB model has been used to apportion different fractions of VOCs in several urban areas mostly in United States. (Mayrsohn et al., 1977; Harley et al., 1992; Scheff and Wadden, 1993; Fujita et al., 1994, Fujita et al., 1995a; Fujita et al., 1995b; Scheff et al., 1996; Fujita et al., 1997a; Fujita et al., 1997b; Fujita and Lu, 1998a; Fujita and Lu, 1998b; Watson et al., 2001). Sweet and Vermettee (1992) applied CMB and wind trajectory analysis to 13 toxic VOCs in Illinois. Scheff and Wadden (1993) used CMB to apportion 23 non-methane organic compounds for each of 55 samples obtained in Chicago to 8 source categories (vehicles, gasoline vapor, refineries, degreasing, coating, graphic arts, dry cleaning and wastewater treatment plant). High levels of VOCs have been observed in Asian countries (Gee and Sollars, 1998; Hussam et al., 2002). These levels have been considered to be originating from vehicular emissions. Srivastava (2004) have reported source apportionment of VOCs in Mumbai city.

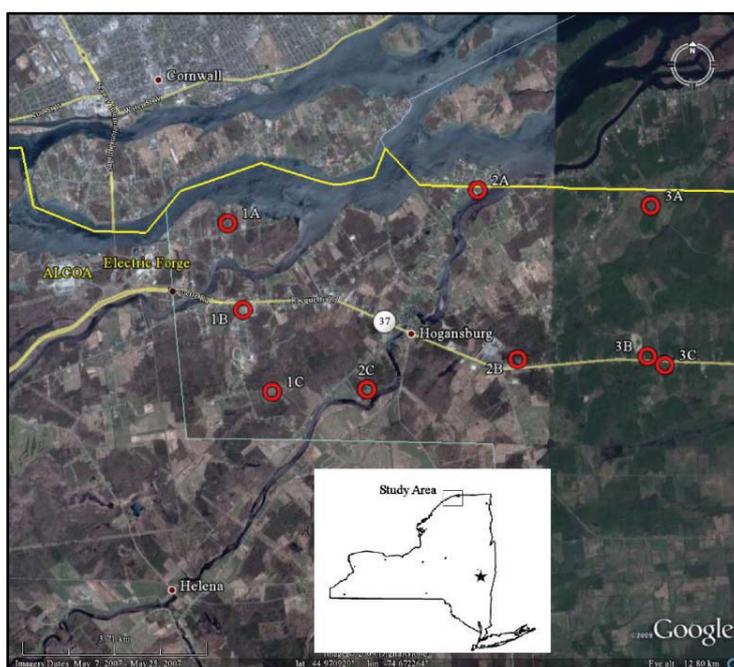


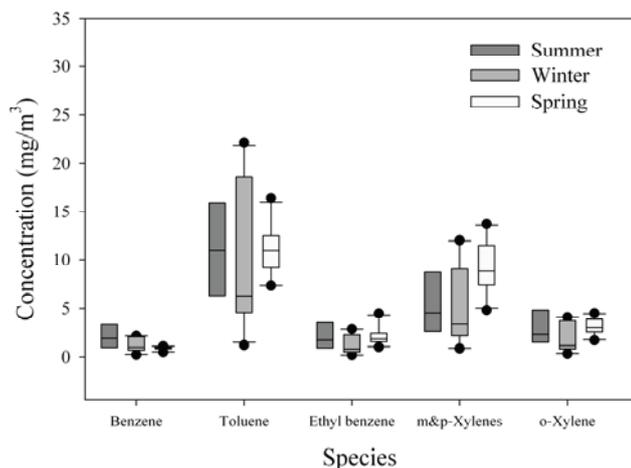
Figure 1. Area of concern showing the sampling sites. Insert: map of New York State showing the location of the study area.

### 3. Results

#### 3.1. Source profiles

**Gasoline vaporization profile.** Regular unleaded, midgrade and premium gasoline types were obtained seasonally from each of ten different service stations because of seasonal changes in the fuel formulation. Six samples of regular gas, two samples of midgrade, and two samples of super grade were collected. Each gasoline sample was prepared for analysis by placing 1.0 g of gasoline into 10 mL of ACS-grade isooctane. The BTEX concentrations were determined by direct injection of the gasoline sample head space into the GC/MS. A BTEX calibration standard was volumetrically prepared by adding 1  $\mu$ L of each of the compounds into 10 ml of isooctane.

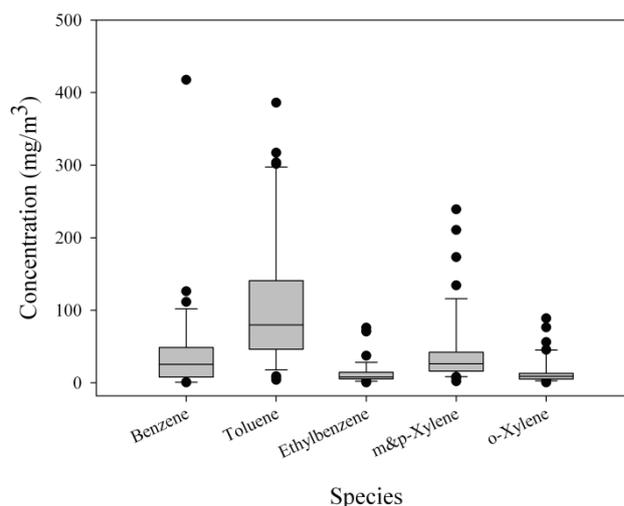
Figure 2 presents the distributions of the measured fuel formulations as box and whisker plots. The gasoline profile in winter was quite similar to that in summer. Samples taken in spring representing the gasoline profile in transitional period between winter and summer showed relatively low toluene and high *m*- and *p*-xylene concentrations.



**Figure 2.** Distributions of the measured BTEX compositions for the gasoline headspace samples collected in the three seasons.

Based on the ten samples collected in each season, profiles were developed by simple averaging over the 10 samples. The uncertainty was estimated by the standard deviation of the measured values. Table 1 presents the gasoline volatilization source profiles used in this study.

**Vehicle exhaust profile.** Vehicle tailpipe samples were collected from the tailpipe into Tedlar bags. Samples were collected on March 26<sup>th</sup> 2008, April 24<sup>th</sup> 2008, May 8<sup>th</sup> 2008, May 29<sup>th</sup> 2008 and June 12<sup>th</sup> 2008. Three samples, cold start, hot start and high speed idling (2 500 rpm), were collected from each of the 22 vehicles that were fueled with unleaded regular gasoline from the reservation. For the cold start samples, the vehicle was started after at least 12 hours of no activity and the sample collected during the initial minutes of operation. During high speed idling, the warm vehicle was revved up to about 2 500 rpm and a sample collected. The engine was then shut off and restarted with the engine still warm to collect the hot start sample. Figure 3 shows the distributions of the BTEX species for the vehicle exhaust samples as box and whisker plots.



**Figure 3.** Distributions of the measured BTEX compositions for the vehicle exhaust samples.

To obtain a “vehicle exhaust” profile, the BTEX values for all of the analyzed exhaust samples were averaged. The uncertainty was estimated by the standard deviation of the measured values. Table 1 presents the vehicle source profile.

**Industrial emissions.** According to 2006 Toxic Release Inventory and information from New York State Department of Environmental Conservation Division of Air Resources, twelve stacks of Alcoa Metal Primary facility, upwind Akwesasne community, released about 29 140 pounds of benzene over the year and could also impact the local air quality. There is no indication from the emissions inventory that there is a release of any other BTEX compound.

**Table 1.** VOCs species source profiles used in this study: fractions by weight of modeled compounds

Source ID	Benzene	Error	Toluene	Error	Ethyl benzene	Error	m,p-Xylene	Error	o-Xylene	Error
GasSm <sup>a</sup>	0.084	0.005	0.485	0.008	0.074	0.002	0.249	0.010	0.108	0.003
Vehicle <sup>b</sup>	0.403	0.025	0.362	0.016	0.044	0.003	0.139	0.009	0.052	0.004
GasSp <sup>c</sup>	0.036	0.001	0.423	0.007	0.078	0.003	0.346	0.004	0.117	0.001
GasWn <sup>d</sup>	0.075	0.002	0.519	0.007	0.059	0.001	0.253	0.006	0.094	0.002

<sup>a</sup> Summer gasoline vapor

<sup>b</sup> Vehicle exhaust

<sup>c</sup> Spring gasoline vapor

<sup>d</sup> Winter gasoline vapor

### 3.2. Selection of species

Vega et al. (2000) selected the major species that had a lifetime longer than that of toluene. Fujita (2001) also took the lifetime of species into account and selected all compounds with a lifetime longer than that of toluene. Hellen et al. (2003) chose to elect all the species with a lifetime longer than that of 1,2,3-trimethylbenzene. In this case, BTEX were all included for the source apportionment calculation.

### 3.3. Model operation

The general approach to operate the CMB model was to select source profiles for CMB modeling by including all of the sources into the analysis. The modeling was repeated by removing sources that give negative contribution or large uncertainties (Fujita et al., 1995b). For each sample, an adequate fit was determined by examining the chi-squared value and related diagnostics provided by the program.

## 4. Results

The average source contributions for each of the sampling sites are presented in Table 2. The time series of the source contributions to benzene concentration in ambient level are shown in Supporting Material (SM) (Figures S1-S3). The results showed that vehicle exhaust was the dominant benzene source. Gasoline vaporization accounted for about 10% of the benzene concentrations in the Akwesasne community. The Alcoa reduction plant had very little impact on sampling sites 1A, 1B, and 1C, those closest to the plant, and had even lower contributions to the other sampling sites.

For benzene emitted by tailpipes, Figures 4a, 4b, and 4c showed that only sampling sites 3B and 3C had similar vehicle exhaust impacts because those locations were quite close to the road. From Table 2, sampling sites 2A and 2C have the highest average benzene concentration caused by tailpipe emissions because 2A is on the St. Regis Road, a frequently used entry into the Quebec portion of the reservation. Site 2C is in a heavily wooded area with frequent All Terrain Vehicles (ATVs) and recreational vehicles observed in the vicinity. Site 2C only had very high benzene concentrations in the summer and early autumn that were prime times for recreational vehicle use.

The highest yearly-average benzene contribution from volatilized gasoline was found at sampling site 1B, a site surrounded by several gas stations. Sampling site 1A had the second highest yearly-average benzene concentration, and may have been the result of its downwind location from several gas stations. Since it was close to one gasoline station, site 3B had a more benzene released from gasoline vaporization than sampling site 3C.

Figure 4 shows spatial variations of BTEX source contributions. Tailpipe emissions represented the source of 50% to 70% of the toluene in the atmosphere at most locations. Gasoline vaporization accounted for the other 30% to 50% of the toluene.

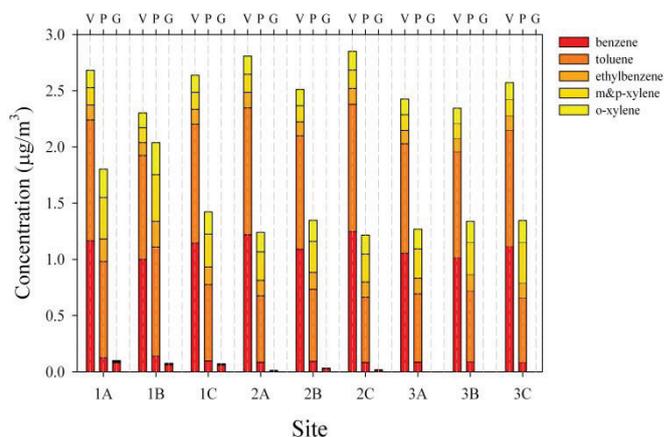


Figure 4. Spatial variability of source contributions (V: vehicle exhaust; P: Al plant; G: gasoline vaporization).

## 5. Conclusions

Source contributions to ambient concentrations of BTEX were determined by applying the CMB receptor model in a rural area of northern New York State. The results showed that vehicle exhaust represented about 85% of measured benzene in the atmosphere. Gasoline vaporization was the source most of the remaining benzene concentrations. Although the industrial plant annually emits 29 140 pounds of benzene, it had little to no impact on local air quality. Its low hourly emission rate coupled with the atmospheric dispersion of the benzene into the downwind region means a low contribution to ambient concentrations. Thus, it is likely that high aggregate emissions may result in relatively low exposures in many similar situations and other, less prominent sources may be responsible for the observed ambient concentrations.

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## Supporting Material Available

Time series of source contributions to sites 1A, 1B, and 1C (Figure S1), Time series of source contributions to sites 2A, 2B, and 2C (Figure S2), Time series of source contributions to sites 3A, 3B, and 3C (Figure S3). This information is available free of charge via the Internet at <http://www.atmospolres.com>.

Table 2. Vehicle exhaust, gasoline vaporization, and Alcoa industrial source's contribution to yearly-average benzene concentration in ambient level

	1A	1B	1C	2A	2B	2C	3A	3B	3C
Vehicle Exhaust	1.163	0.999	1.144	1.218	1.090	1.246	1.053	1.017	1.115
Gasoline	0.123	0.139	0.097	0.084	0.092	0.083	0.086	0.090	0.082
Plant	0.078	0.060	0.056	0.010	0.025	0.014	0.000	0.000	0.000

## References

- Crump, K.S., 1994. Risk of benzene-induced leukemia: a sensitivity analysis of the pliofilm cohort with additional follow-up and new exposure estimates. *Journal of Toxicology and Environmental Health* 42, 219–242.
- Dervent, R.G., Middleton, D.R., Field, R.A., Goldstone, M.E., Lester, J.N., Perry, R., 1995. Analysis and interpretation of air quality data from an urban roadside location in Central London over the period from July 1991 to July 1992. *Atmospheric Environment* 29, 923-946.
- Friedlander, S.K., 1973. Chemical element balances and identification of air pollution sources. *Environmental Science and Technology* 7, 235-240.
- Fujita, E.M., 2001. Hydrocarbon source apportionment for the 1996 Paso del Norte ozone study. *The Science of the Total Environment* 276, 171-184.
- Fujita, E.M., Lu, Z., 1998a. Hydrocarbon Receptor Modeling for the 1996 Phoenix Ozone Study. Prepared for ENSR Corporation, Camarillo, CA, Desert Research Institute, Reno NV.
- Fujita, E.M., Lu, Z., 1998b. Analysis of Data from the 1995 NARSTO–Northern Study. vol. III, Chemical Mass Balance Receptor Modeling. Prepared for Coordinating Research Council, Atlanta, GA, Desert Research Institute, Reno, NV.
- Fujita, E.M., Lu, Z., Sheetz, L., Harshfield, G., Zielinska, B., 1997a. Determination of mobile source emission source fraction using ambient field measurements. Prepared for Coordinating Research Council, Atlanta, GA. Desert Research Institute, Reno, NV.
- Fujita, E.M., Lu, Z., Sheetz, L., Harshfield, G., Hayes, T., Zielinska, B., 1997b. Hydrocarbon source apportionment in Western Washington. Prepared for State of Washington Department of Ecology, Lacey, WA. Desert Research Institute, Reno, NV.
- Fujita, E.M., Lu, Z., Sagebiel, J., Robinson, N.F., Watson, J.G., 1995a. VOC source apportionment for the coast oxidant assessment for Southeast Texas. Prepared for Texas Natural Resource Conservation Commission. Austin, TX, Desert Research Institute Reno, NV.
- Fujita, E.M., Watson, J.G., Chow, J.C., Magliano, K.L., 1995b. Receptor model and emissions inventory source apportionments of nonmethane organic gases in California's San Joaquin valley and San Francisco bay area. *Atmospheric Environment* 29, 3019-3035.
- Fujita, E.M., Watson, J.G., Chow, J.C., Lu, Z.Q., 1994. Validation of the Chemical Mass Balance Receptor Model applied to hydrocarbon source apportionment in the Southern California air quality study. *Environmental Science and Technology* 28, 1633-1649.
- Gee, I.L., Sollars, C.J., 1998. Ambient air levels of volatile organic compounds in Latin America and Asian Cities. *Chemosphere* 36, 2497-2506.
- Gordon, G.E., 1988. Receptor Models. *Environmental Science and Technology* 22, 1132-1142.
- Harley, R.A., Hannigan, M.P., Cass, G.R., 1992. Respeciation of organic gas emissions and detection of excess unburned gasoline in the atmosphere. *Environmental Science and Technology* 26, 2395-2408.
- Hellen, H., Hakola, H., Laurila, T., 2003. Determination of source contributions of NMHCs in Helsinki (60°N, 25°E) using chemical mass balance and the Unmix multivariate receptor models. *Atmospheric Environment* 37, 1413-1424.
- Hussam, A., Alauddin, M., Khan, A.H., Chowdhury, D., Bibi, H., Bhattacharjee, M., Sultana, S., 2002. Solid phase micro extraction: measurement of volatile organic compounds (VOCs) in Dhaka City air pollution. *Journal of Environmental Science and Health Part A-Toxic/Hazardous Substances and Environmental Engineering* 37, 1223-1239.
- Infante, P.F., Rinsky, R.A., Wagoner, J.K., Young, R.J., 1977. Leukemia in benzene workers. *Lancet* 2, 76-78.
- International Agency for Research on Cancer. 1989. Benzene. Occupational exposures in petroleum refining; crude oil and major petroleum fuels. IARC Working Group on the Evaluation of Carcinogenic Risks to Humans. IARC Monographs on the Evaluation of Carcinogenic Risks to Humans 45:1-322.
- Lan, Q., Zhang, L.P., Li, G.L., Vermeulen, R., Weinberg, R.S., Dosemeci, M., Rappaport, S.M., Shen, M., Alter, B.P., Wu, Y.J., Kopp, W., Waidyanatha, S., Rabkin, C., Guo, W.H., Chanock, S., Hayes, R.B., Linet, M., Kim, S., Yin, S.N., Rothman, N., Smith, M.T., 2004. Hematotoxicity in workers exposed to low levels of benzene. *Science* 306, 1774-1776.
- Mayrsohn, H., Crabtree, J.H., Kuramoto, M., Sothorn, R.D., Mano, S.H., 1977. Source reconciliation of atmospheric hydrocarbons 1974. *Atmospheric Environment* 11, 189-192.
- Monod, A., Sive, B.C., Avino, P., Chen, T., Blake, D.R., Rowland, F.S., 2001. Monoaromatic compounds in ambient air of various cities: a focus on correlations between the xylenes and ethylbenzene. *Atmospheric Environment* 35, 135-149.
- Paustenbach, D.J., Price, P.S., Ollison, W., Blank, C., Jernigan, J.D., Bass, R.D., Peterson, H.D., 1992. Reevaluation of benzene exposure for the Pliofilm (rubberworker) cohort (1936-1976). *Journal of Toxicology and Environmental Health* 36, 177-231.
- Rinsky, R.A., Hornung, R.W., Silver, S.R., Tseng, C.Y., 2002. Benzene exposure and hematopoietic mortality: a long-term epidemiologic risk assessment. *American Journal of Industrial Medicine* 42, 474-480.
- Rinsky, R.A., Smith, A.B., Hornung, R., Filloon, T.G., Young, R.J., Okun, A.H., Landrigan, P.J., 1987. Benzene and leukemia. *The New England Journal of Medicine* 316, 1044-1050.
- Scheff, P.A., Wadden, R.A., 1993. Receptor modeling of volatile organic compounds: I. Emissions inventory and validation. *Environmental Science and Technology* 27, 617-625.
- Scheff, P.A., Wadden, R.A., Kenski, D.M., Chung, J., Wolff, G., 1996. Receptor model evaluation of the southeast Michigan ozone study ambient NMOC measurements. *Journal of Air and Waste Management Association* 46, 1048-1057.
- Srivastava, A., Joseph, A.E., Devotta, S., 2006. Volatile organic compounds in ambient air of Mumbai –India. *Atmospheric Environment* 40, 892-903.
- Srivastava, A., Joseph, A.E., More, A., Patil, S., 2005. Emissions of VOCs at urban petrol retail distribution centres in India (Delhi and Mumbai). *Environmental Monitoring and Assessment* 109, 227-242.
- Srivastava, A., 2004. Source apportionment of ambient VOCs in Mumbai city. *Atmospheric Environment* 38, 6829-6843.
- Sweet, C.W., Vermette, S.J., 1992. Toxic volatile organic compounds in urban air in Illinois. *Environmental Science and Technology* 26, 165-173.
- U.S. Environmental Protection Agency (USEPA), 2009. 2002 National Scale Air Toxics Assessment, 2002 Assessment Results, <http://www.epa.gov/ttn/atw/nata2002/tables.html> (accessed on 7/2/2009).
- U.S. Environmental Protection Agency (USEPA), 2007. Control of Hazardous Air Pollutants from Mobile Sources, Regulatory Impact Analysis, EPA Report No. EPA420-R-07-002, Assessment and Standards Division, Office of Transportation and Air Quality, U.S. Environmental Protection Agency.
- U.S. Environmental Protection Agency (USEPA), 1999. Determination Of Volatile Organic Compounds (VOCs) In Air Collected In Specially-Prepared Canisters And Analyzed By Gas Chromatography/Mass Spectrometry (GC/MS), Compendium Method TO-15, EPA Report No. EPA/625/R-96/010b, U.S. Environmental Protection Agency, Cincinnati, OH, January 1999.
- U.S. Environmental Protection Agency (USEPA), 1993. Motor Vehicle-Related Air Toxics Study, Technical Support Branch, Emission Planning and Strategies Division, Office of Mobile Sources, Office of Air and Radiation, U.S. Environmental Protection Agency.
- Utterback, D.F., Rinsky, R.A., 1995. Benzene exposure assessment in rubber hydrochloride workers - a critical-evaluation of previous estimates. *American Journal of Industrial Medicine* 27, 661-676.
- Vega, E., Mugica, V., Carmona, R., Valencia, E., 2000. Hydrocarbon source apportionment in Mexico City using the chemical mass balance receptor model. *Atmospheric Environment* 34, 4121-4129.
- Watson, J.G., Cooper, J.A., Huntzicker, J.J., 1984. The effective variance weighting for least squares calculations applied to the mass balance receptor model. *Atmospheric Environment* 18, 1347-1355.

Watson, J.G., Robinson, N.F., Chow, J.C., Henry, R.C., Kim, B.M., Pace, T.G., Meyer, E.L., Nguyen, Q., 1990. The USEPA/DRI chemical mass balance receptor model, CMB 7.0. *Environmental Software* 5, 38-49.

Watson, J.G., Chow, J.C., Fujita, E.M., 2001. Review of volatile organic compound source apportionment by chemical mass balance. *Atmospheric Environment* 35, 1567-1584.