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Historical Estimation of Exposure to 1,3-Butadiene, Styrene, and Dimethyldithiocarbamate Among Synthetic Rubber Workers

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Quantitative estimates of exposure to 1,3-butadiene (BD), styrene (STY), and dimethyldithiocarbamate (DMDTC) were developed for a follow-up study of workers at six North American synthetic rubber plants. Procedures entailed identifying tasks and jobs involving exposure, identifying factors influencing historical changes in exposure potential, and using mathematical models to calculate job- and time-period-specific exposures. Exposure metrics included 8-hour time-weighted average (TWA) intensity, the annual number of peak exposures (BD: >100 ppm, STY: >50 ppm) and TWA intensity below and above the peak threshold. The 5th and 95th percentiles of the approximate probability distribution of each exposure estimate served as its 90% uncertainty interval. Job- and year-specific estimates were linked with subjects' work histories to obtain cumulative exposure indices. Exposure estimates varied among tasks, jobs, plants, and time periods. BD TWAs were approximately 10 ppm during the 1940s–1960s and declined during the 1970s and 1980s. STY TWAs were always <2 ppm. DMDTC exposure began in the 1950s, was high through the 1960s, and later declined. BD peak exposure accounted for a large proportion of cumulative BD exposure, whereas almost none of the STY exposure was experienced at levels >50 ppm. Exposure indices were correlated. Exposures were higher than previously estimated. Multiple correlations among DMDTC, BD, and STY exposure estimates make it difficult to estimate agent-specific effects. Limitations of the methodology include the potential inaccuracy of the estimates, the lack of adequate industrial hygiene data to validate the estimates, the additional inaccuracy of linkage with poorly specified job groups, and the potential for differential exposure misclassification because the jobs and work areas where excess leukemia mortality occurred were well-known at the time of this study. Nevertheless, the new exposure estimates were highly correlated with the old, yielding equivalent exposure ranking of workers and were comparable to limited industrial hygiene data published by NIOSH.

Keywords 1,3-butadiene, dimethyldithiocarbamate, epidemiologic studies, exposure assessment, leukemia, styrene

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INTRODUCTION

1,3-Butadiene (BD) is a four-carbon olefin, gaseous at room temperature, produced naturally in the combustion of organic matter and commercially through the catalytic cracking of petroleum.(1) Styrene (STY) is an aromatic hydrocarbon, liquid at room temperature, naturally occurring in gummy exudates from the trunks of certain trees and made commercially through the dehydrogenation of ethylbenzene.(2) BD and STY are used widely in the manufacture of styrene-butadiene rubber (SBR) and in other industrial processes. According to the International Agency for Research on Cancer (IARC), there is sufficient evidence that BD causes hematopoietic and other forms of cancer in animals and limited evidence that it causes cancer in humans.(1) For STY, there is limited evidence of carcinogenicity in animals and inadequate evidence of carcinogenicity in humans.(2)

In a previous study of mortality among men employed at eight North American plants that manufactured SBR and related products,(3) we developed job-exposure matrices (JEMs) with quantitative estimates of exposure to BD, STY, and benzene for specific job titles and work areas of the plants, and we linked the estimates with individual workers' jobs as determined from personnel records. We observed that the leukemia death rate increased with cumulative exposure to BD, with no clear independent effect of STY or benzene.(4) Concerns remained about the validity and precision of our exposure estimates.(5) Also, studies of BD production workers found no excess of leukemia, raising the possibility that the association with BD in SBR workers is due to other chemicals used in SBR but not in monomer production.[6] Sodium dimethyldithiocarbamate (DMDTC), which is the salt of a water-soluble, low vapor-pressure synthetic acid, whose strong reducing activity is used to halt the SBR polymerization reaction, has been proposed as an alternative cause of leukemia among SBR workers.[7]

This article provides an overview of our exposure estimation method, summarizes the results of recent enhancements in estimation procedures, and presents a limited validation of the estimates with published industrial hygiene measurements.

METHODS

Overview of Exposure Estimation

Previous papers and reports by the National Institute of Occupational Safety and Health (NIOSH) have described both SBR manufacturing and the study plants.[3,4,8–10] We conducted in-depth walk-through surveys of each plant, reviewed plant records, and carried out over 200 interviews of managers and long-term employees.[4] At each plant, we identified geographically and functionally distinct work areas, the specific operations performed in each area, and the job titles used in personnel records to indicate individuals assigned to carry out operations (tasks) with exposure potential. For each job, we listed specified component tasks associated with exposure potential, task-specific determinants of exposure (equipment used, duration and frequency of the task, work practices, presence of exposure reduction mechanisms) and historical changes in the job with respect to exposure determinants. These procedures resulted in the compilation of historical job profiles that identify all sources of exposure.

Using procedures described later, we developed plant-, year-, and job group-specific exposure estimates. We then linked the estimates with subjects' work histories to derive cumulative exposure estimates for use in epidemiologic analyses.[4]

In this investigation, an industrial hygienist and a chemical engineer participated in an in-depth review of the exposure estimation at one plant; identified new tasks for which exposure estimates were needed; developed further questions about operations and exposure potential; provided reference materials on emission rates from pumps, compressors, and tank vents; and recommended changes in the assumptions used to develop the original estimates. We corresponded with plant technical staff to gather new data and to confirm that the assumptions used in revising exposure estimates were realistic. We sought verification of information required for exposure estimation, such as the surface of certain work areas and the volume and ventilation rates of key buildings. The engineering group at another plant assisted with estimating the content of vessels in the reactor and recovery areas of a typical SBR plant after preparation for cleaning, leading to changes in the estimation of exposure among maintenance laborers (the cleaning crew) and of the background exposure level in polymerization areas. The review also pointed out the need for refining estimation of airflow in jobs that involved work in open air or in semienclosed buildings.

We expanded data collection to all plants and carried out two sets of plant visits, focusing first on a systematic review of production and maintenance tasks involving BD and STY, and next focusing on laboratory tasks and DMDTC exposure. During the plant visits, we took 170 independent short-term air speed measurements (22–36 measurements/plant) at plant locations where operators worked in open air or in semienclosed areas. At each plant we identified the physical location where selected tasks were carried out and measured air speed with a hand-held anemometer with an attached wind vane probe (model 01-241; Fisher Scientific, Hampton, NH). The investigator held the wind vane at arm's length from the body, facing the wind, until the instrument attained a stable reading (usually within 15–30 sec) and recorded the range of readings and the most common reading during the next 30–60 sec. Measurements were taken at any feasible time during the daytime work shift. Because the task was a much larger source of variation than the plant, we decided to pool task-specific air speed measurements across plants.

Exposure Estimation Models

BD and STY Exposure Intensity

We assumed that the exposure in each job group derived from an area background level, corresponding to the average air concentration of BD and STY in the work area where the job was performed, and from task-specific exposure levels that replaced the background level during the performance of specific duties.

For buildings, the background was computed using a dilution ventilation model:[11]

$$E_{ppm} = 4.03 * 10^8 * Q * SG/(MW * VR) \qquad \textbf{(Model 1)}$$

where E_{ppm} is the air concentration of the monomer in parts per million (ppm), Q is the monomer emission rate (pints/min), SG is its specific gravity, MW is its molecular weight, and VR is the ventilation rate (in ft^3/min).

Intensity of exposure from a point source (e.g., minor maintenance of a pump, latex sampling from a reactor) was computed using a near-field air dispersion model:[12]

$$E_{ppm} = 1000 * 24.45 * Q/(MW * 0.136 * D^{1.84} * u) \qquad \textbf{(Model 2)}$$

where E_{ppm} is the monomer concentration in the plume originating from the emission source, Q is the monomer emission rate (in gm/sec), MW is its molecular weight, D is the distance from the source (in meters), and u is the air speed across the field (in m/sec).

In both models the emission rate was estimated taking into account the history of work practices and use of protective equipment (e.g., gloves, respirators) in each plant.

To describe the uncertainty associated with exposure estimation, we specified a lower and upper boundary for the emission rate, ventilation rate/air speed, and distance using

(1) information from interviews and production records for the emission rates, (2) our own measurements and records on the ventilation of production buildings and laboratories for air speed, and (3) interviews and direct observation for distance. We computed the approximate probability distribution of the BD and the STY exposure intensity by assuming that each parameter in the exposure model followed a triangular distribution with mode at the midpoint between the boundaries, identifying the 5th, 10th ... 95th percentile of its distribution and by computing the exposure intensity for all possible combinations of parameter quantiles (i.e., for the approximate joint distribution of the exposure parameters). In the absence of empirical data, we chose the triangular distribution to describe our lower confidence in values away from the midpoint. We evaluated the resulting empirical distribution of exposure estimates to find the approximate 5th, 10th ... 95th percentile of each task- and time period-specific exposure intensity estimate.

DMDTC Exposure Intensity

The details of these methods are presented elsewhere.[13] The model assumes that exposure occurs only through the skin, because of the low vapor pressure and low volatility of DMDTC, and that absorption is so slow that there is no significant depletion of the chemical during the contact. Thus, the dose rate follows Fick's law,[14] $J = K_p * \Delta C$, where J is the dose rate (in mg/cm^2/hr), Kp is the permeability coefficient (in cm/hr), and ΔC is the concentration gradient across the skin (in mg/cm^3).

The permeability coefficient Kp was estimated at 0.0001395 cm/hr from the DMDTC octanol/water partition coefficient (K_{ow}), using an empirical equation.[15] Thus, dermal absorption of DMDTC is so slow that the concentration gradient approximately equals the initial concentration of DMDTC in the solution wetting the skin. To be consistent with BD and STY exposure, for which we estimated the air concentration in the breathing zone of the worker without considering absorption, the permeability coefficient was omitted, and skin exposure to DMDTC was estimated as follows:

$$E_{(mg/cm)} = C * S \qquad \textbf{(Model 3)}$$

where E is the dermal exposure intensity (in mg/cm), C is the concentration of DMDTC in the solution wetting the skin (in mg/cm^3), and S is the skin surface in contact (in cm^2).

Interpretation is not as intuitive for mg/cm units as for ppm units, but both units have the same relation with absorbed dose and with 8-hour TWA exposure estimates. Multiplying mg/cm by the permeability coefficient (cm/hr) yields a measure of the dose rate (mg/hr). A similar rate is obtained by rescaling ppm into mg/m^3 and multiplying by the inhalation rate (m^3/hr) and by the proportion of the chemical that is absorbed. Eight-hour TWAs have the same relation to the dose absorbed during a shift.

The concentration of DMDTC was known for the solution received as raw material (40% in weight = 400,000 ppmw) and was estimated for solutions prepared for daily use and for unstripped latex (513 ppmw), stripped latex (616 ppmw), and finished rubber product (1230 ppmw). The area of skin surface exposed was estimated from the body part likely to have been in contact with DMDTC and from published values of the corresponding average area in adult men.[16] The concentration in the solution wetting the skin, the area wetted, and the duration of exposure were estimated taking into account the history of work practices and use of protective equipment in each plant.

The procedure to obtain the approximate task-specific distribution of DMDTC exposure intensities was similar to that described for BD and STY. These calculations used the @risk software.[17]

Job Group-Specific Exposure Estimates

The personnel records of subjects were abstracted and individual job assignments were coded according to a list of 8281 job titles. The latter were grouped into 308 job groups on the basis of similarities in tasks and exposure potential. We computed job group-specific TWAs as weighted averages of the intensities of the area background and of the tasks comprising the job group, using frequency and duration of each task as weights. For BD and STY, we also estimated the number of peak exposures/year by multiplying the per-shift frequency of tasks entailing exposure >100 ppm (for BD) and >50 ppm (for STY) by 225 shifts/year. These arbitrary values for the peak threshold appear sensitive enough to capture any significant excursions in exposure intensity and specific enough to exclude small excursions compatible with the imprecision of our estimation procedures. To capture high exposures of very short duration, this definition did not take exposure duration into account.

We also partitioned exposure intensity estimates into TWA concentration below and above the peak threshold. For example, if a worker was exposed to BD for 2 hours/shift at 10 ppm and for 5 minutes/shift at 500 ppm, his total exposure was (120 min $*$ 10 ppm + 5 min $*$ 100 ppm) = 1700 ppm-minutes at $\leq$100 ppm, and (5 min $*$ (500–100) ppm) = 2000 ppm-minutes at >100 ppm. Thus, the 8-hour TWA was 7.7 ppm, of which 4.2 ppm was above the threshold, and 3.5 ppm was at or below the threshold. We calculated the same indices of STY exposure using the threshold of 50 ppm.

For generic, supervisory, and plant-wide maintenance jobs, we derived estimates from other job groups. For example, for generic polymerization workers, exposure estimates were averages of the estimates of four groups: tank farm, pigment, reactor, and recovery operators, weighted by the numbers of workers employed in each group.

We computed the approximate distribution of sums of ppm-minutes, mg-minutes/cm, or peaks associated with one task during one shift assuming that duration and frequency of exposure followed a triangular distribution. We summed task-specific values within each job group and computed the approximate empirical distribution of the sum assuming that exposure levels were independently distributed across all tasks.

Subject-Specific Exposure Estimates

We linked each subject's job assignments during each calendar year with the appropriate plant-, year- and job group-specific exposure estimates. To obtain cumulative ppm-years, mg-years/cm, and peaks, we summed the linked exposure estimates, weighted by the length of each employment period, over the subject's work history. We computed the approximate distribution of cumulative ppm-years, mg-years/cm, or peaks cumulative exposure indices assuming that exposure levels were independently distributed across years and job groups.

Comparison with Published Industrial Hygiene Measurements

NIOSH conducted two surveys of SBR manufacturing facilities, designed to describe average exposure conditions. The first survey(9) was carried out in 1976–1977 at two facilities included in a mortality study.(18) These facilities merged during the 1980s and correspond to one of the six plants in our study. We summarized STY measurements tabulated in the NIOSH report(9) by pooling measurements across jobs that in our study would be classified within the same job group, attributing 50% of the limit of detection to measurements below the limit. We compared statistics based on 10 or more measurements with our job group- and year-specific estimates for the same plant. We did not analyze BD data from this survey because we believe that BD exposure was underestimated (see Discussion).

NIOSH also conducted an industry-wide evaluation of occupational BD exposure among workers in monomer, polymer, and end-user facilities in 1984–1987.(10,19,20) The survey included five of the plants evaluated in our study but did not include the largest of the study plants. We compared job group-specific BD exposure data summarized by Fajen et al.(20) with our job group- and year-specific estimates for the same plants. The second NIOSH survey did not evaluate STY.

Analysis

We present selected task-, job group-, and subject-specific exposure estimates to illustrate the exposure estimation results. The 5th and 95th percentiles of the distribution of each estimate are used as the lower and upper 90% uncertainty limits (UL), or 90% uncertainty interval (UI). Historical variation in exposure levels was analyzed by task, by job group, and by plant. We used the estimates in cross-sectional analyses of exposure levels at different points in time to obtain historical cohort exposure profiles. Cumulative exposure indices were computed as of the end of follow up for the sub-group included in the analyses presented in a companion paper (subjects who accrued $\geq$40 years of age, $\geq$10 years since hire, and $\geq$1 year of employment during follow up).(21)

We used descriptive statistics (mean, median, frequency distributions, and contingency tables) to present most of the results and used plots to evaluate the historical exposure profiles of specific job groups and of the entire cohort. To assess the potential for multiple correlation in regression models examining the effect of multiple exposure indices on leukemia and other causes of death, we calculated Spearman's rank correlation coefficients between estimates of cumulative exposure to BD, STY, and DMDTC. We did not use statistical inference methods because of the uncertainty associated with the estimation error and because the large number of observations (task-years, job-years, and individual workers) would make even small differences statistically significant.

RESULTS

Task-Specific Exposure Estimates

We developed exposure estimates and supporting documentation for 653 individual tasks. Prolonged exposure to BD and STY arose from monomer losses from equipment such as pumps or compressors. Tank farm operators spent a considerable proportion of their time monitoring monomer transfers from a pump house (Table I). Changes in exposure levels were determined by technology changes, from high-loss reciprocating pumps with packing during the 1940s–1950s, to centrifugal pumps with single mechanical seals during the 1950s–1970s, to the present technology based on double mechanical seals or sealless pumps. The Appendix describes this task in detail.

Production area tasks entailing peak exposure to BD included purging excess water from tanks containing recycled BD, charging reactors in batch mode, and performing minor maintenance on reactor area equipment (Appendix Table A1). STY exposure was low for most tasks because of the low vapor pressure of STY. High DMDTC skin exposure was experienced by operators who received shipments, prepared dilute solutions, and performed certain recovery tasks.

Laboratory tasks such as sampling new BD shipments and sampling unstripped latex entailed peak BD exposure (Table I). STY exposure may have been high in some tasks involving hot operations, such as coagulation of latex samples in the laboratories (about 20 ppm) (Appendix Table A2). Laboratory technicians who handled latex with bare hands experienced high exposure to DMDTC.

Maintenance tasks included those done by skilled trades personnel and by unskilled laborers who cleaned vessels and lines taken out of operation and performed other cleaning (Table I and Appendix Table A3). High and prolonged BD exposure occurred in tasks performed by the unskilled maintenance laborers. The formation of coagulum in reactors, other vessels, and lines in the polymerization area often interfered with SBR manufacturing and was particularly frequent shortly after the conversion to the cold emulsion polymerization process during the late 1950s. The frequency of high-exposure cleaning tasks (e.g., reactor cleaning) and low-exposure cleaning tasks (e.g., dryer cleaning) varied across plants and time periods. High STY exposure (20–70 ppm) occurred during reactor cleaning. Vessel cleaners also had high-intensity skin exposure to DMDTC, particularly before the adoption of impermeable clothing.

Job Group-Specific Exposure Estimates

Tank farm and recovery operators had BD TWAs above 50 ppm during the 1940s–1960s, while the BD TWAs of reactor operators were lower (Table II, Appendix Table A4). BD

TABLE I. Typical Tasks Carried Out in a Synthetic Rubber Manufacturing Plant, with Corresponding Historical Exposure Estimates

Task Description (Work Area)	Agent^A	Time Period	Duration Range (Min)	Frequency Range (Per Shift)	Exposure Estimate^B Min–Max	Mean	90% UI^C
Monitoring monomer shipments from pumphouse (tank farm)	BD	1943–1952	240	1	27–119	62	41–84
		1953–1976	240	1	18–78	40	27–55
		1977–1989	240	1	1.8–7.8	4.0	2.7–5.5
		1990–1992	158–202	1	0.9–3.9	2.0	1.4–2.8
	STY	1943–1952	240	1	1.5–6.7	3.5	2.3–4.7
		1953–1976	240	1	1.0–4.5	2.3	1.6–3.2
		1977–1989	240	1	0.1–0.45	0.23	0.16–0.32
		1990–1992	158–202	1	0.05–.22	0.12	0.08–0.16
Sampling unstripped latex (reactor control/rubber control laboratory)	BD	1943–1949	2	33	0–3000	310	0–1900
		1950–1955	2	5.3	0–3000	310	0–1900
		1956–1959	2	8	0–1100	110	0–700
		1960–1987	5–10	8	0–1200	120	0–715
	STY	1943–1949	2	33	0–2.6	0.27	0–1.6
		1950–1955	2	5.3	0–2.6	0.27	0–1.6
		1956–1959	2	8	0–0.38	0.04	0–0.23
		1960–1987	5–10	8	0–0.38	0.04	0–0.23
	DMDTC	1951–1970	—	17–18	26–130	66	37–100
		1970–1992	—	18	4.8–34	17	9.3–25
Reactor cleaning (maintenance–unskilled labor)	BD	1943–1955	240	0.17–0.37	70–400	230	120–350
		1956–1959	240	0.17–0.37	220–1200	720	370–1100
		1960–1969	240	0.17–0.37	110–600	360	180–540
		1970–1979	240	0.17–0.37	8.6–77	43	19–66
		1980–1992	240	0.17–0.37	0.7–12	6.3	2.4–10
	STY	1943–1955	240	0.17–0.37	7.1–38	23	12–33
		1956–1959	240	0.17–0.37	22–120	71	37–100
		1960–1969	240	0.17–0.37	11–59	35	18–52
		1970–1979	240	0.17–0.37	6.7–42	24	12–36
		1980–1992	240	0.17–0.37	5.5–35	20	9.9–30
	DMDTC	1951–1968	—	0.17–0.37	2900–6800	4900	3500–6200

^A BD = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.
^B Units = ppm for BD and STY; = mg/cm for DMDTC.
^C 90% uncertainty interval.

concentration was low in latex after stripping, and exposure was considered nil in finishing operations. The estimates indicated a 5- to 30-fold decline in exposure levels over the 50-year period. The 90% UIs of TWAs were a function of the mean, reflecting the skewed distribution of task-specific exposures, and the ULs were within 2–5 times the mean. The annual number of BD peaks was more variable, and the downward trend was more pronounced for BD peaks than for TWA estimates.

During the 1940s, the BD exposure of tank farm operators was due mainly to levels at $\leq$100 ppm (average of 44 ppm due to levels $\leq$100 ppm, vs. 10 ppm due to levels $>$100 ppm). In contrast, recent exposure was largely due to peaks (Table II: 1.9 ppm due to levels $\leq$100 ppm, vs. 9.5 ppm due to levels $>$100 ppm). Other production job groups displayed different patterns (Appendix Table A4).

STY exposure tended to be low among production operators throughout the history of SBR manufacturing. However, recovery operators commonly were exposed to levels above 50 ppm during the 1940s–1950s (Appendix Table A4).

Job group-specific estimates of exposure to DMDTC changed markedly over time. For example, DMDTC exposure among reactor operators was around 400 mg/cm during the 1950s, but was nil before and after because opportunity for exposure occurred only when cold polymerization of SBR was carried out in batch mode and disappeared with the introduction of continuous polymerization (Appendix Table A4).

Laboratory technicians experienced a large variation in exposure levels according to the specific laboratories where they worked and according to time period (Table II and Appendix Table A5). Technicians assigned to reactor sampling and testing

TABLE II. Typical Job Groups in a Synthetic Rubber Manufacturing Plant, with Corresponding Historical Exposure Estimates (Mean and 90% Uncertainty Interval, UI)

		Year											
		1945		1955		1965		1975		1985		1992	
Work Area/ Job Group	Agent,[A] Exposure Index	Mean	90% UI	Mean	90% UI	Mean	90% UI	Mean	90% UI	Mean	90% UI	Mean	90% UI
Tank farm operator	BD, 8-hr TWA (ppm)	54	33–110	43	25–98	36	19–91	33	16–88	15	3.9–70	11	1.2–66
	BD, peaks/year (≥100 ppm)	114	0–415	104	0–394	104	0–394	81	0–347	80	0–346	80	0–346
	BD TWA ≥100 ppm	10	0–65	9.6	0–64	9.6	0–64	9.5	0–64	9.5	0–64	9.5	0–64
	BD TWA <100 ppm	44	31–57	34	24–45	27	18–37	23	15–33	5.4	3.7–7	1.9	1.1–2.6
	STY, 8-hr TWA (ppm)	2.4	1.7–3.4	1.8	1.3–2.5	1.9	1.3–2.6	1.8	1.2–2.4	.74	.41–1	.67	.34–.95
	STY, peaks/year (≥50 ppm)	.56	0–5.6	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA ≥50 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA <50 ppm	2.4	1.7–3.4	1.8	1.3–2.5	1.9	1.3–2.6	1.8	1.2–2.4	.74	.41–1	.67	.34–.95
	DMDTC, 8-hr TWA (mg/cm)	0	0–0	59	30–83	59	30–83	15	2.5–25	15	2.5–25	15	2.5–25
Reactor control laboratory technician	BD, 8-hr TWA (ppm)	59	16–295	9.5	2.5–47	21	2.9–120	21	2.9–120	21	2.3–119	3	1.7–4.5
	BD, peaks/year (≥100 ppm)	1581	0–7847	254	0–1193	428	0–1845	428	0–1845	405	0–1800	0	0–0
	BD TWA ≥100 ppm	35	0–257	5.5	0–41	14	0–102	14	0–102	14	0–102	0	0–0
	BD TWA <100 ppm	25	16–39	3.9	2.5–6	7	2.9–18	7	2.9–19	6.3	2.3–18	3	1.7–4.5
	STY, 8-hr TWA (ppm)	56	42–77	9.1	6.9–12	8.5	6.4–12	8.5	6.4–12	6.5	5–8.3	1.4	1.1–1.8
	STY, peaks/year (≥50 ppm)	10828	7031–11250	1733	1125–1800	1553	1283–1692	1553	1283–1692	788	704–871	0	0–0
	STY TWA ≥50 ppm	36	23–58	5.8	3.7–9.2	5.2	3.3–8.4	5.2	3.3–8.4	4	2.6–5.8	0	0–0
	STY TWA <50 ppm	20	18–21	3.2	2.9–3.6	3.3	2.9–3.8	3.3	2.9–3.8	2.5	2.1–2.9	1.4	1.1–1.8
	DMDTC, 8-hr TWA (mg/cm)	0	0–0	340	239–457	194	122–280	35	18–55	0	0–0	0	0–0
Unskilled labor (cleanup crew)	BD, 8-hr TWA (ppm)	77	43–115	77	41–117	72	41–108	7.5	3.7–12	2.3	1.2–3.6	2.3	1.2–3.6
	BD, peaks/year (≥100 ppm)	69	21–88	69	23–89	73	55–88	1.8	0–11	.79	0–7.9	.79	0–7.9
	BD TWA ≥100 ppm	61	28–98	61	26–100	55	26–90	.06	0–.53	.01	0–.15	.01	0–.15
	BD TWA <100 ppm	16	12–20	16	12–20	16	12–20	7.5	3.7–12	2.3	1.2–3.4	2.3	1.2–3.5
	STY, 8-hr TWA (ppm)	22	11–33	22	11–34	14	7.9–20	10	5.8–15	8.2	4.6–12	7.9	4.3–12
	STY, peaks/year (≥50 ppm)	16	10–26	16	12–26	21	9.2–76	14	8.3–24	11	7.6–13	11	7.6–13
	STY TWA ≥50 ppm	15	4.4–26	15	4.6–26	6.7	1.7–12	4.3	.89–8.3	3.4	.57–6.9	3.4	.57–6.9
	STY TWA <50 ppm	7.1	5.2–9.4	7.1	5.4–9.5	7.2	4.6–10	5.7	3.8–8.2	4.8	3.1–6.8	4.5	2.8–6.5
	DMDTC, 8-hr TWA (mg/cm)	0	00	432	327–555	432	327–555	0	0–0	0	0–0	0	0–0

[A]BD = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.

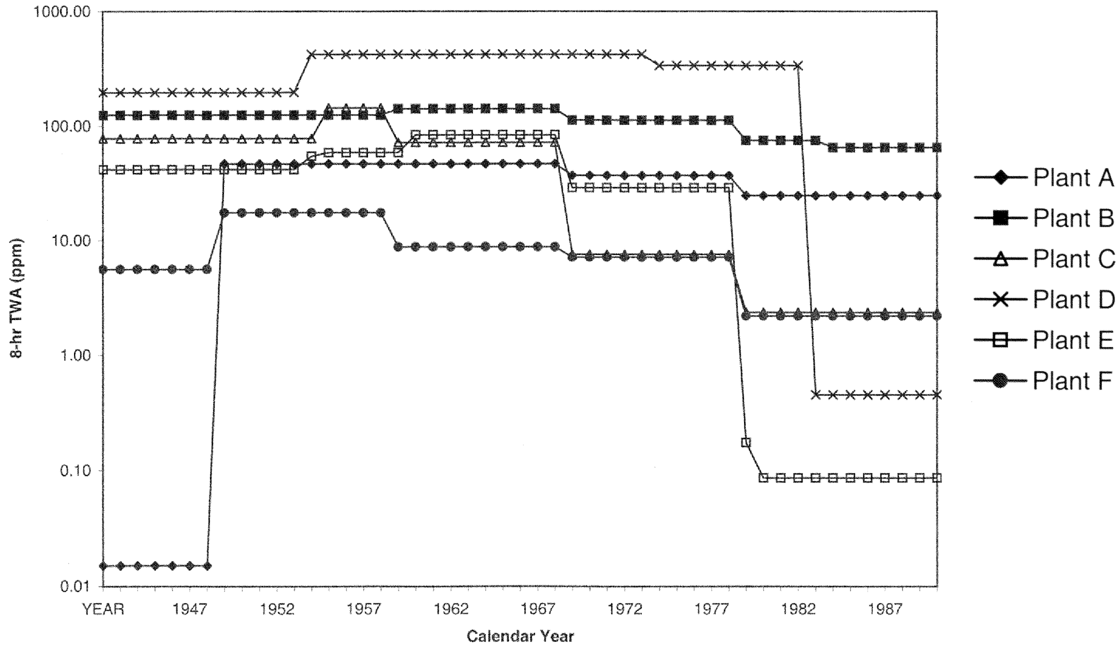

FIGURE 1. Average BD exposure levels by plant and year, unskilled labor (cleanup crew)

of unstripped latex (i.e., latex containing high concentrations of unreacted monomers) during the 1940s–1950s experienced high levels of exposure to BD and to STY due to the large number and the size of the samples that were taken to monitor the polymerization process. On the other hand, technicians who tested the physical properties of rubber made out of stripped latex were not exposed. Unfortunately, many work histories did not identify specific lab assignments, and exposure estimates

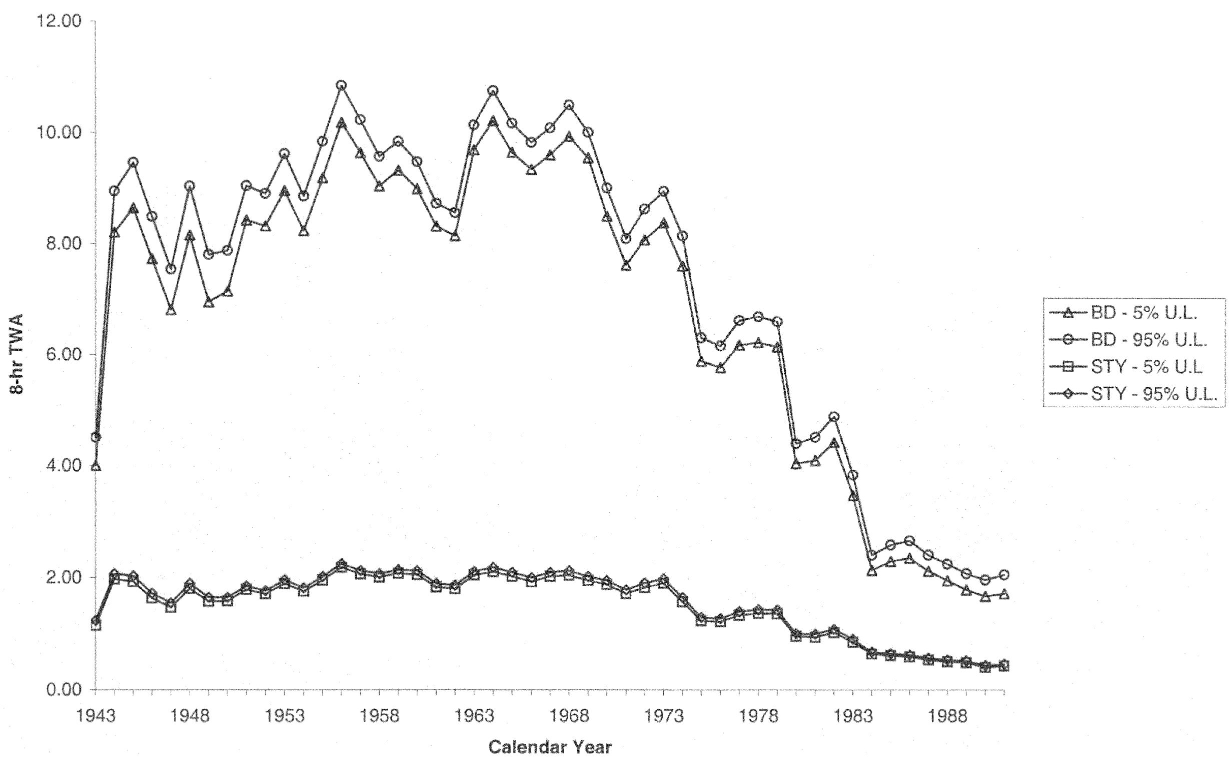

FIGURE 2. Historical average BD and STY exposure, all employees

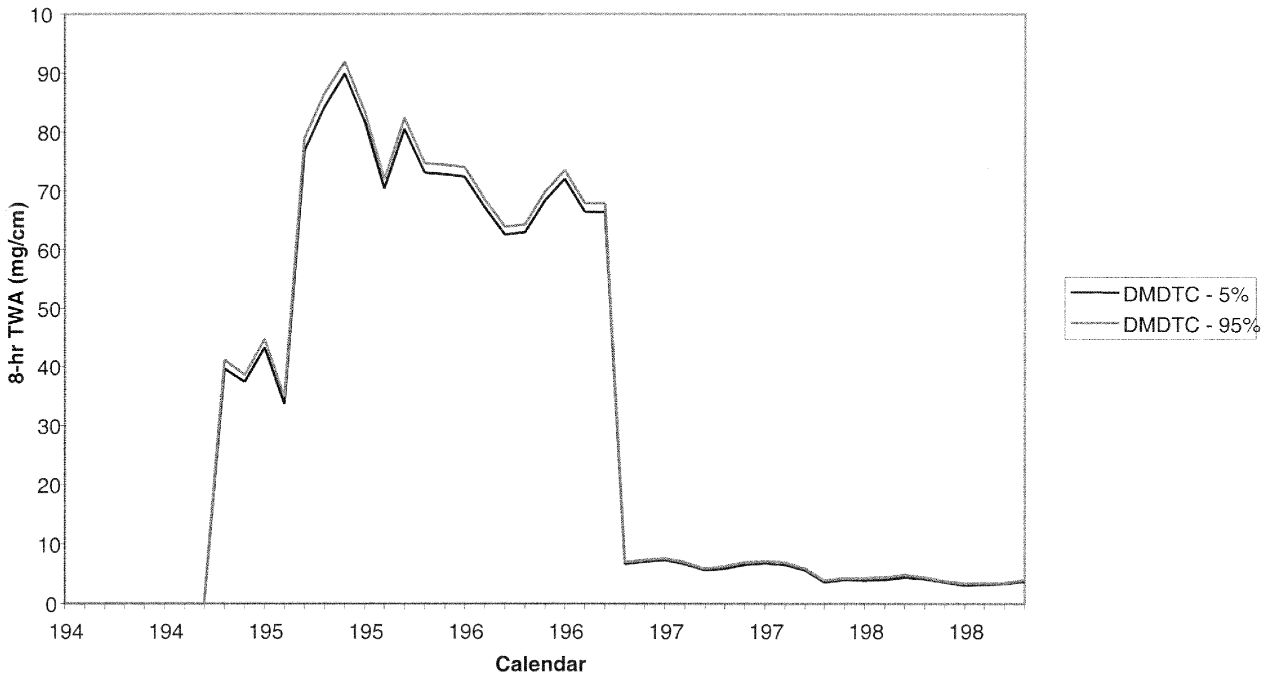

FIGURE 3. Historical average DMDTC exposure levels, all employees

for unspecified technicians were developed as weighted averages of laboratory-specific estimates, with weights proportional to the number of the technicians in different labs.

Unskilled laborers in maintenance had high BD and STY exposure that declined sharply in the 1970s and 1980s with the introduction of hydroblasting techniques and with the outsourcing of equipment cleaning to contractors (Table II and Appendix Table A6). The BD exposure profile of unskilled laborers varied considerably by plant and time period, reflecting differences in procedures used to prepare equipment for cleaning and to reduce exposure levels during cleaning operations, and in the frequency of high-exposure and low-exposure

TABLE III. Number of Subjects Ever Exposed and Median pp. 363–374, Value of the Mean, of the 5th and of the 95th Uncertainty Limits (UL) of Cumulative Exposure (Unit-Years or Total Peaks) Among the Exposed for Four Groups of Study Subjects

			Cumulative Unit-Years,[B] Median		Total Peaks, Median	
Subject Group	Agent[A]	Ever Exposed (%)	Mean	5th–95th UL[B]	Mean	5th–95th UL
All employees (N = 13,130)	BD	10,429 (79)	71	42–125	499	126–694
	STY	11,199 (85)	17	14–21	70	1–83
	DMDTC	8150 (62)	374	308–448	—	—
All decedents (N = 3892)	BD	3074 (79)	91	52–166	528	130–713
	STY	3296 (85)	18	16–22	64	0–116
	DMDTC	1910 (49)	836	718–991	—	—
Leukemia decedents (N = 59)	BD	52 (88)	209	151–369	1066	441–2156
	STY	54 (92)	37	31–39	224	37–374
	DMDTC	46 (78)	964	796–1124	—	—
NHL[C] decedents (N = 38)	BD	33 (87)	138	76–364	487	212–899
	STY	34 (89)	35	33–42	67	5–202
	DMDTC	23 (61)	1061	977–1147	—	—

[A] BD = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.
[B] Unit-years = ppm-years for BD and STY; mg-years/cm for DMDTC.
[C] Non-Hodgkin's lymphoma.

TABLE IV. Median Value of the Mean, 5th, and 95th Uncertainty Limits (UL) of Cumulative 1,3-Butadiene (BD) and Styrene (STY) Exposure Intensity (ppm-Years) Due to Peak or Nonpeak Exposure Levels in Four Groups of Study Subjects

	BD ppm-Years ≥100 ppm, Median		BD ppm-Years <100 ppm, Median		STY ppm-Years ≥50 ppm, Median		STY ppm-Years <50 ppm, Median	
Subject Group	Mean	5th–95th UL	Mean	5th–95th UL	Mean	5th–95th UL	Mean	5th–95th UL
All employees	42	1–80	24	20–28	0.2	0–0.6	13	11–15
All decedents	56	14–115	30	24–35	0.2	0–0.4	14	11–17
Leukemia decedents	157	62–268	63	57–76	0.7	0.2–1.5	29	25–32
NHL[A] decedents	64	24–125	58	43–64	1.7	0.2–3.5	31	25–33

[A]Non-Hodgkin's lymphoma.

cleaning tasks (Figure 1). There was substantial among-plant variability in job group- and time period-specific estimates, although exposure estimates for similar job groups were correlated (results not shown).

Historical Exposure Profiles

BD TWAs increased from 4–5 ppm in 1943–1944 to 8–9 ppm in 1946–1947, fluctuated between 8 and 11 ppm through the early 1970s, and declined to about 2 ppm during the 1980s (Figure 2). STY exposure was always low, declining from 12 ppm in the early decades to about 0.5 ppm in the late 1980s. Because of the large number of employees, the 90% UIs of the average exposure levels of the cohort at any given point in time were narrow, even though individual worker exposure levels had wide UIs.

DMDTC exposure began with the introduction of cold polymerization in the 1950s, with average exposure around 50 mg/cm, increased to 70–80 mg/cm during the 1950s–1960s, and dropped to less than 10 mg/cm during the early 1970s, mostly because of the increase in use of gloves and other protective clothing (Figure 3).

TABLE V. Rank Correlation Coefficients (Spearman) Between Estimates (Mean Value) of Cumulative Exposure to 1,3-Butadiene (BD), Styrene (STY) (ppm-Years), and Dimethyldithiocarbamate (DMDTC) (mg-Years/m^3) in Four Groups of Study Subjects

Subject Group		STY	DMDTC
All subjects (N = 13,130)	BD	0.78	0.60
	STY		0.62
All decedents (N = 3892)	BD	0.74	0.58
	STY		0.57
Leukemia decedents (N = 59)	BD	0.84	0.72
	STY		0.66
NHL[A] decedents (N = 38)	BD	0.80	0.76
	STY		0.72

[A]Non-Hodgkin's lymphoma.

Cumulative Exposure Indices

The proportions of subjects exposed to BD, STY, or DMDTC were 79%, 85%, and 62%, respectively (Table III). Among BD-exposed workers, the median cumulative exposure was 71 ppm-years, with 90% UL of 42–125 ppm-years. The median cumulative number of BD peaks was 499 (90% UL: 126–694). The median cumulative STY exposure among STY-exposed employees was 17 ppm-years (90% UL: 14–21), and the median cumulative number of STY peaks was 70 (90% UL: 1–83). The median cumulative DMDTC exposure among the exposed was 374 mg-years/cm (90%UL: 308–448). Cumulative BD and DMDTC exposure were higher for all decedents than for all employees and were highest among leukemia and non-Hodgkin's lymphoma (NHL) decedents. Cumulative STY exposure showed a weaker trend in the same direction.

The median cumulative BD exposure due to levels >100 ppm among all subjects was 42 ppm-years (90% UL: 11–80), and that due to levels >100 ppm was 24 ppm-years (90% UL: 20–28) (Table IV). The ratio of cumulative BD exposure due to levels >100 ppm to that due to levels ≤100 ppm was higher for leukemia decedents (157/63 ppm-years) than for all decedents (56/30 ppm-years), all employees (42/24), or NHL decedents (64/58 ppm-years). Cumulative STY exposure was due to levels ≤50 ppm.

Among all subjects, the cumulative estimates for BD and STY had a rank correlation coefficient (r) of 0.78 (Table V). Cumulative DMDTC exposure was moderately correlated with exposure to BD and STY ($r \approx 0.6$). Results were similar for all decedents, leukemia decedents, and NHL decedents (Table V). Despite the effort to disentangle exposure due to BD intensities >100 ppm from exposure due to intensities ≤100 ppm, all measures of cumulative BD exposure were highly correlated (Table VI).

Comparison with Previous Estimates

The proportion of all employees, all decedents, all leukemia decedents, and NHL decedents who were ever exposed to BD or STY was very similar according to the original and the revised JEM (Table VII). About 78% of all employees were ever exposed to BD. Among BD-exposed employees,

TABLE VI. Rank Correlation Coefficients (Spearman) Between Alternative Indices of Cumulative Exposure to 1,3-Butadiene (BD) in Four Groups of Study Subjects

Subject Group		BD ppm-Years Total	BD ppm-Years <100 ppm	BD ppm-Years >100 ppm
All subjects (N = 13,130)	BD peaks	0.86	0.78	0.90
	BD ppm-years total		0.94	0.94
	BD ppm-years <100 ppm			0.81
All decedents (N = 3892)	BD peaks	0.86	0.77	0.89
	BD ppm-years total		0.94	0.94
	BD ppm-years <100 ppm			0.79
Leukemia decedents (N = 59)	BD peaks	0.74	0.73	0.73
	BD ppm-years total		0.89	0.97
	BD ppm-years <100 ppm			0.79
NHL[A] decedents (N = 38)	BD peaks	0.86	0.83	0.87
	BD ppm-years total		0.96	0.93
	BD ppm-years <100 ppm			0.85

[A]Non-Hodgkin's lymphoma.

TABLE VII. Number of Subjects Ever Exposed and Median Cumulative Exposure (ppm-Years) Among the Exposed for Four Groups of Study Subjects

		Original JEM			Revised JEM		
Subject Group	Agent[A]	Ever Exposed (%)	Median ppm-Years	Median Peaks	Ever Exposed (%)	Median ppm-Years	Median Peaks
All employees (N = 13,130)	BD	10,230 (78)	15	582	10,429 (79)	71	499
	STY	11,068 (84)	9.7	0	11,199 (85)	17	70
All decedents (N = 3892)	BD	3000 (77)	20	662	3074 (79)	90	528
	STY	3296 (83)	10	0	3296 (85)	18	64
Leukemia decedents (N = 59)	BD	51 (86)	38	2,377	52 (88)	209	1066
	STY	53 (90)	22	0	54 (92)	37	224
NHL[B] decedents (N = 38)	BD	32 (84)	18	574	33 (87)	138	487
	STY	34 (89)	26	0	34 (90)	35	66

[A]BD = 1,3-butadiene, STY = styrene.
[B]Non-Hodgkin's lymphoma.

TABLE VIII. Job Group-Specific 1,3-Butadiene (BD) and Styrene (STY) Time-Weighted Average (TWA) Exposure Measurements from NIOSH Surveys and Estimates from the Present Study

	BD 8-Hour TWA (ppm)				STY 8-Hour TWA (ppm)			
	Measurements[A]		Estimates		Measurements[B]		Estimates	
Job Group	Mean (SD)	Range	Mean	90% UI[C]	Mean (SD)	Range	Mean	90% UI
Tank farm operator	2 (4)	0–24	13	2–113	0.7 (1)	0.14–3.35	1.7	1–2.4
Reactor operator	1.8 (4)	0–25	4	0–28	No data			
Recovery operator	No data				0.61(1)	0.12–4.4	5.5	2.9–8.5
Finishing operator	0.35 (1)	0–7	0	—	1.0 (1)	0.0–3.7	1.4	1.0–1.7
Maintenance, skilled	1.8 (7)	0–43	3.8	0–22	0.14 (0.14)	0.02–0.8	0.9	0.6–1.2
Maintenance, unskilled	No data				2.9 (4)	0.11–12.3	9.4	5.4–14
Laboratory technician	3 (7)	0–38	5	0–58	0.6 (0.75)	0.09–2.86	4.6	3.5–6.9
All workers	1.1 (4)	0–43	2	2–2	0.77 (1.02)	0–12	1.3	1.2–1.4

[A]From 1984–1987 extent-of-exposure survey[10].
[B]From 1974–1977 survey of two facilities[9].
[C]Uncertainty interval.

the median cumulative exposure to butadiene was 68 ppm-years according to the revised JEM, almost five times higher than the original estimate. The median cumulative number of butadiene peaks at or above 100 ppm was 853 according to the revised JEM, about 50% higher than the original estimate. About 85% of all employees were ever exposed to STY. The median cumulative exposure to styrene among all exposed employees was 18 ppm-years according to the revised JEM, about twice as high as the original estimate. STY exposure at 50 ppm or higher was rare according to either set of estimates. As for the original estimates, cumulative BD exposure was considerably higher for all decedents than for all employees and was highest among leukemia decedents. Cumulative STY exposure showed a weaker trend in the same direction.

Comparison with Published Industrial Hygiene Measurements

The 1984–1987 NIOSH survey[10,19,20] reported an average BD exposure of 1.1 ppm among 438 personal full-shift measurements, with a range of 0–43 ppm, whereas our estimate of the average BD exposure among all workers was 2 ppm during the same period (Table VIII). Our job group-specific BD exposure estimates were higher than the NIOSH averages for five of six job groups, with absolute differences between the mean exposure estimate and the mean measurement ranging from −35 ppm to +11 ppm (relative differences: –100% to +500%). The exposure estimates, however, were within 1–2 SD, while the 90% UIs overlapped with the ranges reported by NIOSH. The average STY levels in the NIOSH survey of two facilities[9,18] were 1.02 ppm and 0.77 ppm, based on 111 and 103 personal full-shift measurements, respectively, with a measurement range of 0–12 ppm. Our average STY exposure estimates were 1.2–1.4 ppm for workers of both plants combined during the same period. As for BD, our estimates were generally higher than the NIOSH averages, with absolute differences between the mean exposure estimate and the mean measurement ranging from +0.4 ppm to +6.5 (relative differences: +40% to +800%). The 90% UIs of the exposure estimates overlapped with the ranges reported by NIOSH.

DISCUSSION

This study indicates that our original exposure estimates were low. The revised BD exposure estimates were up to one order of magnitude higher than the original estimates, particularly for the 1940s–1960s. The revised STY estimates also were higher than the original estimates, although the differences were not as large as for BD.

The new estimates describe a pattern of high BD exposure prevalence and intensity during the 1940s–1960s, with 8-hour TWAs around 10 ppm, followed by a sharp decline in the 1970s and a lesser reduction in the 1980s. STY exposure was lower than 2 ppm throughout the history of the industry. DMDTC exposure prevalence and intensity were high during the 1950s–1960s and declined dramatically thereafter.

A substantial proportion of the BD ppm-years accumulated by an employee during the 1940s–1960s occurred at exposure levels above 100 ppm. Partitioning BD ppm-years should assist with evaluating whether excess leukemia mortality was due to intermittent exposure to high levels or to chronic exposure to low levels.

An important enhancement of the estimates was the quantification of uncertainty. The 90% UI used in this report summarize the empirical distribution of task-, job group-, and worker-specific estimates. The ratio between the 95th and the 5th percentile of BD and STY TWA exposure estimates for BD-exposed job groups indicates that our estimates have an average error margin of ±400% (median: ±100%, results not shown in detail). The TWA estimates for DMDTC-exposed jobs had an average error margin of ±150% (median: ±100%). The error was smaller for cumulative exposure indices.

Despite extensive changes, the revised exposure estimates were equivalent to the original set of estimates in ranking individual employees according to cumulative exposure levels (Spearman's r = 0.9 for both BD and STY, results not shown). Analyses of mortality as a function of cumulative BD and STY exposure confirmed the relation between exposure to BD and leukemia but indicated that the excess leukemia rate per ppm-year of cumulative exposure would be smaller than previously estimated.[21]

Finally, exposure estimates for BD, STY, and DMDTC, as well as alternative indices of cumulative BD exposure, were highly correlated. Multiple correlation among exposure variables complicated the interpretation of previous results, and the moderate to high correlation between DMDTC exposure and BD and STY exposure made it difficult to disentangle the effect of these agents.[21]

Our estimation procedures have several limitations. First, although the estimates are quantitative, they are not measurements. The validity of the estimates depends on the assumptions used in the models, and misclassification of exposure levels is likely. Even if the models were correct and the estimates developed for well-specified job groups were valid, personnel records did not always characterize job assignments with precision. The exposure estimates developed for generic job groups are imprecise assessments of the exposure levels experienced by any individual worker.

Alternative strategies for developing exposure estimates in the SBR industry were not considered feasible. Industrial hygiene (IH) data were not suitable for estimating exposure for several reasons. Plant data were limited, as IH monitoring programs began only in the late 1970s at most plants and were not necessarily designed to describe average workplace exposure levels. Some of the IH measurements were made to assess "worst case" exposure scenarios or to document problems, and overestimated average exposure levels. On the other hand, IH sampling done after the installation of new equipment or after scheduled maintenance may have underestimated average exposure conditions. Thus, it is difficult to interpret the published summaries of these data.[22,23] Furthermore, whereas the design of the two NIOSH surveys was adequate, only a select group of work areas and jobs were evaluated, and the number of measurements taken for specific jobs was relatively small.(9,10,18–20) Few historical measurements were available for STY or DMDTC.

Evidence gathered during our study questioned the validity of historical IH data and suggested that technical problems with the sampling, storage, and analytic procedures used in the past may have led to substantial underestimation of BD exposure levels. NIOSH reported that over 80% of the tubes in one survey showed breakthrough, suggesting that BD exposure levels were underestimated.(9) It is also possible that a substantial proportion of IH data from the plants(22,23) underestimated BD exposure.

We could have developed ordinal or semiquantitative exposure scores, as was done in a case-control study of leukemia and other neoplasms among SBR workers.(24) On the other hand, the process by which independent raters assign subjective exposure scores is difficult to document, and inter-rater agreement is usually not very high.(25–27) Furthermore, quantitative exposure estimates were highly desirable for risk assessment.

The second limitation was that we could not thoroughly validate the exposure estimates. This problem was due mainly to the absence of comprehensive, technically adequate historical IH data and to the fact that extensive changes in process engineering and safety practices occurring during the 1970s and 1980s have dramatically lowered BD exposure levels.

A third limitation was that, whereas we developed the original BD and STY exposure estimates without knowledge of the employment history of leukemia decedents, this information was available when the present work began. Thus, although our review was systematic and was carried out for all tasks and jobs, the potential for bias was higher for the revised BD and STY estimates and for the DMDTC estimates than for the original estimates.

Despite limitations, the exposure estimation procedures described here have substantial strengths. The procedures entailed several enhancements: (1) the exposure scenarios were made more specific by separating multiple tasks previously grouped in broadly defined background exposure; (2) the values of the parameters of the exposure models were verified through review of published materials whenever possible; (3) plant personnel provided feedback on the adequacy of the exposure scenarios specified by the investigators and, to the extent feasible, provided confirmation of the validity of assumptions made to compute the estimates; (4) the measurement of air velocities at selected locations within each plant replaced arbitrary assumptions in the original estimates with empirical data; (5) the computer management of the estimation process was further improved, together with the documentation of the estimates; (6) the estimates were improved by providing uncertainty ranges for the exposure parameters; (7) exposure to peaks was further characterized.

In conclusion, this work refined the BD and STY exposure estimates that were developed for a study of causes of death among synthetic rubber manufacturing workers. The most salient results of the re-estimation were: (1) a more extensive documentation of the parameters of the exposure models, (2) the development of uncertainty ranges for use in sensitivity analyses, and (3) the refinement of peak exposure indices. In addition, the exposure estimation procedures were extended to DMDTC to allow testing the hypothesis that DMDTC causes leukemia.

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APPENDIX

Exposure Estimation Details for One Task at a Synthetic Rubber Manufacturing Plant

Monitoring Monomer Shipments from Pumphouse (tank farm)

The emission sources for BD totaled 20–50 lb/day. STY emissions were 2–5 lb/day. The volume of the pump house was 29,250 ft^3 (blueprint dimensions: 65′ × 30′ × 15′). The industrial hygienist had measured a ventilation rate of 4–7 air changes per hour.

Multiple source equation: PPM = 403,000,000 ∗ Q(pt/min) ∗ SG/(Vent. Rate ∗ MW).

1943–1952 (BD)

1. Multiple emission sources from a single pump are considered to leak simultaneously. Examples include pipe connections, pump seals, valves, etc. During this period reciprocating pumps with packing were used in BD service. Assume that the multiple emission sources from a single pump collectively leak at about 20–50 lb/day (0.02–0.05 pt/min, LA Study). Bleeding and priming pumps also adds to the multiple emission leakage.

2. 4–7 air changes per hour occurred in the old pumphouse (approximate size = 29,250 ft^3). As a result, the ventilation rate of the building = 1950–3413 cfm. The majority of the year the wind blows from the South through a door with an area of 22.6 ft^2. The louvers on the building are open most of the year. The louver area is 60.4 ft^2on the south side of the building. Wind speed at the door in August 1997 was measured at 33–48 ft/min.

Duration of task (min) = 240; duration of exposure (min) = 240; frequency of exposure = 1/shift
Lower Limit: Q (in pints per minute) = 0.02; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.05; ventilation rate (cfm) = 1950

1953–1976 (BD)

The change to centrifugal pumps with single mechanical seals and improvements in general working conditions resulted in a 1/3 reduction of emissions. Q (lower and upper) = 0.02–0.05 pt/min ∗ 2/3 = 0.013–0.033 pt/min.

Lower Limit: Q (in pints per minute) = 0.013; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.033; ventilation rate (cfm) = 1950

1977–1989 (BD)

The change to centrifugal pumps with double mechanical seals and improvements in general working conditions decreased emissions by 90%. Q (lower and upper) = 0.013–0.033 pt/min ∗ 0.10 = 0.0013–0.0033 pt/min.

Lower Limit: Q (in pints per minute) = 0.0013; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.0033; ventilation rate (cfm) = 1950

1990–1992 (BD)

A new pumphouse was built away from pumps and the double seals were further improved which resulted in a 50% decrease in exposure (from the previous period). Q (lower and upper) = 0.0013−0.0033 ∗ 0.5 = 0.00065−0.00165 pt/min.

Duration of exposure (min) = 158–202.
Lower Limit: Q (in pints per minute) = 0.00065; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.00165; ventilation rate (cfm) = 1950

1943–1952 (STY)

Multiple emission sources from a single pump are considered to leak simultaneously. Examples include pipe

TABLE A1. Typical Tasks Carried Out in the Production Areas of a Synthetic Rubber Plant, with Corresponding Historical Exposure Estimates

Task Description (Work Area)	Agent[A]	Time Period	Duration Range (min)	Frequency Range (Per Shift)	Exposure Estimate		
					Min–Max	Mean	90% UI[B]
Purging water from recycled BD tanks (tank farm)	BD	1943–1992	0.5–1	1.5	0–35,000	3400	0–21,000
Purging water from recycled STY tanks (tank farm)	STY	1943–1972	0.5–1	1–3	0–13.5	1.8	0–10.6
		1973–1992	0.5–1	0.5–1	0–13.5	1.8	0–10.6
Monitoring monomer shipments from pumphouse (tank farm)	BD	1943–1952	240	1	27–119	62	41–84
		1953–1976	240	1	18–78	40	27–55
		1977–1989	240	1	1.8–7.8	4.0	2.7–5.5
		1990–1992	158–202	1	0.9–3.9	2.0	1.4–2.8
	STY	1943–1952	240	1	1.5–6.7	3.5	2.3–4.7
		1953–1976	240	1	1.0–4.5	2.3	1.6–3.2
		1977–1989	240	1	0.1–0.45	0.23	0.16–0.32
		1990–1992	158–202	1	0.05–0.22	0.12	0.08–0.16
Receiving DMDTC shipments (pigment prep.)	DMDTC	1951–1970	—	0.05	3800–18,000	9900	6100–14,000
		1971–1992	—	0.05	82–6000	2500	740–4400
Charging reactors in batch mode (reactor)	BD	1943–1949	0.5–1	3–6	0–4000	327	0–1850
	STY	1943–1949	0.5–1	3–6	0–8.5	0.7	0–3.9
Minor maintenance of equipment (reactor)	BD	1943–1952	10	1	0–5500	371	0–1900
		1953–1976	10	0.5	0–3600	248	0–1300
		1977–1989	10	0.2	0–362	25	0–130
		1990–1992	10	0.2	0–181	12	0–65
	STY	1943–1952	10	1	0–140	9.0	0–46
		1953–1960	10	1	0–93	6.0	0–30
		1961–1976	10	0.2	0–93	6.0	0–30
		1977–1989	10	0.2	0–9.3	0.6	0–3.0
		1990–1992	10	0.2	0–4.8	0.3	0–1.5
Inspection + minor maintenance of compressors (recovery)	BD	1943–1974	10–20	4	0–1100	91	0–500
		1975–1986	10–20	4	0–285	24	0–140
	STY	1943–1974	10–20	4	0–19	1.8	0–10
		1975–1986	10–20	4	0–10	0.9	0–5.2
Draining latex strainers between flash tanks and stripping columns (recovery)	STY	1943–1959	1	4–6	0–112	10	0–59
		1960–1974	1	2–4	0–112	10	0–59
		1975–1984	1	1–3	0–112	10	0–59
		1985–1992	1	1	0–112	10	0–59
	DMDTC	1951–1970	—	2–6	640–2300	1400	900–1900
Latex coagulation area Background	STY	1943–1961	480	1	2.6–5.3	4.0	3.0–4.9
		1962–1979	480	1	1.3–1.7	1.5	1.4–1.7
		1980–1989	480	1	0.6–1.1	0.9	0.7–1.0
		1990–1992	480	1	0.4–0.5	0.4	0.4–0.5

[A]D = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.
[B]90% uncertainty interval.

connections, pump seals, valves, etc. During this period reciprocating pumps with packing were used in STY service. Assume that the multiple emission sources from a single pump collectively leaks at about 2–5 lb (completely evaporated)/day (0.0015–0.0037 pt/min, LA Study). Bleeding and priming pumps also adds to the multiple emission leakage.

Duration of exposure (min) = 240

Lower Limit: Q (in pints per minute) = 0.0015; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.0037; ventilation rate (cfm) = 1950

1953–1976 (STY)

The change to centrifugal pumps with single mechanical seals and improvements in general working conditions resulted

TABLE A2. Typical Tasks Carried Out by Laboratory Technicians at a Synthetic Rubber Manufacturing Plant, with Corresponding Historical Estimates

Task Description (Work Area)	Agent[A]	Time Period	Duration Range (Min)	Frequency Range (Per Shift)	Exposure Estimate Min–Max	Mean	90% UI[B]
Sampling BD shipments (process control lab)	BD	1943–1963	0.25	1	0–38,000	3200	0–18,000
		1964–1974	0.25	0.33	0–34,000	2700	0–15,000
		1975–1979	0.25	2	0–34,000	2700	0–15,000
		1980–1988	0.25	1–2	0–34,000	2700	0–15,000
Sampling dilute DMDTC	DMDTC	1951–1970	—	1	830–3500	2000	1300–2900
		1971–1992	—	2	220–890	500	300–700
Sampling unstripped latex (reactor control/rubber control laboratory)	BD	1943–1949	2	33	0–3000	310	0–1900
		1950–1955	2	5.3	0–3000	310	0–1900
		1956–1959	2	8	0–1100	110	0–700
		1960–1987	5–10	8	0–1200	120	0–715
	STY	1943–1949	2	33	0–2.6	0.27	0–1.6
		1950–1955	2	5.3	0–2.6	0.27	0–1.6
		1956–1959	2	8	0–0.38	0.04	0–0.23
		1960–1987	5–10	8	0–0.38	0.04	0–0.23
	DMDTC	1951–1970	—	17–18	26–130	66	37–100
		1970–1992	—	18	4.8–34	17	9.3–25
Coagulating unstripped latex (reactor control/rubber control laboratory)	BD	1943–1949	2–5	25	17–108	58	29–85
		1950–1955	2–5	4	17–108	58	29–85
		1956–1959	2–5	3–4	17–108	58	29–85
		1960–1985	2–5	3–4	7.1–46	25	13–47
		1986–1992	2–5	3–4	1.2–7.7	4.1	2.1–6.1
	STY	1943–1949	2–5	25	20–25	23	21–24
		1950–1955	2–5	4	20–25	23	21–24
		1956–1959	2–5	3–4	20–25	23	21–24
		1960–1985	2–5	3–4	20–25	23	21–24
		1986–1992	2–5	3–4	1.5–1.8	1.6	1.5–1.8

[A]BD = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.
[B]90% uncertainty interval.

in a 1/3 reduction of emissions. Q (lower and upper) = 0.0015–0.0037 pt/min ∗ 2/3 = 0.001–0.0025 pt/min.

Lower Limit: Q (in pints per minute) = 0.001; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.0025; ventilation rate (cfm) = 1950

1977–1989 (STY)

The change to centrifugal pumps with double mechanical seals and improvements in general working conditions decreased emissions by 90%. Q (lower and upper) = 0.001–0.0025 ∗ 0.10 = 0.0001–0.00025pt/min.

Lower Limit: Q (in pints per minute) = 0.0001; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints per minute) = 0.00025; ventilation rate (cfm) = 1950

1990–1992 (STY)

A new pumphouse was built away from pumps and the double seals were further improved which resulted in a 50% decrease in exposure (from the previous period). Q (lower and upper) = 0.0001–0.00025 = 0.00005–0.000125 pt/min.

Duration of exposure (min) = 158–202
Lower Limit: Q (in pints/min) = 0.00005; ventilation rate (cfm) = 3413
Upper Limit: Q (in pints/min) = 0.000125; ventilation rate (cfm) = 1950

TABLE A3. Typical Tasks Carried Out by Maintenance Operatives at a Synthetic Rubber Manufacturing Plant, with Corresponding Historical Exposure Estimates

Task Description (Work Area)	Agent[A]	Time Period	Duration Range (Min)	Frequency Range (Per Shift)	Exposure Estimate		
					Min–Max	Mean	90% UI[B]
Reactor cleaning (maintenance-unskilled labor)	BD	1943–1955	240	0.17–0.37	70–400	230	120–350
		1956–1959	240	0.17–0.37	220–1200	720	370–1100
		1960–1969	240	0.17–0.37	110–600	360	180–540
		1970–1979	240	0.17–0.37	8.6–77	43	19–66
		1980–1992	240	0.17–0.37	0.7–12	6.3	2.4–10
	STY	1943–1955	240	0.17–0.37	7.1–38	23	12–33
		1956–1959	240	0.17–0.37	22–120	71	37–100
		1960–1969	240	0.17–0.37	11–59	35	18–52
		1970–1979	240	0.17–0.37	6.7–42	24	12–36
		1980–1992	240	0.17–0.37	5.5–35	20	9.9–30
	DMDTC	1951–1968	—	0.17–0.37	2900–6800	4900	3500–6200
Stripping column cleaning (maintenance-unskilled labor)	STY	1945–1959	240	0.2–0.43	0.24–1.2	0.73	0.39–1.1
		1960–1969	240	0.2–0.43	0.12–0.61	0.37	0.2–0.54
		1970–1979	240	0.2–0.43	0.11–0.43	0.27	0.16–0.38
		1980–1992	240	0.2–0.43	0.06–0.37	0.21	0.1–0.32
	DMDTC	1951–1957	—	0.2–0.43	2800–6900	4900	3500–6200
		1958–1970	—	0.2–0.43	2800–6900	4900	3500–6200
Opening lines, vessels (maintenance-skilled trades)	BD	1943–1959	2–5	4	0–8400	1200	0–4200
		1960–1979	2–5	3	0–4200	600	0–2100
		1980–1992	2–5	2	0–2100	300	0–1100
	STY	1943–1959	2–5	4	0–66	8.7	0–29
		1960–1979	2–5	3	0–33	4.4	0–14
		1980–1992	2–5	2	0–22	2.7	0–9.1
	DMDTC	1951–1970	—	1	830–3500	2000	1300–2900
		1971–1992	—	2	220–890	500	300–700

[A] BD = 1,3-butadiene, STY = styrene, DMDTC = dimethyldithiocarbamate.
[B] 90% uncertainty interval.

TABLE A4. Typical Job Groups in the Production Areas of a Synthetic Rubber Manufacturing Plant, with Corresponding Historical 1,3-Butadiene (BD), Styrene (STY), and Dimethyldithiocarbamate (DMDTC) Exposure Estimates (mean and 90% uncertainty interval, UI)

Work Area/ Job Group	Exposure Index[A]	1945 Mean	1945 90%UI	1955 Mean	1955 90%UI	1965 Mean	1965 90%UI	1975 Mean	1975 90%UI	1985 Mean	1985 90%UI	1992 Mean	1992 90%UI
Tank farm operator	BD, 8-hr TWA	54	33–110	43	25–98	36	19–91	33	16–88	15	3.9–70	11	1.2–66
	BD, peaks/year	114	0–415	104	0–394	104	0–394	81	0–347	80	0–346	80	0–346
	BD TWA >100 ppm	10	0–65	9.6	0–64	9.6	0–64	9.5	0–64	9.5	0–64	9.5	0–64
	BD TWA <100 ppm	44	31–57	34	24–45	27	18–37	23	15–33	5.4	3.7–7	1.9	1.1–2.6
	STY, 8-hr TWA	2.4	1.7–3.4	1.8	1.3–2.5	1.9	1.3–2.6	1.8	1.2–2.4	.74	.41–1	.67	.34–.95
	STY, peaks/year	.56	0–5.6	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA >50 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA <50 ppm	2.4	1.7–3.4	1.8	1.3–2.5	1.9	1.3–2.6	1.8	1.2–2.4	.74	.41–1	.67	.34–.95
	DMDTC, 8-hr TWA	0	0–0	59	30–83	59	30–83	15	2.5–25	15	2.5–25	15	2.5–25
Reactor operator	BD, 8-hr TWA	16	4.6–76	8.1	3.9–24	10	5.4–27	5.2	2–21	2.3	1.5–3.6	.95	.61–1.5
	BD, peaks/year	224	0–1232	20	0–113	20	0–113	20	0–113	3.4	0–34	1.1	0–11
	BD TWA >100 ppm	9.1	0–67	2.1	0–17	2.1	0–17	2.1	0–17	.03	0–.31	.01	0–.08
	BD TWA <100 ppm	7	4.6–11	6.1	3.9–9.2	8.2	5.4–12	3.1	2–4.7	2.2	1.5–3.4	.94	.61–1.5
	STY, 8-hr TWA	.92	.38–2.2	.84	.36–1.7	.86	.41–1.5	.86	.41–1.5	.84	.36–1.4	.69	.26–1.2
	STY, peaks/year	5.6	0–56	5.6	0–56	1.1	0–11	1.1	0–11	0	0–0	0	0–0
	STY TWA >50 ppm	.05	0–.47	.02	0–.22	0	0–.04	0	0–.04	0	0–0	0	0–0
	STY TWA <50 ppm	.87	.38–1.7	.82	.36–1.4	.86	.41–1.5	.86	.41–1.5	.84	.36–1.4	.69	.26–1.2
	DMDTC, 8-hr TWA	0	0–0	431	252–588	0	0–0	0	0–0	0	0–0	0	0–0
Recovery operator	BD, 8-hr TWA	53	15–192	53	15–190	53	15–182	31	7.7–136	23	2.3–129	1.5	.57–2.2
	BD, peaks/year	329	0–1164	329	0–1138	329	0–1103	233	0–1014	233	0–1014	0	0–0
	BD TWA >100 ppm	29	0–161	29	0–168	29	0–166	18	0–122	18	0–122	0	0–0
	BD TWA <100 ppm	25	12–41	25	13–39	25	12–41	13	7.7–25	6	2.3–17	1.5	.57–2.2
	STY, 8-hr TWA	3.7	1.1–6.9	3.7	1.3–7.3	4.4	1.9–8.1	4.3	1.6–7.5	4.3	1.8–7.8	3.9	1.4–7
	STY, peaks/year	137	0–1142	136	0–1131	80	0–681	51	0–456	17	0–169	17	0–169
	STY TWA >50 ppm	.04	0–.37	.04	0–.35	.02	0–.21	.01	0–.14	0	0–.04	0	0–.04
	STY TWA <50 ppm	3.6	1.1–6.8	3.6	1.2–7	4.4	1.8–8	4.3	1.6–7.5	4.3	1.8–7.8	3.9	1.3–7
	DMDTC, 8-hr TWA	0	0–0	705	385–1075	705	385–1075	0	0–0	0	0–0	0	0–0

TABLE A4. Typical Job Groups in the Production Areas of a Synthetic Rubber Manufacturing Plant, with Corresponding Historical 1,3-Butadiene (BD), Styrene (STY), and Dimethyldithiocarbamate (DMDTC) Exposure Estimates (mean and 90% uncertainty interval, UI) *(Continued)*

Work Area/ Job Group	Exposure Index[A]	Year 1945 Mean	1945 90% UI	1955 Mean	1955 90% UI	1965 Mean	1965 90% UI	1975 Mean	1975 90% UI	1985 Mean	1985 90% UI	1992 Mean	1992 90% UI
Coagulation operator	BD, 8-hr TWA	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	BD, peaks/year	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	BD TWA >100 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	BD TWA <100 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY, 8-hr TWA	3.4	2.4–4.2	3.4	2.4–4.2	1.3	1.2–1.4	1.3	1.2–1.4	.75	.59–.87	.37	.33–.41
	STY, peaks/year	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA >50 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA <50 ppm	3.4	2.4–4.2	3.4	2.4–4.2	1.3	1.2–1.4	1.3	1.2–1.4	.75	.59–.87	.37	.33–.41
	DMDTC, 8-hr TWA	0	0–0	126	63–204	126	63–204	63	31–99	63	31–99	63	31–99
Production operator (unspecified)	BD, 8-hr TWA	17	6.9–50	11	4.5–36	7.2	2.6–26	4.9	1.6–19	3.6	.64–18	.62	.21–2.5
	BD, peaks/year	96	.08–286	50	.01–156	34	0–110	29	0–118	29	0–119	2.6	0–11
	BD TWA >100 ppm	8.2	0–39	5.5	0–29	3.7	0–21	2.6	0–16	2.5	0–16	.31	0–2.1
	BD TWA <100 ppm	8.4	6.1–1 2	5.9	4.2–8.6	3.6	2.3–5.6	2.2	1.5–3.8	1	.6–2.4	.31	.20–.44
	STY, 8-hr TWA	2	1.6–2.8	1.9	1.5–2.5	1	.77–1.5	1.1	.78–1.6	.86	.56–1.3	.66	.37–1.1
	STY, peaks/year	23	0–167	18	0–137	7.6	0–61	6.1	0–50	1.9	0–17	1.9	0–17
	STY TWA >50 ppm	.02	0–.14	.01	0–.07	0	0–.03	0	0–.02	0	0–.01	0	0–01
	STY TWA <50 ppm	2	1.6–2.7	1.9	1.5–2.5	1	.76–1.5	1.1	.78–1.5	.86	.56–1.3	.66	.37–1.1
	DMDTC, 8-hr TWA	0	0–0	177	124–245	91	57–138	19	13–25	9.2	4.5–15	9.2	4.5–15

[A]Units: BD and STY TWA, ppm; BD peaks, number >100 ppm; STY peaks, number >50 ppm; DMDTC TWA, mg/cm.

TABLE A5. Typical Job Groups in the Laboratories of a Synthetic Rubber Manufacturing Plant, with Corresponding Historical 1,3-Butadiene (BD), Styrene (STY), and Dimethyldithiocarbamate (DMDTC) Exposure Estimates (mean and 90% uncertainty interval, UI)

		Year											
		1945		1955		1965		1975		1985		1992	
Work Area/ Job Group	Exposure Index[A]	Mean	90% UI	Mean	90% UI	Mean	90% UI	Mean	90%UI	Mean	90% UI	Mean	90% UI
Reactor control technician	BD, 8-hr TWA	59	16–295	9.5	2.5–47	21	2.9–120	21	2.9–120	21	2.3–119	3	1.7–4.5
	BD, peaks/year	1581	0–7847	254	0–1193	428	0–1845	428	0–1845	405	0–1800	0	0–0
	BD TWA >100 ppm	35	0–257	5.5	0–41	14	0–102	14	0–102	14	0–102	0	0–0
	BD TWA <100 ppm	25	16–39	3.9	2.5–6	7	2.9–18	7	2.9–19	6.3	2.3–18	3	1.7–4.5
	STY, 8-hr TWA	56	42–77	9.1	6.9–12	8.5	6.4–12	8.5	6.4–12	6.5	5–8.3	1.4	1.1–1.8
	STY, peaks/year	10828	7031–11250	1733	1125–1800	1553	1283–1692	1553	1283–1692	788	704–871	0	0–0
	STY TWA >50 ppm	36	23–58	5.8	3.7–9.2	5.2	3.3–8.4	5.2	3.3–8.4	4	2.6–5.8	0	0–0
	STY TWA <50 ppm	20	18–21	3.2	2.9–3.6	3.3	2.9–3.8	3.3	2.9–3.8	2.5	2.1–2.9	1.4	1.1–1.8
	DMDTC, 8-hr TWA	0	0–0	340	239–457	194	122–280	35	18–55	0	0–0	0	0–0
Monomer control technician	BD, 8-hr TWA	63	49–82	63	49–82	16	13–28	6	2.3–23	3.9	.36–20	.27	.2–.38
	BD, peaks/year	1156	591–1629	1156	591–1629	224	172–414	254	174–458	218	122–444	141	119–162
	BD TWA <100 ppm	8.6	5.7–11	8.6	5.7–11	.79	.58–1	.75	.55–.99	.37	.21–.6	.09	.08–.1
	BD TWA >100 ppm	54	41–74	54	41–74	15	12–28	5.3	1.6–22	3.5	.12–20	.18	.12–28
	STY, 8-hr TWA	2.1	1.4–3	2.1	1.4–3	2	1.3–2.9	2	1.3–2.7	.15	.1–.2	.15	.1–.2
	STY, peaks/year	387	317–457	387	317–457	338	273–402	338	275–400	0	0–0	0	0–0
	STY TWA >0 ppm	.8	.48–1.2	.8	.48–1.2	.7	.4–1.1	.69	.42–1.1	0	0–0	0	0–0
	STY TWA <50 ppm	1.3	.93–1.8	1.3	.93–1.8	1.3	.85–1.8	1.3	.89–1.7	.15	.1–.2	.15	.1–.2
	DMDTC, 8-hr TWA	0	0–0	425	287–571	213	132–311	94	57–138	94	57–138	94	57–138
Physical tester	BD, 8-hr TWA	0	0–0	0	0–0	0	0–0	.34	.33–.35	.17	.17–.18	.17	.17–.18
	BD, peaks/year	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	BD TWA >00 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	BD TWA <100 ppm	0	0–0	0	0–0	0	0–0	.34	.33–.35	.17	.17–.18	.17	.17–.18
	STY, 8-hr TWA	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY, peaks/year	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA >0 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA <50 ppm	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0	0	0–0
	DMDTC, 8-hr TWA	0	0–0	4.5	2.7–6	4.5	2.7–6	0	0–0	0	0–0	0	0–0
Technician (unspecified)	BD, 8-hr TWA	67	41–162	49	36–73	23	13–63	19	8.2–60	18	7.1–58	9.6	6–17
	BD peaks/year	1289	424–4428	736	421–1242	408	175–993	421	175–1011	389	171–855	226	146–261
	BD TWA >100 ppm	53	30–141	43	30–66	18	9.4–54	14	5–51	14	4.2–49	6.8	3.5–15
	BD TWA <100 ppm	13	9.1–21	6.4	5–7.8	4.4	2.8–8.9	4.5	2.9–9	4	2.6–8.3	2.8	2.2–3.5
	STY, 8-hr TWA	20	15–31	4.9	3.8–6.9	4.6	3.6–6.6	4.6	3.5–6.6	3.2	2.5–4.2	1.5	1.2–2.3
	STY, peaks/year	3702	2650–3913	751	611–842	669	528–757	669	528–757	290	254–363	34	23–107
	STY TWA >50 ppm	13	8.2–24	3	2.1–4.9	2.7	1.8–4.5	2.7	1.8–4.5	2	1.4–2.8	.71	.37–1.4
	STY TWA <50 ppm	7.2	6.1–8.1	1.9	1.7–2.2	1.9	1.6–2.2	1.9	1.6–2.2	1.2	.98–1.4	.84	.7–1
	DMDTC, 8-hr TWA	0	0–0	288	210–383	155	113–206	49	33–69	38	22–57	38	22–57

[A] Units: BD and STY TWA, ppm; BD peaks, number >100 ppm; STY peaks, number >50 ppm; DMDTC TWA, mg/cm.

TABLE A6. Typical Job Groups in the Maintenance Department of a Synthetic Rubber Manufacturing Plant, with Corresponding Historical 1,3-Butadiene (BD), Styrene (STY), and Dimethyldithiocarbamate (DMDTC) Exposure Estimates (mean and 90% uncertainty interval, UI)

Work Area/ Job Group	Exposure Index[A]	1945 Mean	1945 90% UI	1955 Mean	1955 90% UI	1965 Mean	1965 90% UI	1975 Mean	1975 90% UI	1985 Mean	1985 90% UI	1992 Mean	1992 90% UI
Skilled trades	BD, 8-hr TWA	27	2.3–113	29	2.2–128	11	2.3–42	11	1–48	3.8	.49–16	3.4	.18–15
(pipefitters,	BD, peaks/year	243	.01–676	258	0–801	178	0–494	175	0–467	111	0–297	111	0–297
boilermakers,	BD TWA >100 ppm	24	0–108	25	0–123	7.7	0–38	9.2	0–45	2.8	0–14	2.8	0–14
mechanics)	BD TWA <100 ppm	3.7	2.2–5.7	3.7	2.2–5.5	3.4	2.2–5.1	1.9	1–3.2	.99	.49–1.8	.63	.18–1.5
	STY, 8-hr TWA	1.5	.83–2.8	1.5	.85–2.9	.97	.55–1.9	1.1	.51–2.9	.88	.4–2.6	.78	.3–2.4
	STY, peaks/year	20	0–197	21	0–209	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA >50 ppm	.02	0–.15	.02	0–.16	0	0–0	0	0–0	0	0–0	0	0–0
	STY TWA <50 ppm	1.5	.83–2.6	1.5	.85–2.6	.97	.55–1.9	1.1	.51–2.9	.88	.4–2.6	.78	.30–2.4
	DMDTC, 8-hr TWA	0	0–0	656	367–1037	603	338–953	41	17–77	40	16–74	40	16–74
Unskilled labor	BD, 8-hr TWA	77	43–115	77	41–117	72	41–108	7.5	3.7–12	2.3	1.2–3.6	2.3	1.2–3.6
(cleanup crew)	BD, peaks/year	69	21–88	69	23–89	73	55–88	1.8	0–11	.79	0–7.9	.79	0–7.9
	BD TWA >100 ppm	61	28–98	61	26–100	55	26–90	.06	0–.53	.01	0–.15	.01	0–.15
	BD TWA <100 ppm	16	12–20	16	12–20	16	12–20	7.5	3.7–12	2.3	1.2–3.4	2.3	1.2–3.5
	STY, 8-hr TWA	22	11–33	22	11–34	14	7.9–20	10	5.8–15	8.2	4.6–12	7.9	4.3–12
	STY, peaks/year	16	10–26	16	12–26	21	9.2–76	14	8.3–24	11	7.6–13	11	7.6–13
	STY TWA >50 ppm	15	4.4–26	15	4.6–26	6.7	1.7–12	4.3	.89–8.3	3.4	.57–6.9	3.4	.57–6.9
	STY TWA <50 ppm	7.1	5.2–9.4	7.1	5.4–9.5	7.2	4.6–10	5.7	3.8–8.2	4.8	3.1–6.8	4.5	2.8–6.5
	DMDTC, 8-hr TWA	0	0–0	432	327–555	432	327–555	0	0–0	0	0–0	0	0–0

[A] Units: BD and STY TWA, ppm; BD peaks, number >100 ppm; STY peaks, number >50 ppm; DMDTC TWA, mg/cm.