
Environmental Sources of Benzene Exposure: Source Contribution Factors

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ABSTRACT

The National Interim Primary Drinking Water Regulations are undergoing review. As part of that effort, the health risks associated with selected organic drinking water contaminants for which standards were not promulgated in the interim regulations are being assessed. This study is intended to assist the Office of Drinking Water, U.S. Environmental Protection Agency, in that effort by identifying the frequency of occurrence of benzene in the various environmental media, characterizing the benzene levels in these media, and determining the relative benzene contribution of each of these sources to an individual's total daily benzene uptake.

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EXECUTIVE SUMMARY

The MITRE Corporation/Metrek Division has been assisting the Criteria and Standards Division, Office of Drinking Water, U.S. Environmental Protection Agency in assessing the adequacy of the Interim Primary Drinking Water Regulations. Part of this effort has been the identification of the frequency of occurrence of benzene in the various environmental media, characterization of the benzene levels in these media, and determination of the relative benzene contributions of each of the pertinent environmental sources to an individual's total daily benzene uptake.

Benzene is emitted to the environment from petroleum refineries and coke ovens, the two major sources of commercial benzene production, and from chemical manufacturing facilities, the major avenue of benzene consumption. Benzene is highly volatile, and there is therefore a considerable potential for evaporative emissions to the atmosphere during production, storage, transport, and use of the compound. Facilities which produce benzene and its major by-products (styrene, phenol, and cyclohexane) are primarily located near the major domestic sources of oil and coal, i.e., in the Gulf Coast States and the Middle Atlantic States, respectively, and emissions from these sources will be greatest in these areas. The majority of benzene transport in the U.S. is between these centers of production and consumption, and thus, losses during transport are largely restricted to the interconnecting transportation routes. Emissions from all of these sources in 1971 have been estimated to be as much as 738 million pounds (42 percent of total quantified U.S. benzene emissions).

Benzene is a component of gasoline, and motor vehicle emissions are thought to constitute the greatest source of benzene emissions. Atmospheric emissions from this source contained an estimated 1 billion pounds in 1971 (57 percent of total 1971 emissions). Benzene is also emitted to the environment by evaporation of gasoline during transfer. Additional losses result from evaporation of benzene-containing solvents and from oil and fuel spills.

Data on atmospheric benzene levels are scarce, as there has been no routine program for monitoring atmospheric pollution by this compound. Reported values range from 3 to 900,000 $\mu\text{g}/\text{m}^3$, although levels at the high end of this range were measured in areas where production, use, or disposal of benzene was thought to create a local air pollution problem. A conservative estimate for the national average urban benzene concentration is 50 $\mu\text{g}/\text{m}^3$.

Data on levels on benzene in food are extremely limited although benzene has been measured qualitatively in a large number of food-stuffs. Eggs have been found to contain high levels (1900 $\mu\text{g}/\text{kg}$) of the compound. Daily dietary benzene intake has been estimated to be as much as 250 μg .

Benzene has been detected in 6 percent of the 113 U.S. water supplies surveyed in the National Organics Monitoring Survey (NOMS). The median concentration for all samples ranged from less than 0.1 to 0.2 $\mu\text{g}/\text{l}$. The highest concentration was 1.8 $\mu\text{g}/\text{l}$. Benzene was detected in four of ten drinking water supplies in the National Organics Reconnaissance Survey (NORS). Concentrations in these four water supplies ranged from 0.1 to 0.3 $\mu\text{g}/\text{l}$.

Inhalation of benzene is the most frequent cause of industrial benzene poisoning, and thus inhalation has been the most intensely studied exposure route. At ambient airborne concentrations, up to 80 percent of inhaled benzene may be absorbed by the lungs. However, studies in which persons were exposed to benzene concentrations over 1000 times higher than urban ambient levels revealed a steady-state absorption rate of about 45 percent. The rate of benzene uptake via the gastrointestinal tract is believed to be high, although no conclusive data are available. It has been conservatively assumed, therefore, that 100 percent of the ingested benzene is absorbed. Dermal absorption is insignificant under ambient environmental conditions.

After inhalation exposure as much as half or as little as 10 percent of the benzene absorbed by the body is excreted unchanged through the lung. Most of the remainder is excreted as metabolites in the urine. Metabolism takes place in the liver, and possibly also in the bone marrow. The major metabolic products are phenol and its congeners.

The total daily benzene uptake and the percent contribution to this total uptake from each of these environmental sources have been calculated for an adult male in an urban setting. These calculations are based upon average concentrations in the various environmental media (air, food, and water), and estimated consumption and absorption rates for these media and the benzene contained therein. Based upon the assumptions utilized, air is the predominant source of benzene absorbed by the general populations. This source contributes more than 65 percent of the total daily benzene uptake at all drinking water concentrations considered. Drinking water contributes less than 3 percent at benzene concentrations of 10 $\mu\text{g}/\text{l}$, and well below 1 percent at assumed urban ambient average conditions.

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1.0 INTRODUCTION

The Office of Drinking Water (ODW) within the United States Environmental Protection Agency (EPA) in accordance with the Safe Drinking Water Act as amended has promulgated National Interim Primary Drinking Water Regulations for a number of physical, chemical, biological and radiological contaminants in potable water systems. These interim standards, which specify maximum contaminant levels (MCLs) for substances in drinking water, will be replaced by final Primary Drinking Water Regulations as more definitive information describing the health risks associated with each contaminant is accumulated and analyzed.

Because of a paucity of data on the occurrence of various organic chemicals in drinking water supplies and the associated risks to human health, and uncertainties over appropriate methods of treatment, the only organic chemicals for which MCLs were specified in the Interim Primary Drinking Water Regulations were selected pesticides. In order to be able to specify MCLs for additional organic contaminants in the final Primary Drinking Water Regulations, EPA has published Special Monitoring Regulations, and in accordance with these regulations, is conducting a National Organics Monitoring Survey (NOMS) of drinking water supplier in 113 U.S. cities.

The MITRE Corporation/METREK Division has been assisting the Criteria and Standards Division, Office of Drinking Water in the identification of the frequency of occurrence of benzene in the

various environmental media, characterization of the benzene levels in these media, and determination of the relative benzene contribution of each of the pertinent environmental sources to an individual's total daily benzene uptake. The source contribution model utilized in this study identifies those environmental sources affording the greatest potential for exposure to benzene, enabling the most effective regulatory action to be initiated.

1.1 Background

Benzene is widely distributed throughout the environment. The compound is a component of petroleum and light oil produced from coal, and it is produced commercially from both of these sources. Benzene is also a component of gasoline. Benzene is highly volatile and therefore the production and use of the compound, and of gasoline, offer substantial opportunity for atmospheric benzene emissions. Consequently benzene appears to be ubiquitously distributed in the atmosphere. Benzene has also been detected in a number of U.S. waterways and community water supplies and in some foods.

Because of the multiple exposure pathways, the relative contributions to an individual's daily benzene uptake arising from specific environmental media are being defined. In this way, if benzene appears to pose a significant health risk as a result of exposure via daily drinking water intake alone, or if drinking water intake contributes significantly to the total daily benzene uptake, then an intensive review and analysis of the problem will be initiated.

1.2 Approach

In order to properly assess the health significance of the ingestion of benzene contaminated drinking water, it is necessary to define the contributions to an individual's total daily benzene uptake from each major source of exposure. These source contribution factors can be defined in three successive steps, i.e.,

- define and quantify the major environmental sources of benzene exposure,
- determine the absorption/metabolism/retention and elimination characteristics of benzene in man via each exposure route, and
- estimate total daily uptake of benzene in man, based on ambient exposures and absorption/retention characteristics.

By examining the percent contribution to the total uptake from each route of exposure, one can calculate the source contribution factors for each type of benzene exposure. In this way, the significance of benzene exposure via drinking water can be assessed in view of the other possible exposure routes.

This report defines the percent contribution to the total daily benzene uptake from all the major environmental sources of exposure. The report does not, however, consider or evaluate the toxicological implications of such benzene uptake. Those instances when critical data were insufficient or lacking are pointed out in the text.

2.0 BENZENE INPUT TO THE ENVIRONMENT

Benzene is emitted to the environment from petroleum refineries and coke ovens, the two major production sources, and chemical manufacturing facilities; by evaporation of benzene during storage and transport and during use of benzene as a solvent; and by evaporation of petroleum-based fuels. Combustion of fossil fuels may also be an important source of benzene emissions, although the contribution from this source has not been quantified. Many of the industrial emission sources are located near the major domestic sources of oil and coal (in the Gulf Coast and Middle Atlantic states, respectively). The quantitative and geographical distributions of benzene emissions from the major quantified emission sources are shown in Table 2-1.

2.1 Benzene Production, Storage and Transport

Benzene has been commercially produced from light oil (generated by the carbonization of coal to coke) since 1849 and from petroleum since 1941 (Ayers and Muder, 1964). The compound is still derived from both sources but petroleum currently supplies most of the benzene produced in the U.S. Approximately 92 percent is derived from this source (Mara and Lee, 1977). As of early 1975, the total capacity of U.S. benzene production facilities was 1.74 billion gallons (12.7 billion pounds) per year (SRI, 1975). Actual production of chemical benzene in 1975 was 8.04 billion pounds (USITC, 1977). U.S. benzene production capacity was more than doubled during the decade from 1963 to 1973 (SRI, 1975).

TABLE 2-1

DISTRIBUTION OF U.S. BENZENE EMISSIONS, 1971

<u>Origin</u>	<u>Primary Geographic Location</u>	<u>Quantity (10⁶ lbs.)</u>
Commercial Benzene Production, Storage, and Transport	Gulf Coast States, Middle Atlantic States	80 ^a
By-product Manufacture	Gulf Coast States, Middle Atlantic States	658 ^b
Oil Spills	Oceans, Rivers	23
Motor Vehicle Emissions	Approximates Population Distribution	1000
<hr/> Total of quantified emissions		<hr/> 1761

^aOne percent of total 1971 benzene production.

^bUpper limit (see Table 2-2).

SOURCE: Adapted from Howard and Durkin, 1974.

Although the Compilation of Air Pollution Emission Factors (EPA, 1973) states that "there are essentially no emissions from petroleum reforming operations" the high volatility of benzene suggests that some degree of evaporative loss during production, storage, transfer and transport is almost inevitable. Benzene is normally stored and/or transported in steel tanks, 55-gallon metal drums, tank trucks and barges (Erskine, 1972) and there is a potential for vapor emission during transfer to and from each of these containers. In addition, the rupture of a benzene container may result in high local atmospheric benzene levels, the absolute magnitudes of which will depend upon the extent of benzene loss and local physical conditions. Quantitative estimates of the total benzene emissions from these sources are not available; however, Howard and Durkin (1974) have assumed that economic constraints on benzene loss would limit emissions to 1 percent or less of the total quantity produced. The majority of benzene production facilities are located near major domestic sources of oil (in the coastal areas of Louisiana and Texas) and coal (predominantly in Ohio and Pennsylvania) (Howard and Durkin, 1974); therefore, the quantity of benzene emissions associated with production will be greatest in these areas. Benzene transport is mainly from the Gulf Coast States to the Middle Atlantic states, and thus, losses during transport will be largely restricted to the major interconnecting transportation routes (Howard and Durkin, 1974; as indicated in Table 2-1).

TABLE 2-2

UPPER LIMIT OF BENZENE LOSSES
FROM BY-PRODUCT MANUFACTURING IN 1971^a

<u>By-Product</u>	<u>Consumption (10⁶ lbs.)</u>	<u>Percent Yield</u>	<u>Upper Limit of Losses^b (10⁶ lbs.)</u>
Styrene	3709	97	111
Phenol	1610	82	290
Cyclohexane	1311	100	0
Maleic Anhydride	325	57	140
Detergent Alkylate	323	80	65
Aniline	297	93	21
Dichlorobenzene	94	85	14
DDT	43	60	17
All Other Non- fuel Uses ^c	<u>676</u>	---	<u>---</u>
	8388(7712 ^d)		658

^aQuantity not accounted for by end-product yield.

^bLosses may not only be benzene but also process intermediates.

^cIncludes synthesis of anthraquinone, benzene hexachloride, chlorobenzene (for use other than as an intermediate for DDT, aniline, and phenol manufacture), diphenyl, nitrobenzene (other than for aniline), cumene (other than for phenol), and ethylbenzene (other than for styrene); and solvent uses.

^dTotal excluding "Other Nonfuel Uses".

SOURCE: Adapted from Howard and Durkin, 1974.

2.2 Commercial Uses of Benzene

Chemical manufacture accounts for most of the benzene used in the U.S. (more than 7.7 billion pounds, or 92 percent of the total U.S. consumption, in 1971 [Howard and Durkin, 1974]). The manufacturing processes used in the production of benzene-derived chemicals vary widely in efficiency; 100 percent of the theoretical yield of cyclohexane is produced, whereas a yield of 57 percent is attained in maleic anhydride production (Table 2-2). The difference between the maximum potential yield of these benzene by-products (100 percent) and the actual yield, has been used to develop an upper bound of 658 million pounds for the 1971 benzene emissions from facilities manufacturing the principal by products (Howard and Durkin, 1974; as shown in Table 2-2).

The geographical distribution of the major benzene by-product manufacturing facilities is not uniform. The majority of these facilities are located in the Gulf Coast states (24 of the 49 U.S. manufacturing facilities are located in Texas, Louisiana, Mississippi, and Alabama; 14 of these are at the site of a benzene production facility) and the Middle Atlantic States (New Jersey, Pennsylvania, West Virginia, and Maryland have 14 such facilities). Texas alone has 20 such manufacturing facilities (Howard and Durkin, 1974).

Benzene is used to some extent as an ingredient in paint brush cleaners, paint and varnish removers, and other multicomponent solvent formulations (Gosselin et al., 1976). The compound is an

excellent solvent for rubber, and has been used as such in rubber manufacture (Mara and Lee, 1977) and in rubber cements (Ayers and Muder, 1964). Benzene will be emitted to the atmosphere by evaporation during use of these products, and may also be emitted to streams and rivers via disposal of these products in domestic and industrial wastewater.

2.3 Contamination from Petroleum and Petroleum-Derived Fuels

Benzene is a component of petroleum and of gasoline and other fuels which are derived from petroleum (Howard and Durkin, 1974). Before 1974, most gasoline produced in the U.S. contained less than 1 liquid volume (lv) percent benzene (1.3 percent by weight), although concentrations as high as 2 lv percent were reported (Runion, 1975). Sanders and Maynard (1968) analyzed regular and premium gasolines and found them to contain 1.35 and 0.81 percent benzene by weight, respectively. As the average lead content of U.S. gasoline has decreased, however, it has been necessary to increase the benzene concentration to maintain the same average octane rating. More recent estimates (PEDCo Environmental, Inc., 1977) of the average benzene content of U.S. gasoline range from 1.24 to 2.5 lv percent.

The concentrations of benzene in U.S. gasolines are limited by both the refinery process methods used and economic considerations. Because of the refinery methods utilized, most gasolines produced in the U.S. contain between 15 and 35 percent aromatic-rich reformates, whereas European gasolines generally contain 85 to 90 percent

reformates (Runion, 1975). Furthermore, selective separation of benzene is economically practical, as it offers a much higher return to the refiner than when benzene is sold as a fuel component (Runion, 1975).

Howard and Durkin (1974) have calculated the total 1971 benzene motor vehicle emissions based on total hydrocarbon emissions of 2.94 billion pounds. If it is assumed that evaporated gasoline constitutes 20 percent by weight of the total emissions, and benzene constitutes 1 percent of these vapors, then benzene emissions from gasoline evaporation would amount to 58.8 million pounds. In addition, benzene constitutes 2.15 percent by volume of the hydrocarbon exhaust emissions from a reciprocating (piston) engine (Schofield, 1974). This is about 4 percent by weight (Howard and Durkin, 1974). Therefore, the amount of benzene in the hydrocarbon exhaust emissions (the remaining 80 percent of the total hydrocarbon emissions) would be about 941 million pounds, and the total 1971 motor vehicle benzene emissions would be about 1 billion pounds (Table 2-1). From these projections, motor vehicle emissions were projected to be the largest source of atmospheric benzene in 1971. The geographic distribution of these emissions would vary with traffic density and would therefore be approximately the same as that of U.S. population. Evaporation of gasoline during pumping and bulk loading operations will also result in atmospheric benzene emissions; however, these emissions have not been quantified.

Environmental benzene contamination may also result from oil and fuel spills and from the evaporation and incomplete combustion of benzene-containing fuels other than gasoline. The total influx of oil into the oceans from routine discharges from tankers, tanker accidents, leaks during storage, pipeline breaks, disposal of spent lubricants, incompletely burned fuels, and untreated industrial and domestic sewage is estimated to be between 11 and 12 billion pounds per year (Blumer et al., 1971). Assuming that the concentration of benzene in these discharges is the same as the average concentration in crude oil (0.2 percent by weight, Howard and Durkin, 1974), the total annual emission of benzene into the oceans is 22 to 24 million pounds.

3.0 ENVIRONMENTAL SOURCES OF BENZENE EXPOSURE

Although many potential sources of environmental benzene contamination have been identified, monitoring data that would allow prediction of the extent of the benzene exposure of the general population attributable to these sources are extremely limited. Benzene levels have been measured in the ambient air and water in a number of locations throughout the western world and in a small number of food-stuffs. The results of these measurements can be used to develop tentative estimates of average ambient environmental levels and exposure rates.

3.1 Benzene Concentrations in Ambient Air

The ambient concentration of benzene in urban air is estimated to range from about 4 to 200 $\mu\text{g}/\text{m}^3$; (Altshuller, 1969; Bertsch et al., 1974; Pilar and Graydon, 1973). This estimate is based on a very small body of data, as the level of benzene in ambient air is not routinely monitored. Concentrations of airborne benzene reported in the literature range from a trace to 900,000 $\mu\text{g}/\text{m}^3$ for areas as widely dispersed as Zurich, Switzerland; Vancouver, Canada; Edison, New Jersey; and Iberville Parish Louisiana (Grob and Grob, 1971; Williams, 1965; RTI #9, 1976; RTI #2, 1977). Values at the upper end of this range probably do not reflect conditions encountered by a large majority of the population, however, as many of the reported atmospheric benzene concentrations were measured in areas where production use, or disposal of organic chemicals was thought to produce

a local air pollution problem. A summary of reported benzene levels in air is presented in Table 3-1.

Mara and Lee (1977) calculated the number of persons exposed to benzene from each of the major emission sources in selected concentration ranges above 0.1 ppb ($0.32 \mu\text{g}/\text{m}^3$) and the total exposure (in ppb-person-years) attributable to each source. The results are shown in Table 3-2.

Schewe (1977) estimated the average atmospheric benzene concentrations in four U.S. cities (Dallas, Los Angeles, St. Louis, and Chicago) based upon estimated automotive emissions, area, and average wind conditions. The estimated concentrations ranged from 3.0 (Dallas) to $13.8 \mu\text{g}/\text{m}^3$ (Chicago). However, these estimates are contradicted by reported levels in Los Angeles and other cities (Table 3-1), and a more realistic estimate of the average urban value is about $50 \mu\text{g}/\text{m}^3$. This high benzene concentration is primarily associated with high levels of motor vehicle traffic.

Evaporative emissions from gasoline service stations are also responsible for a large amount of human exposure to atmospheric benzene, through exposure of both nearby residents and customers, especially those using self-service facilities. Based upon limited data, Runion (1975) reported that gasoline vapor concentrations to which service station attendants were exposed were less than 10 ppm. Assuming benzene constituted 1 percent of these vapors, this corresponds to a benzene concentration of $320 \mu\text{g}/\text{m}^3$.

TABLE 3-1

BENZENE CONCENTRATIONS IN AIR			
Concentration ($\mu\text{g}/\text{m}^3$)	Location	Reference	Remarks
1	Theruville Parish, LA	RTI #2, 1977	Average value from 11 samples (maximum reported $18.08 \mu\text{g}/\text{m}^3$). Near heavy organic chemical industry.
3-31	Vancouver, Canada	Williams, 1965	Range of levels in ambient air.
4-19	Houston, TX	Lonneman, 1978	Range of ambient levels.
4-48	Houston, TX	Bertsch et al., 1974	Range from more than 150 samples analyzed.
5-100	New York, New Jersey	Lonneman, 1978	Range of levels detected in New York City Metropolitan area.
7-59	Denver, CO	Lonneman, 1978	Range of levels.
Trace-200	Fallston, NJ	EPA, 1978	Samples taken upwind from landfill (or disposal of chemical wastes).
16-70	Los Angeles Basin, CA	Nollman et al., 1965	
17	Baton Rouge, LA	EPA/Report #1000/ Benzene/LA	Average of 7 samples. Concentration at the upwind site ($11.7 \mu\text{g}/\text{m}^3$) was determined to be the background level.
18	Los Angeles, CA	RTI #3, 1976	Single sample.
25-76	Riverside, CA	Stephens, 1973	
27-59	Denver, CO	Lonneman, 1978	
32-160	Urban ambient air (U.S.)	Altshuller, 1968	
34	Dominguez, CA	RTI #3, 1976	
42	Toronto, Canada	Pilar and Grawdon, 1973	Average of over 1000 samples (maximum value $313 \mu\text{g}/\text{m}^3$).
48	Los Angeles Basin, CA	Lonneman et al., 1968	Average value (maximum value $181.8 \mu\text{g}/\text{m}^3$).
48-191	Downtown Los Angeles, CA	Altshuller and Bellar, 1963	
172	Zurich, Switzerland	Grob and Greb, 1971	Sample taken near Celanese Corporation.
300	Newark, NJ	RTI #11, 1976	Samples taken on or downwind from landfill site.
Trace-1550	Edison, NJ	EPA, 1978, RTI #2, 1976	Highest value found in a valley near a chemical plant which recovered solvents from discarded materials.
73,400	Elberton, MD	Capurro, 1973	

TABLE 3-2

ATMOSPHERIC BENZENE EXPOSURES ATTRIBUTABLE TO MAJOR EMISSION SOURCES:
NUMBER OF PERSONS EXPOSED AT VARIOUS CONCENTRATIONS

Emission Source	Concentration (ppb) ^a				Total Exposed Population ^b	Total Exposure (ppb-person-years)
	2.5 to 25.0 0.1 to 1.0	25.1 to 100.0 1.1 to 4.0	100.1 to 250.0 4.1 to 10.0	>250.0 > 10.0		
8 Hr Worst Case: Annual Average:	2.5 to 25.0 0.1 to 1.0	25.1 to 100.0 1.1 to 4.0	100.1 to 250.0 4.1 to 10.0	>250.0 > 10.0	Total Exposed Population ^b	Total Exposure (ppb-person-years)
Chemical Manufacturing.	6,000,000	1,000,000	200,000	80,000	7,300,000	8,500,000
Coke Ovens	300,000	---	---	---	300,000	200,000
Gasoline Service Stations						
1) Persons using self-service	---	---	---	---	37,000,000	1,600,000 ^c
2) Persons residing in immediate vicinity	20,000,000	900,000	---	---	21,000,000	12,000,000
Petroleum Refineries	5,000,000	3,000	4,000	< 500	5,000,000	2,500,000
Solvent Operations ^d		---	---	---	---	---
Storage and Transport ^e		---	---	---	---	---
Automobile Emissions	69,000,000	45,000,000	---	---	110,000,000	150,000,000

^a 1ppb = 3.19 ug/m³.

^b Total number of persons exposed in each exposure range not calculated due to possible overlap. Highest value in each column is the lower limit for the population exposed. Totals are rounded to two significant figures.

^c Estimated at 265 ppb for 1.5 hr./yr./person.

^d Cannot be determined.

^e Estimated at <0.1 ppb annual average. Exposed population not determined but assumed to be small.

SOURCE: Adapted from Mata and Lee, 1978.

The use of benzene-containing solvents and the misuse of gasoline as a solvent cleaner for machine parts, paint brushes, hands, etc., probably results in the greatest short-term atmospheric benzene levels encountered by the general public (Runion, 1975). Limited testing in an enclosed room with no positive ventilation showed that when gasoline is used in this way, concentrations of 100 ppm total hydrocarbons (about 3200 $\mu\text{g}/\text{m}^3$ benzene) would be reached frequently in the breathing zone, and momentary peaks would be as high as 500 to 1000 ppm total hydrocarbons (16 to 32 mg/m^3 benzene).

Reclamation of spent solvents may be another source, however minor, of atmospheric benzene. In May 1970 the Maryland State Health Department contracted with the Thiokol Chemical Company to collect and analyze air samples from a small valley near Elkton, Maryland. It was believed that higher-than-normal concentrations of various solvents would be found due to the presence of a reclamation facility in the vicinity (Capurro, 1973). Benzene was found in the "...air of the valley within two miles of the plant," in "...the blood of people in the valley," and in water from a nearby creek. A maximum atmospheric concentration of 73,375 $\mu\text{g}/\text{m}^3$ was reported.

3.2 Benzene Concentrations in the Diet

According to Mr. Corbin Miles, Chief of the GRAS* Review Branch of the Food and Drug Administration, exposure to benzene via

*Generally regarded as safe.

the diet is not considered to be a problem of the general population (Miles, 1977). However, benzene has been detected in fruits, nuts, vegetables, dairy products, meat, poultry, eggs, fish, and several different beverages (Table 3-3), and is thought to occur naturally (possibly as a flavor component) in many or all of the foods in which it is found. Concentrations of benzene have been measured in only a small number of these foods: butter (0.5 $\mu\text{g/kg}$; Siek and Lindsay, 1970); cooked beef (2 to 19 $\mu\text{g/kg}$; National Cancer Institute, 1977); eggs (500 to 1900 $\mu\text{g/kg}$ *; MacLeod, 1976; MacLeod and Cave, 1976); haddock (100 to 100 $\mu\text{g/kg}$; Merritt, 1972); and Jamaican Rum (120 $\mu\text{g/kg}$; Liebich et al., 1970). The benzene level in heated lamb, mutton, and veal, and in chicken, is less than 10 $\mu\text{g/kg}$ (Merritt, 1972).

In some cases, the concentration of benzene in foods may be affected by food preparation techniques. Chang and Peterson (1977) found large amounts of benzene in the volatile fraction of boiled beef and canned beef stew. It has been speculated that the cooking of meats causes an increase in their benzene content due to the breakdown of the aromatic amino acids (phenylalanine and tyrosine) (FASEB, 1977). However, the benzene concentration in nonirradiated haddock (stored for 14 days) was found to be twice as great as that in irradiated haddock (stored for 30 days) (Merritt, 1972).

*Calculated from the fraction of benzene in total egg volatiles (0.1 to 0.38 percent) and the fraction of volatiles in the whole egg (0.05 percent) for a 50 g egg.

TABLE 3-3

FOODS REPORTED TO CONTAIN BENZENE

<u>Fruits</u>	<u>Dairy Products</u>
Apple	Butter (0.5) ^{1,2}
Citrus Fruits	Bleu Cheese
Cranberry and Bilberry	Cheddar Cheese
Currants	Other Cheese
Feyoa and Guave	
Pineapple	
Strawberry	
Tomato	
<u>Nuts</u>	<u>Meat, Fish and Poultry</u>
Filbert (roasted)	Beef (cooked) (2 to 19) ³
Peanut (roasted)	Chicken (<10) ⁴
Macademia Nut	Egg (hard boiled) (500 to 1900) ⁵
	Haddock (100 to 200) ⁶
	Lamb (heated) (<10) ⁴
	Mutton (heated) (<10) ⁴
	Veal (heated) (<10) ⁴
<u>Vegetables</u>	<u>Beverages</u>
Beans	Cocoa
Leek	Coffee
Mushroom	Jamaican Rum (120) ⁷
Onion (roasted)	Tea
Parsley	Whiskey
Potatoe	
Soya Bean	
Trassi (cooked)	

¹Numbers in parentheses are concentrations in µg/kg (ppb).

²Siek and Lindsay, 1970.

³National Cancer Institute, 1977.

⁴Merritt, 1972.

⁵MacLeod, 1976; MacLeod and Cave, 1976.

⁶Irradiated and non-irradiated haddock, respectively. Merritt, 1972.

⁷Liebich et al., 1970.

SOURCE: Adapted from Van Stratten, 1977; Others (see footnotes).

It has been estimated that an individual's dietary benzene intake from beef, eggs, and rum alone, may be as high as 250 $\mu\text{g}/\text{day}$ (National Cancer Institute, 1977). Of the foods in which benzene levels have been quantified, eggs are the most significant source; one egg may contain as much as 100 μg of benzene.

3.3 Benzene Concentrations in Drinking Water

The literature does contain a small number of references to benzene concentrations in drinking water (Table 3-4). Benzene was one of a number of organic drinking water contaminants identified in U.S. community water supplies in the National Organics Monitoring Survey (NOMS) of the U.S. Environmental Protection Agency (See Table 3-4); NOMS Phase I; Phase II; Phase III). The majority of water supplies tested were located in urban areas. The median benzene concentration was less than 0.2 $\mu\text{g}/\text{l}$. Benzene was detected in only about 6 percent of the 113 water supplies surveyed. These results essentially verified the drinking water benzene concentrations reported in the earlier National Organics Reconnaissance Survey (U.S. Environmental Protection Agency, 1975). Benzene was detected in 4 of 10 water supplies surveyed, in concentrations ranging from 1.0 to 3.0 $\mu\text{g}/\text{l}$.

An analytical study of tap water derived from the Mississippi River compared chemicals in the water with substances in waste effluents of 60 industries discharging wastes into the river (U.S. Environmental Protection Agency, 1972). A total of 53 organic chemicals were detected in the effluent from 11 of the plants monitored.

TABLE 3-4
BENZENE CONCENTRATIONS IN DRINKING WATER

Benzene Concentration ($\mu\text{g/l}$)			Location	Reference	Remarks
Mean (positive samples)	Median (all samples)	Range (positive samples)			
-	- Not detected -	-	111 U.S. community water supplies	National Organics Monitoring Survey (NOMS), Phase I, March-April, 1976	Minimum quantifiable limit was 2 $\mu\text{g/l}$.
-	- Not detected -	-	Seattle, Washington; Tucson, Arizona; New York, New York; Lawrence, Massachusetts; Grand Forks, North Dakota; Terrebonne Parish, Louisiana	U.S. Environmental Protection Agency, 1975 (National Organics Reconnaissance Survey) (NORS)	
-	- Not detected -	-	Nassau County, New York	Myott, 1977	Results of 110 samples obtained from 88 wells.
-	- Trace -	-	Derived from Mississippi River	U.S. Environmental Protection Agency, 1972	
-	- Trace -	-	Carville, Louisiana	Friloux, 1971	
0.4	<0.1-0.2	0.1-1.8	113 U.S. community water supplies	National Organics Monitoring Survey (NOMS), Phase II, May-July, 1976	Benzene was detected ($\geq 0.1 \mu\text{g/l}$) in 7 water supplies in 7 states.
0.54	<0.1	0.23-0.82	Huntington, New York	Glick et al., 1978	Benzene was detected ($\geq 0.1 \mu\text{g/l}$) in 4 of 10 samples.
0.95	<0.1-0.2	0.9-1.5	16 U.S. community water supplies	NOMS Phase III, November 1976-January 1977	Benzene was detected ($\geq 0.1 \mu\text{g/l}$) in 4 water supplies in 4 states.
0.1-0.3			Miami, Florida; Ottumwa, Iowa; Philadelphia, Pennsylvania; Cincinnati, Ohio	U.S. Environmental Protection Agency, 1975 (NORS)	
2.5	<0.1	1.0-6.0	14 Industrial river basins	Ewing et al., 1977	Benzene was detected ($\geq 1.0 \mu\text{g/l}$) in 4 of 18 samples.

Although a trace of benzene was found in the tap water, it was not detected in the effluent from any of the facilities, suggesting a source of contamination other than the industrial waste.

Dowty et al., (1975) thermally extracted low molecular weight organics from water samples obtained at the intake of a New Orleans area municipal water treatment plant, in the effluent from the clarifier before chlorination, and at the tap. Values of various organics were reported as relative percent abundance in a gas chromatogram. Absolute concentrations were not determined. The samples taken from the Mississippi River at the plant entrance had a relative percent abundance of a combination of benzene, carbon tetrachloride, and dichloroethane (which were inseparable chromatographically) of 12.17 while the value for this same combination from the clarifier effluent was 3.26 and from New Orleans tap water was 36.61. The high relative abundance of this mixture in tap water was apparently the result of chemical disinfection using chlorine and ammonia. Commercially bottled artesian water and deionized, charcoal-filtered tap water processed by a commercial filter unit, were also sampled and analyzed. The relative percent abundance of benzene was 16.16 in the bottled artesian water and 2.17 in the deionized charcoal-filtered water.

Samplings of the effluent from five benzene production and/or consumption facilities revealed concentrations from less than 1.0 to 179 $\mu\text{g/l}$ benzene in the effluent from the plants. However, these

concentrations soon dissipated, as samples from downstream receiving waters had lower benzene concentrations, ranging from less than 1.0 to 13.0 $\mu\text{g/l}$ (Battelle-Columbus Laboratories, 1977).

3.4 Benzene Intake From Smoking

One source that could be of significance to selected individuals is the vapor phase of tobacco smoke. The quantity of benzene in one 40 ml pull of cigarette smoke is 6.1 μg (Newsome et al., 1965). Assuming 15 pulls per cigarette, an individual smoking one pack of cigarettes each day would inhale 667.95 mg of benzene each year from smoking alone.

4.0 ABSORPTION, RETENTION, AND ELIMINATION OF BENZENE IN HUMANS

Benzene can be absorbed into the body after inhalation, ingestion, and, to some extent, dermal contact. Approximately half of the absorbed benzene is rapidly eliminated as unchanged benzene via the pulmonary route, and a small amount of benzene is eliminated in the urine. The remainder is metabolized to a number of different compounds, or retained at various sites. Benzene is retained for the longest time in the fatty tissues and bone marrow.

Metabolism of benzene takes place primarily in the liver, mainly producing phenolic compounds. The toxic effects associated with benzene exposure are thought to be caused by one or more of these metabolic products. The metabolites conjugate with glycine, sulfuric acid, and glucuronic acid, and are subsequently eliminated in the urine. The following sections describe the primary absorption, retention, and elimination mechanisms for benzene.

4.1 Absorption Characteristics

Inhalation of benzene vapors is the predominant cause of benzene poisoning and is therefore the subject of most pharmacokinetic studies. Benzene is rapidly and efficiently absorbed from the lungs and presumably also from the GI tract. Dermal absorption is an insignificant route of uptake under ambient environmental conditions.

4.1.1 Pulmonary Absorption

Because of the high vapor pressure of benzene (100 mm Hg at 26.075°C [Ayers and Muder, 1964]) most incidents of human benzene poisoning in the workplace have been attributed to inhalation (NIOSH,

1974). Therefore, most of the research on benzene absorption has focused on uptake from the lung. A summary of the reported pulmonary benzene absorption rates is given in Table 4-1.

Determinations of the rate of pulmonary benzene absorption have been based upon human exposures to airborne concentrations ranging from 80 to 19140 mg/m³. These concentrations are at least three orders of magnitude higher than ambient atmospheric levels. Under the conditions of these studies, absorption rates varied from 20 to 68 percent, although values found in the older literature are as high as 85 percent (Srbova et al., 1950). The mean absorption rate for benzene, based on the results of the eight studies reported in Table 4-1, is about 45 percent.

The rate of pulmonary absorption, at least at these intake levels, is dependent upon the duration of exposure, and is presumably also dependent upon the concentration of benzene in the inhaled air. Srbova and coworkers (1950) reported that 81 percent of the benzene in inhaled air containing 306 mg/m³ of the compound was absorbed through the lungs of one subject after 5 minutes of exposure, whereas the absorption rate declined to 52.5 percent after 15 minutes, and remained at approximately this level thereafter. In similar studies with additional subjects (Srbova et al., 1950; Nomiyama and Nomiyama, 1974b), absorption rates continued to decline very slowly, reaching an apparent steady state after 2 to 3 hours. This decrease in absorptive efficiency is thought to be due to increasing saturation of the blood and tissues with benzene (Srbova et al., 1950; Nomiyama and

Table 4-1

SUMMARY OF REPORTED PULMONARY ABSORPTION
RATES FOR BENZENE

<u>Percent Absorption</u>	<u>Concentration (mg/m³)</u>	<u>Duration of Exposure</u>	<u>Reference</u>
20,42 ^a	191-255	4 hours	Nomiyama and Nomiyama, 1969
20-50	150-350	2-3 hours	Srbova et al., 1950
28-34	19140	---	Duvoir et al., 1946
45.8,48.0 ^a	166-198	4 hours	Nomiyama and Nomiyama, 1974b
46	320	5 hours	Teisinger et al., 1952
47	112	5-7 minutes	Hunter, 1966
53-63	80-100	3-4 hours	Hunter and Blair, 1972
68	b	>2 hours	Fiserova-Bergerova et al., 1974

^aValues for males and females, respectively.

^bNot specified.

Nomiyama, 1974B). If this is the case, then at much lower atmospheric concentrations, such as those ordinarily encountered by the general population, the degree of saturation achieved at an equilibrium state will be quite low (since metabolism and elimination of most of the absorbed benzene is fairly rapid; See section 4.1.4) and the absorption rate should never drop far below the initial value (60 to 80 percent based on studies of Srbova et al., 1950; Fiserova-Bergerova et al., 1974). Although the absorption rates given in Table 4-1 do not show a clear dependence upon concentration, as would be required to confirm this reasoning, a comparison of absorption rates and concentrations utilized suggests that there were significant differences in the methods utilized and/or considerable variability in individual physiological parameters of the test subjects. Because of the uncertainty over pulmonary absorption kinetics in the ambient exposure situation, two values, 80 and 45 percent, will be used in subsequent calculations.

One study (Nomiyama and Nomiyama, 1969) revealed significant differences in the absorption rates of males and females. It was suggested that females would therefore be more susceptible to benzene intoxication. However, a more recent study by the same authors (Nomiyama and Nomiyama, 1974b) failed to confirm the original results.

An individual's degree of physical activity may be an important mediating factor. Egle and Gochberg (1976) observed an inverse

relationship between the degree of benzene uptake and the ventilatory rate in dogs.

4.1.2 Gastrointestinal Absorption

Acute benzene poisoning due to ingestion of the compound is relatively uncommon (Gosselin et al., 1976), therefore little or no research has been undertaken to determine the rate of gastrointestinal absorption. However, because benzene is miscible with organic solvents and fairly soluble in water (the solubility in water is 820 µg/l) (NIOSH, 1974; Howard and Durkin, 1974), it can be estimated that nearly 100 percent of a small quantity of ingested benzene would be absorbed. This estimate is supported by the high initial pulmonary absorption rate. The presence of food in the GI tract may inhibit complete benzene absorption, since the compound may bind with or be otherwise sequestered within bulk food materials. However, 100 percent will be considered a reasonable value for GI absorption.

4.1.3 Dermal Absorption

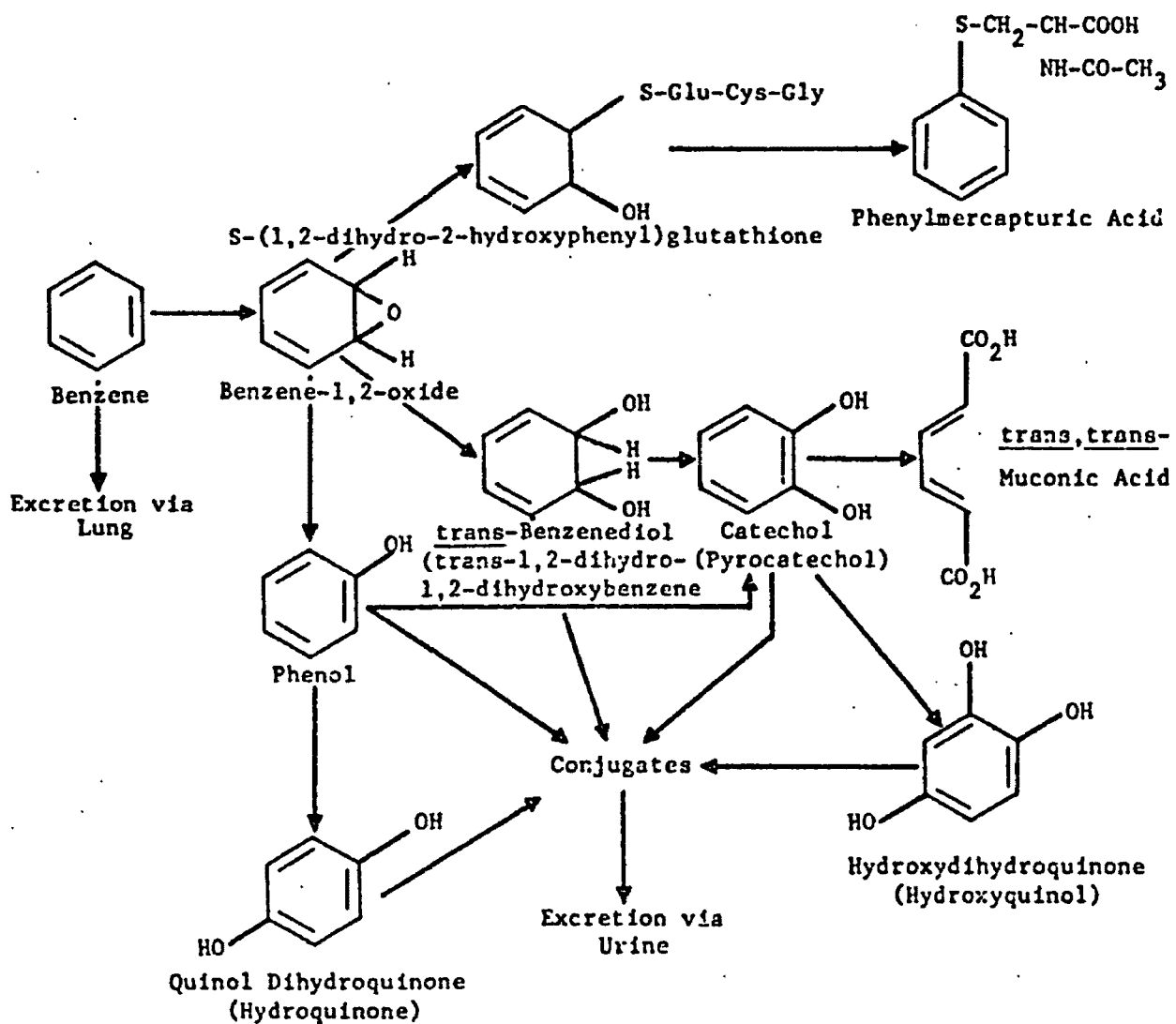
Dermal contact with benzene should not be appreciable under ambient environmental conditions, although exposure may result from occasional contact with gasoline and benzene-containing solvents. Benzene may be slowly absorbed through the skin (Hanke et al., 1961), although in one study, in which subjects arms were immersed in benzene for 25 to 35 minutes, no evidence of dermal absorption was obtained (Conca and Maltagliati, 1955). Given the extent of dermal

exposures to benzene for the general population, dermal absorption can be considered insignificant.

4.2 Metabolic Pathways

The proposed scheme of benzene metabolism in humans (Figure 4-1) has been inferred from in vivo studies with mice, rats and rabbits, and in vitro studies with isolated tissues and tissue fractions from these animals (Gibson, 1971; NIOSH, 1974; Howard and Durkin, 1974). The metabolic end-products shown in Figure 4-1 have been identified in the urine of benzene-exposed persons (Teisinger et al., 1952; Hunter and Blair, 1972). The relative proportion of metabolic products has been determined in laboratory animals (Rusch et al., 1977) but similar data from humans are not available.

Oxidation of benzene to the arene oxide (benzene-1,2-oxide) is thought to be the initial metabolic step although this has not been conclusively demonstrated (Gibson, 1971). The arene oxide is then converted to one of three hydroxylated benzene derivatives; phenol, trans-benzenediol (trans-1,2-dihydro-1,2-dihydroxybenzene), or S-(1, 2-dihydro-2-hydroxyphenyl)glutathione. The latter is converted to phenylmercapturic acid. Phenol may be conjugated with sulfates, glycine, and glucuronides or converted to quinol dihydroquinone (hydroquinone) and conjugated. trans-Benzenediol is also excreted in conjugated form. Catechol (pyrocatechol), formed from both phenol and trans-benzenediol, is transformed to either hydroxydihydroquinone (hydroxyquinol) or trans, trans-muconic acid. Catechol and



SOURCE: Adapted from Truhaut, 1968; Gibson, 1971; Howard and Durkin, 1974.

FIGURE 4-1
PROPOSED PATHWAYS OF HUMAN BENZENE METABOLISM

hydroxyquinol are also eliminated as conjugates. Conjugated phenol appears to be the primary metabolic end-product in humans (Hunter and Blair, 1972).

Benzene metabolism takes place mainly in the liver (Gibson, 1971; Howard and Durkin, 1974) although it is not restricted to this organ. Experiments with mice suggest that benzene is also metabolized in bone marrow (Andrews et al., 1977).

4.3 Retention Characteristics

The presence of benzene in the body is, for the most part, highly transient (Howard and Durkin, 1974; Srbova et al., 1950; Hunter and Blair, 1972; Fiserova-Bergerova et al., 1974). Benzene is retained for the longest period in those tissues which exchange the compound most slowly with the blood, i.e., fat and bone marrow (Fiserova-Bergerova et al., 1974; Hunter and Blair, 1972), although the available evidence suggests that the compound is almost completely eliminated from these compartments within a few days after the cessation of exposure (Fiserova-Bergerova et al., 1974; Howard and Durkin, 1974). Parke and Williams (1953) found only 2.6 percent of a benzene dose in rabbit fat after two days. Most of the remaining tissues appear to freely equilibrate with the blood (Fiserova-Bergerova et al., 1974).

Andrews and coworkers (1977) obtained evidence suggesting that benzene is metabolized within the bone marrow of the mouse. If human

bone marrow also has the capacity to metabolize benzene, then benzene lifetime within the marrow will be shorter than that dictated by exchange kinetics. However, metabolites thereby produced may be responsible for some of the toxic consequences of benzene exposure.

4.4 Elimination Characteristics

The primary routes of elimination of benzene from the body are excretion, as benzene, from the lung, and as phenolic compounds in the urine. Srbova and coworkers (1950) determined that 30 to 50 percent of the absorbed benzene is eliminated as benzene by the lungs. Furthermore, the rate of elimination via this route was seen to decline rapidly, obeying a logarithmic relationship (indicating that the rate of benzene removal from the blood is proportional to the blood-benzene level). In 10 subjects, 16.4 to 41.6 percent of the absorbed benzene was eliminated via the lungs in 5 to 7 hours.

Elimination via the kidney is the second main route of benzene excretion, although in this case the major excretion products are phenol and its congeners, produced in the liver and possibly also in the bone marrow. Only 0.1 to 0.2 percent of the absorbed benzene dose is eliminated as benzene in the urine.

Following relatively short exposures (several hours), up to 87.1 percent of the absorbed benzene has been found to be eliminated within 50 hours as phenol (free and conjugated) by the urinary route (Hunter and Blair, 1972). As with pulmonary benzene excretion, the

rate of phenol excretion in the urine is proportional to the absorbed benzene dose (and therefore the level in the blood) (Hunter and Blair, 1972).

5.0 SOURCE CONTRIBUTIONS TO DAILY BENZENE UPTAKE IN HUMANS

To evaluate the potential health risks associated with benzene in drinking water, it is necessary to ascertain an individual's total dose of benzene, from all exposure sources, and to determine the relative magnitude of the benzene contribution from drinking water.

5.1 Approach

The method employed in this study to estimate the degree to which each major environmental source of benzene exposure contributes to an individual's total daily uptake is based on probable exposure conditions (i.e., ambient benzene levels) as well as absorption rates for each exposure route. The method consists of a five-step process:

- o Definition of ambient concentrations of benzene for the major exposure source (i.e., air, food, and drinking water)
- o Determination of daily benzene intake from each exposure source according to the relationship

$$I_i = C_i \cdot (\text{Benzene})_i$$

where I_i is the daily benzene intake from each source, C_i is the consumption per day of each source (i.e., air, food, drinking water), and $(\text{Benzene})_i$ is the concentration of benzene in each source i

- o Calculation of the amount of benzene absorbed from each exposure source:

$$U_i = I_i \cdot A_j$$

where U_i is benzene uptake for each exposure source i , I_i is daily benzene intake from each source i , and A_j is the fraction of benzene absorbed for each particular exposure route j (i.e., inhalation or ingestion)

- o Calculation of the total daily benzene uptake (U_t):

$$U_t = \sum(I_i \cdot A_j) = \sum U_i$$

for all appropriate pairs of i and j

- o Determination of percent (P_i) of total daily uptake (U_t) provided by each of the three exposure sources (i.e., source contribution factors):

$$P_i = \frac{U_i}{U_t} \cdot 100$$

5.2 Basic Assumptions

Several assumptions were made in defining the amount of each source material consumed each day. Reference Man (ICRP, 1975) values are utilized for daily air and food consumption rates. Values for daily consumption of drinking water are those suggested by NAS (1977) as conservative estimates (see Table 5-1).

Pulmonary and gastrointestinal absorption rates utilized in subsequent calculations are specified in Table 5-1. Two pulmonary absorption rates have been used. The first, 80 percent, is the approximate initial rate in humans exposed to high atmospheric concentrations (see Section 4.1.1). The second pulmonary rate, 45 percent, is the average steady-state value measured in the same studies. The gastrointestinal absorption rate is a worst case estimate but is justified, to some extent, by a number of considerations (see Section 4.1.2).

5.3 Estimated Daily Benzene Uptake

The relative contribution from each exposure route (i.e., air food, drinking water) to an individual's total daily benzene uptake

TABLE 5-1

BASIC ASSUMPTIONS EMPLOYED IN THE
CALCULATION OF INDIVIDUAL SOURCE CONTRIBUTION FACTORS

<u>Basic Assumptions</u>		<u>Remarks</u>
• Reference Man:		
Adult consumes:		
	2.0% H ₂ O/day	- Daily intake as suggested by NAS (1977); conservative estimate, since all beverage intake assumed to be water.
	~2200g food/day	- Approximate daily intake for 18-yr. old in FDA total diet studies; comparable to Reference Man (ICRP report 23); however, since daily benzene intake from total diet will be assumed, this figure is not used in the calculations.
	22.8 m ³ air/day	- Assumes 8 hrs. light work, 8 hrs. non-occupational, and 8 hrs. resting.
• Absorption Characteristics:		
Pulmonary	80%	- Initial rate in humans in high exposure (>150 mg/m ³) situations. (See Section 4.1.1).
	45%	- Steady-state value in humans in high exposure (>80 mg/m ³) situations.
Gastrointestinal	100%	- Conservative approximation based on pulmonary rate, chemical and physical considerations.
Dermal	Insignificant	- Relatively unimportant, except in rare circumstances.

was determined by using the estimated average environmental benzene occurrence levels and absorption rates in the calculation sequence previously described. Several concentrations of benzene in drinking water were selected to represent the range of empirically determined values. The benzene concentrations are thought to be representative of average and maximum urban values. The level in food is a crude estimate (see Section 3.2). Table 5-2 provides the exposure values used in subsequent calculations. Table 5-3 provides an example of the actual calculation sequence employed. In Table 5-4, the source contribution factors for air, food, and drinking water are indicated for an average adult.

Based upon the assumed urban ambient exposure levels, air is the predominant source of absorbed benzene, contributing over 65 percent of the total daily uptake at even the highest drinking water concentrations utilized. Assuming the benzene concentration in air is $50 \mu\text{g}/\text{m}^3$ (the estimated urban average) and the pulmonary absorption rate is 80 percent, drinking water contributes 1.7 percent of the daily uptake of benzene when the benzene concentration is $10 \mu\text{g}/\text{l}$, 0.1 percent at $1 \mu\text{g}/\text{l}$, and well below 0.1 percent at 0.1 and $0.3 \mu\text{g}/\text{l}$, the values presumed to represent average ambient conditions. Using the low estimate of pulmonary benzene absorption (45 percent) adds at most 1.7 percent to the source contribution factor for water. At the estimated maximum ambient urban air-benzene level of $200 \mu\text{g}/\text{m}^3$, greater than 88 percent of the total daily benzene uptake is

TABLE 5-2

REPRESENTATIVE ENVIRONMENTAL BENZENE EXPOSURE LEVELS

<u>Exposure Route</u>	<u>Exposure Level</u>	<u>Remarks</u>
Diet	250 µg/day	NCI estimate based on limited data.
Ambient Air	50 µg/m ³	Estimated average urban level based on limited data (Table 3-1).
	200 µg/m ³	Estimated maximum ambient urban level.
Drinking Water	0.1 µg/l	Approximate lower limit for median of U.S. ambient concentrations.
	0.2 µg/l	Upper limit for median of U.S. ambient concentrations (see Section 3-3).
	1 µg/l	-----
	10 µg/l	Maximum Value in 1975 EPA survey.

TABLE 5-3

CALCULATION SEQUENCE IN DETERMINING SOURCE CONTRIBUTION FACTORS

<u>Source</u>	<u>Ambient Concentration</u> X	<u>Consumption Rate</u>	<u>Absorption Rate</u>	<u>Daily Uptake</u>	<u>Percent of Total Uptake</u>
Drinking Water	10 µg/ℓ	2ℓ/day	1.0	20.0 µg/day	1.7
Food	-----	250 µg/day	1.0	250.0 µg/day	21.2
Air	50 µg/m ³	22.8 m ³ /day	0.8	<u>912.0 µg/day</u>	<u>77.2</u>
			TOTAL	1182.0 µg/day	100.1 ^a

^a Source contribution factors may not add to exactly 100 percent due to rounding.

TABLE 5-4
ESTIMATED DAILY BENZENE UPTAKE

Benzene Concentration			Pulmonary Absorption Rate	Total Daily Benzene Uptake (µg/day)	Source Contribution Factors (Percent of Total Uptake)		
Drinking Water	Air	Food			Drinking Water	Air	Food
0.1 µg/l	50 µg/m ³	250 µg/day	0.8	1162.2	<0.1	78.5	21.5
	200 µg/m ³	250 µg/day	0.8	3898.2	<0.1	93.6	6.4
0.1 µg/l	50 µg/m ³	250 µg/day	0.45	763.2	<0.1	67.2	32.8
	200 µg/m ³	250 µg/day	0.45	2302.2	<0.1	89.1	10.9
0.2 µg/l	50 µg/m ³	250 µg/day	0.8	1162.4	<0.1	78.5	21.5
	200 µg/m ³	250 µg/day	0.8	3898.4	<0.1	93.6	6.4
0.2 µg/l	50 µg/m ³	250 µg/day	0.45	763.4	<0.1	67.2	32.7
	200 µg/m ³	250 µg/day	0.45	2302.4	<0.1	89.1	10.9
1.0 µg/l	50 µg/m ³	250 µg/day	0.8	1164.0	0.2	78.4	21.5
	200 µg/m ³	250 µg/day	0.8	3900.0	0.1	93.5	6.4
1.0 µg/l	50 µg/m ³	250 µg/day	0.45	765.0	0.3	67.1	32.7
	200 µg/m ³	250 µg/day	0.45	2304.0	0.1	89.1	10.9
10.0 µg/l	50 µg/m ³	250 µg/day	0.8	1182.0	1.7	77.2	21.2
	200 µg/m ³	250 µg/day	0.8	3918.0	0.3	93.1	6.4
10.0 µg/l	50 µg/m ³	250 µg/day	0.45	783.0	2.6	65.5	31.9
	200 µg/m ³	250 µg/day	0.45	2322.0	0.9	88.4	10.8

contributed by this source at all drinking water levels utilized and less than 1 percent is contributed by drinking water.

The distribution of benzene in the atmosphere is apparently highly non-uniform. Because gasoline combustion is a major source of benzene emissions, concentrations of benzene in air are presumed to generally be higher in areas with high traffic density (urban areas) than in areas with low traffic density (rural areas). This has not yet been confirmed, as ambient benzene levels in rural areas have not been reported. Atmospheric concentrations of benzene are also expected to vary on a regional basis, that is, levels will generally be higher in areas near benzene production and by-product manufacturing facilities (particularly the Gulf Coast and Middle Atlantic States) than in other areas of the country. Whether or not these same factors also affect drinking water benzene concentrations has not been determined.

Smoking may be a major source of absorbed benzene. The results of one study indicate that a person may inhale as much as 91.5 μg of benzene per cigarette or 1830 $\mu\text{g}/\text{pack}$. The latter figure is higher than the total daily benzene intake from air (at 50 $\mu\text{g}/\text{m}^3$), food and drinking water. The percentage of benzene absorbed from the inhaled smoke has not been determined.

Benzene intake during use of gasoline as a solvent cleaner may also be significant. A person exposed to a gasoline concentration of 100ppm (3200 $\mu\text{g}/\text{m}^3$ benzene) as a result of this practice would

inhale about 3840 μg of benzene per hour*, and would absorb 1728 to 3072 $\mu\text{g}/\text{hour}$.

5.4 Identification of Critical Receptors

As mentioned in Section 4.0, there is some evidence to suggest that females are more susceptible to benzene intoxication than males. These results have been attributed to the female's higher percentage of body fat. Nomiyama and Nomiyama (1969) reported that female subjects absorbed benzene from the lungs more than twice as efficiently as males; however, this result was contradicted by a more recent study (Nomiyama and Nomiyama, 1974b). In another study by these authors (Nomiyama and Nomiyama, 1974a), the percentage of absorbed benzene excreted by the respiratory route was three times higher in men than in women and, therefore, women excreted a greater proportion as urinary metabolites. This is presumably supported by Hunter and Blair's (1972) finding in men that as the proportion of body fat increases, the proportion of benzene excreted as urinary phenol also increases. These results may indicate an increased susceptibility in women, since the toxic effects of benzene may be due, at least in part, to one or more of the metabolic products (Andrews et al., 1977).

*Assuming a consumption rate of 1.2 m^3 air/hr during "light activity" (ICRP, 1975).

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