REEVALUATION OF BENZENE EXPOSURE FOR THE PLIOFILM (RUBBERWORKER) COHORT (1936–1976)

D. J. Paustenbach

ChemRisk, A Division of McLaren/Hart, Alameda, California

P. S. Price

ChemRisk, A Division of McLaren/Hart, Portland, Maine

W. Ollison, C. Blank

American Petroleum Institute, Washington, D.C.

J. D. Jernigan, R. D. Bass

ChemRisk, A Division of McLaren/Hart, Springfield, Missouri

H. D. Peterson

Bryan, Cave, McPheeters & McRoberts, Washington, D.C.

The Pliofilm cohort is the most intensely studied group of workers chronically exposed to benzene. Information on this cohort has been the basis for regulations and/or guidelines lor occupational and environmental exposure to benzene. Rinsky et al. (1986, 1987) and Crump and Allen (1984) developed different approaches lor reconstructing the exposure history of each member of the group. The predicfed levels of exposure, combined with the data on the incidence of disease. have been used to estimate benzene's carcinogenic potency. In this paper. recent information from worker interviews and historical records from the National Archives and elsewhere were used to evaluate the accuracy of prior exposure estimates and to develop better ones for the cohort. The following factors were accounted for: (1) uptake of benzene due to short-term, high-level exposure to vapors, (2) uptake due to background con. centrations in the manufacturing building, (3) uptake due to contact with the skin, (4) morbidity and mortality data on workers in the Pliofilrn process, (5) the installation of industrial hygiene engineering controls, (6) extraordinarily long work weeks during the 1940s, (7) data indicating that airborne concentrations of benzene were underestimated due to inaccurate monitoring devices and the lack of adequate held calibration

Requests for reprints should be sent to Dennis J. Paustenbach, ChemRisk, A Division of McLaren/Hart, 1135 Atlantic Avenue, Alameda, CA 94501.

journal of Toxicology and Environmental Health, 36:177–231, 1992

mated due to inaccurate monitoring devices and the lack of adequate field calibration of these devices, and (8) likely effectiveness of respirators and gloves. Our estimates suggest that Crump and Allen (1984) overestimated the exposure of workers in some job classifications and underestimated others, and that Rinsky et al. (1981, 1986) almost certainly underestimated rhe exposure of nearly all workers. Airborne concentrations of benzene at the St. Marys facility during the years of ifs operation were found (on average) to be about half those of fhe two Akron facilities. Our analysis indicates that short-ferm, high-level exposure to benzene vapors and dermal exposure significantly increased (by about 25-50%) the total absorbed dose of benzene for some workers. One of the key findings was that, unlike prior analyses, the fhree facilities probably had significantly different airborne concentrations of benzene, especially during the 1940s and 1950s.

INTRODUCTION

The health hazards of human exposure to benzene are well documented (Agency for Toxic Substances and Disease Registry, 1989; Goldstein, 1977, 1983; IARC, 1982). In humans, exposure to high levels of benzene is associated with a variety of disorders of the hematopoietic system, including leukemia and aplastic anemia (Coldstein, 1977; IARC, 1982). Evidence of the leukemogenic properties of benzene in humans comes both from collections of case reports (Aksoy, 1980; Greenburg, 1926; Hamilton, 1929, 1931; Vigliani, 1976) and from epidemiology studies (Infante et al., 1977; Ott et al., 1978; Rinsky et al., 1981; Wong, 1983; Yin et al. 1987). Unlike most chemicals, federal regulatory agencies in the United States have used epidemiology studies, rather than animal bioassays, to derive cancer potency factors for benzene (OSHA, 1987; U.S. EPA, 1985).

The Pliofilm workers are among the most intensely studied group in the history of occupational epidemiology (Cody et al., 1991; Crump and Allen, 1984; Infante and White, 1983; Infante et al., 1377; Kipen et al., 1988, 1989a, 1989b; Lamm et al., 1989; Rinsky et al., 1931, 1986, 1907; Tabershaw and Lamm, 1977). The cohort consists of workers at three different facilities in two cities in Ohio (one facility in St. Marys and two in Akron). This group of rubberworkers is regarded as superior to other epidemiological cohorts for understanding the hazards of benzene because there are reasonably good exposure data, there is a lack of significant exposure to chemicals, employment and work history data are available on individual employees, there is evidence of a dose-response relationship in the cohort, and epidemiology methods can be applied to the group (Brett et al., 1989; OSHA, 1985; Voytek and Thorslund, 1991). The studies conducted by Crump and Allen (1984) and Rinsky et al. (1986, 1987) estimated the workplace concentrations of airborne benzene. These estimates have been used as the basis for predicting the cancer

risk to humans (Albert, 1979; Austin et al., 1988; IARC, 1982; OSHA, 1985; Rinsky et al. 1987; White et al., 1982). Risk assessments based on this cohort have played a major role in setting the current occupational exposure limits for benzene as well as numerous air, water, and soil standards (American Conference of Governmental Industrial Hygienists, 1991; OSHA, 1987; U.S. EPA, 1985).

In light of the importance of this cohort, we conducted a search of historical records and conducted interviews with workers to identify additional information that might reduce the uncertainty associated with prior estimates of the workplace concentrations made by Kinsky et al. (1986, 1987) and Crump and Allen (1984). This paper critically evaluates the two previous efforts and presents information not considered in either estimate.

A significant source of the information contained in the paper comes from interviews with three St. Marys employees (Allman, 1991; Hanning, 1990, 1991a, 1991b; Osborne, 1991). These individuals had from 25 to 39 years of workplace and/or management experience at the St. Marys facility from 1942–1976. One of the individuals had been employed in the Akron I facility from 1934–1942. While many employees of St. Marys were interviewed by earlier investigators, it is uncertain that they were questioned concerning their experience during the early years of production (1936–1950). These are almost certainly the years of greatest exposure.

We present an approach that quantitatively accounts for the following factors: (1) short-term, high-level airborne concentrations of benzene; (2) dermal exposure and uptake; (3) longer work weeks during the 1940s and 1950s; (4) the quality of the available air sampling data; (5) improved local exhaust ventilation, and (6) the less-than-complete effectiveness of respirators. New estimates of worker exposure were developed and compared with previous published values. Our analysis indicates that exposure at the facilities was significantly greater in the 1940s and early 1950s than previously reported by Rinsky et al. (1986), and not unlike those predicted by Crump and Allen (1984).

BACKGROUND INFORMATION

The Pliofilm Manufacturing Process

Pliofilm was a strong, thin, flexible material similar to plastic wraps now commonly used in home food storage. The chemical process of Pliofilm manufacture was described in detail by Rinsky et al. (1981) based on a survey by the National Institute of Occupational Safety and Health (NIOSH). In 1976, several NIOSH investigators conducted a walk-through survey of the Pliofilm operations at the St. Marys facility (Young et al., 1977). From this survey, NIOSH developed a schematic diagram (flow chart) of the Pliofilm manufacturing process. We have revised that dia-

gram (Fig. 1) based on information gathered in recent worker interviews (Allman, 1991; Hanning, 1990, 1991a, 1991b; Osborne, 1991). Figure 2 presents our best reconstruction of the floor plan of the St. Marys facility (1946-1976). The primary differences between the two diagrams are the addition of several operations, including (1) the scale tank between the blend tank and the reactor *to* weigh the materials so that the proper amounts would be used; (2) the scrubber unit after the reactor and neutralizer, which was used to remove the gases released during the reaction; (3) centrifuge between the quencher and the storage tank (it separated unwanted particles and broke the water/benzene emulsion); and (4) the finishing and shipping operations. The diagram helps explain how the airborne concentrations for one job category (or areas in the plant) may have been related to those for another.

The production process can be summarized as foilows. Natural rubber was dissolved in benzene and converted to rubber hydrochloride by the addition of hydrochloric acid. After a ripening period, the unreacted hydrogen chloride in the mixture was neutralized with sodium carbonate and the resulting slurry was filtered and stored. The solid materials filtered from the solution were transferred as a cake to a "quencher" unit where residual benzene was separated and recovered by steam distillation. The rubber hydrochloride solution, often referred to as cement, was turned into film on a casting unit. During this process, the benzene content of the film was reduced from 90% to 10%. Evaporated benzene was swept out of the casting unit into a wet scrubber that cooled the vapor and removed residual hydrogen chloride before discharging the benzene-laden air to charcoal absorbing unit. The benzene was recovered and reused. The resulting Pliofilm was further dried in a drying unit and stored on rolls before moving to finishing operations. In the finishing operations, the film was rerolled, cut, and stretched before packing and shipping. Benzene levels in the dried Pliofilm is believed to have been negligible.

Those processes known to have produced especially high airborne concentrations of benzene were (1) mixing the rubber/benzene solution, (2) neutralizing the solution, (3) filtering the solution, (4) quenching the solution, (5) adjusting the thickness of the Pliofilm in the casting unit, and (6) gauging tanks of the cement in the storage room. The highest degree *of* exposure generally is believed to have occurred when the filter press (a plate and frame filter) was cleaned and during operation of the quencher (Hanning, 1990a). These particular unit operations, which are not unique to Pliofilm manufacturing, have been known for decades to be associated with high exposure.

Previous descriptions of the Pliofilrn Operations have divided the operation into two sections called the "wetside" and the "dryside." The definition of these terms has varied (United Rubber Workers, 1977). Workers at St. Marys defined the "wetside" as the operations that oc-

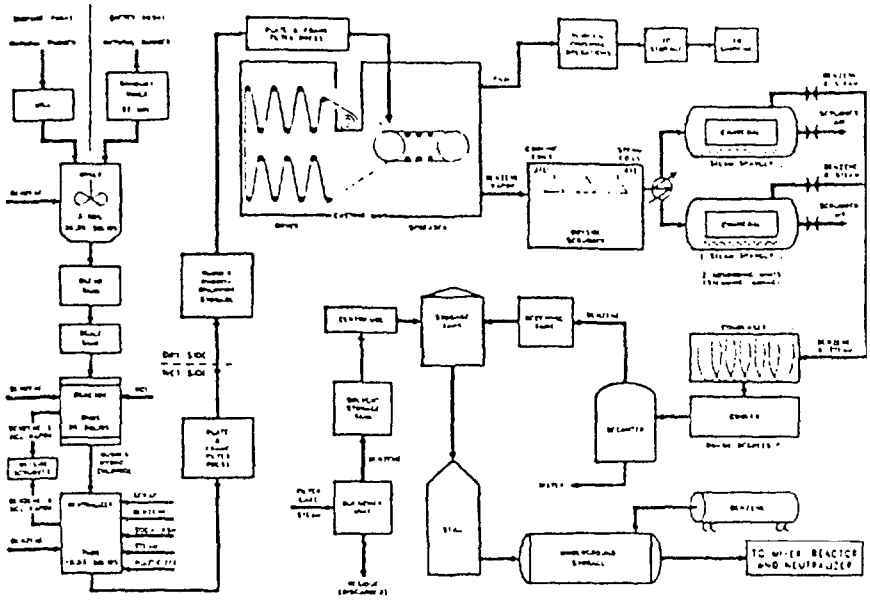

FIGURE 1. Pliofilm process, St. Mary's, Ohio

cured before the casting of the film. Dryside operations included rubber hydrochloride storage, casting, finishing, and shipping. Workers on the wetside were considered separate from the dryside workers and reported to different operations managers (Allrnan, 1991; Hanning, 1990; Osborne, 1991). In this paper, we adopted the St. Marys definition: that is, workers who were involved in precasting operations were considered wetside, and all others were dryside workers.

The Pliofilm Manufacturing Facilities

Pliofilm was produced at three facilities (see Fig. 3) in two locations, 300 miles apart (Rinsky et al., 1981). The first facility (Akron I) was located in Akron, Ohio, and it began commercial production in 1936. It was originally an experimental pilot plant, which was expanded into commercial production. It was located on the second and third floors of a multistory factory building. The facility shared the second floor with a balloon fabric manufacturing operation that also used large amounts of benzene. The second Pliofilm manufacturing facility was opened in the 1940s at St. hlarys, a small town 300 miles southwest of Akron. The St. Marys facility was built to meet production needs for Pliofilm as demand increased at the end of the Depression. The St. Marys facility was located in a one- and two-story building adjacent to a larger manufacturing facility. In 1948, the third facility (Akron II) opened in Akron a few miles away from

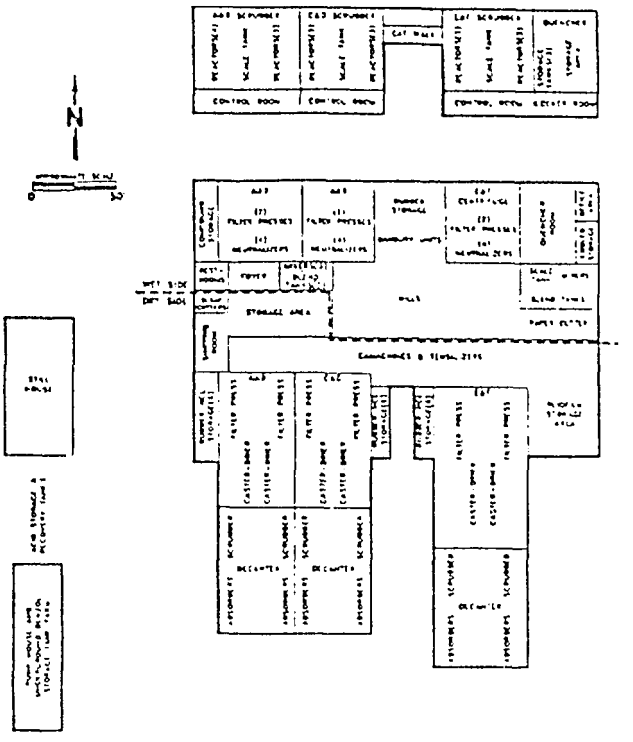

FIGURE 2. Pliofilrn **plant,** St. Marys, Ohio

Akron I. This facility replaced the initial one (Akron I), which shut down in the same year.

Description of Previous Exposure Estimates

To date, two attempts have been made to reconstruct the job-specific exposure history of the Pliofilm cohort (Crump and Allen, 1984; Rinsky et **al.,** 1986). Both studies are based on the available industrial hygiene monitoring data presented in Rinsky et al., (1981); however, the two studies reached significantly different conclusions regarding the airborne concentrations of benzene to which the workers were exposed.

Both approaches used the extensive job history records available for Pliofilm workers. Those records specify the job title, as well as the starting and finishing dates of the job assignments for each worker. There are 30 jobs titles listed for the St. Marys workers and 64 for the workers at the two Akron facilities. In many instances, several job titles refer to the same worker activity, or to activities with similar potential for benzene exposures. To simplify the exposure assessment, both Crump and Allen (1984) and Rinsky et al. (1986) collapsed the job titles into approximately

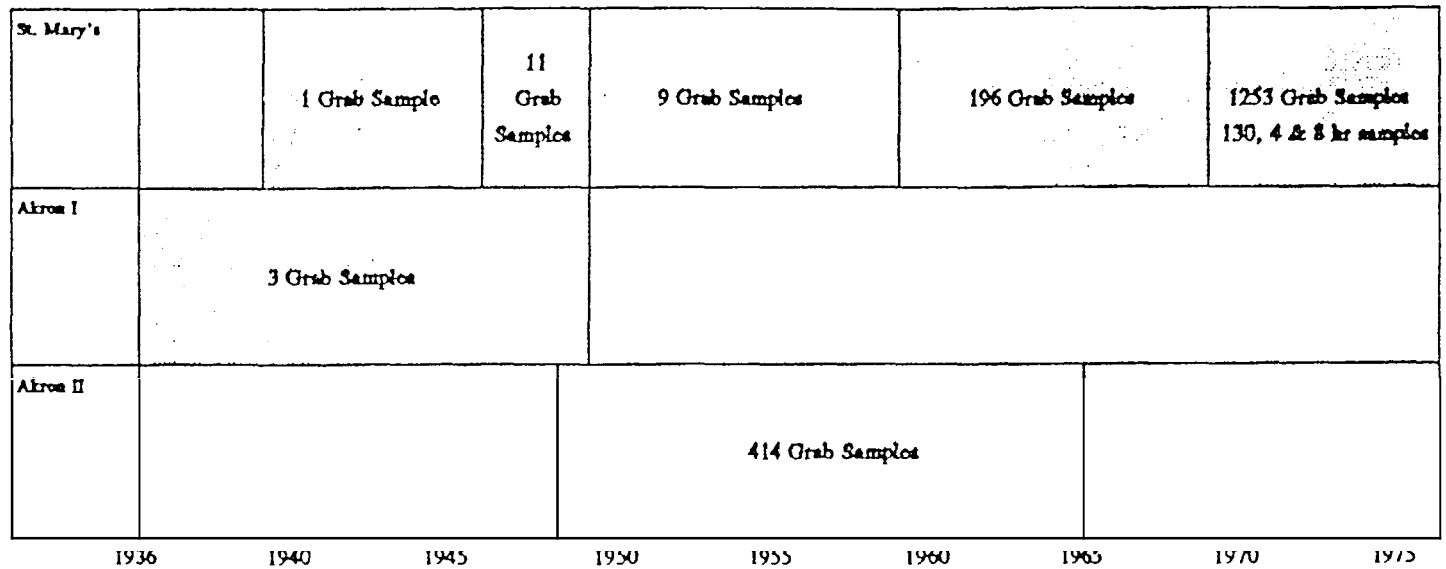

FIGURE 3. Summary of the number of discrete industrial hygiene air samples taken at the three facilities. Shaded areas indicate when facilities were in operation.

10 exposure categories, which they believed represented similar types of activities and exposure. Airborne concentrations of benzene were estimated for each of the job categories for each of the years during which the facilities were in operation. Industrial hygiene monitoring data were used whenever available. Finally, the individual workers' exposure histories were reconstructed from the individual workers' records (by job) and the benzene levels for each exposure category.

Estimates of the likely concentration of benzene vapors for each exposure category differed significantly between Crurnp and Allen (1984) and Rinsky et al. (1986), with the former usually having higher estimates. The differences in benzene concentrations result from differences in the way each researcher estimated the workplace concentrations for the years prior to 1963 when there were limited monitoring data. While more than 2000 measurements of the airborne concentration of benzene are available for the three sites, the majority of the values comes from the St. Marys facility, and these values were collected after 1969 (see Fig. 3). Only a handful of air samples was collected at St. Marys prior *to* 1956. The two Akron facilities have less data than St. Marys. The results of 400 short-term (length *of* stain tube) samples are available for *the* Akron II facility (in operation from 1949–1965), but it is *not* known in what years they were collected (Mclnerney, 1977). The results of only three samples are available for Akron I. Faced with this absence of data for 1936–1956, both Rinsky et al. (1986) and Crump and Allen (1984) were forced to make numerous assumptions when developing their estimates of airborne benzene. In this paper, we address the differences in the exposure factors they selected and evaluate each of them in light of information not considered when their analyses were conducted.

NEW INFORMATION ON EXPOSURE

We identified new information involving seven factors that could significantly change prior exposure estimates for the Pliofilm workers: (1) accuracy of air sampling devices, (2) length of the work week, (3) rubber shortages during World War II, (4) local exhaust ventilation controls, (5) dermal uptake, (6) effectiveness of respirators, and (7) medical evidence of overexposure.

Inaccurate Monitoring Devices

Before 1963, airborne concentrations of benzene were determined before 1963 using one of two analytical methods: detector tube kits and combustible gas indicators (Rinsky et al., 1981, 1986). Verbal accounts by industrial hygienists who worked in the industry confirm that these were used in the Pliofilm building (Mclnerney, 1977; Rinsky et al., 1981). Detector tube kits consisted of a package of two unmixed reagents, empty

glass tubes, and a squeeze-bulb aspirator. just prior to use, the reagents were mixed and the tubes were filled and capped to form the detectors. An aspirator was used to obtain an air sample of a fixed volume of 33 ml nominal capacity (Rinsky et al., 1981). Benzene concentrations were proportional to the length of stain produced when air was drawn through the tube (Rinsky *et* al., 1981; Silverman, 1956).

Several authors have assessed the reliability of measurements using these detector tubes (Kusnetz et al., 1960; Silverman, 1956), and each has listed their deficiencies. Specifically, the accuracy of detector tubes was evaluated by Hay (1964). He conducted a laboratory experiment where he sampled known concentrations (from 25 to 250 ppm) of benzene vapor. Hay found that the detector kit gave readings that were, on average, only 60% of the actual value at a benzene concentration at 25 ppm. That is, the detector kit displayed a reading of 15 ppm when the actual benzene concentration in air was 25 ppm (Hay, 1964). This underreporting (by about 40%) was fairly consistent for benzene concentrations ranging from 25 to 100 ppm. When the tubes were used to measure concentrations above 100 ppm, the underreporting increased. For example, at concentrations of 250 ppm, the tubes reported concentrations of only 100 ppm (Hay, 1964). In contrast, a subsequent field evaluation by Hay showed that tube readings overestimated the airborne concentration of benzene thought to be present in a plant that refined coke-oven light-oil products. Hay attributed these disparate results to interace from toluene, xylene, thiophene, and phenols present in the manufacturing process (Hay, 1990). Fortunately, the solvent used in Pliofilm production during the 1940s was about 95% benzene, with the major contaminant being toluene (Wilson, 1942). Based upon Hay's work, we conclude that it is appropriate to adjust reported levels of benzene obtained by this method by a factor of 1.5.

The second analytical technique for measuring workplace concentrations of benzene vapor (prior *to* 1963) was the combustible gas indicator (CGI) (Rinsky et al., 1981; Wilson, 1942). The CGI relied on the catalytic combustion of gas or vapor over a heated platinum filament and the subsequent imbalance of an electrical resistance bridge. Pagnatto et al. (1961) evaluated this device in a study of benzene exposure in the rubber coating industry. The authors noted that, when correctly operated, the CGI reported only about half the actual benzene concentration (when compared with gas chromatography) in several areas of the facility where airborne concentrations of benzene ranged from 5 to 125 ppm.

In addition to evidence provided by Pagnatto et al., there are two other reasons why the benzene levels were likely underestimated by the CGI. First, the wire used in the CGI's electrical bridge loses sensitivity with age (Silverman, 1956). Second, field calibration of the CGI used in the Pliofilm operations was often rudimentary during the 1940s—for ex-

ample, employees frequently used a Zippo lighter to determine whether the instrument was operating (Hanning, 1990; McInerney, 1977).

Based on this information, benzene concentrations measured at the St. Marys facility before 1963, and at the Akron I and II factilities, were likely to have been underreported by at least a factor of 1.5. Where such measurements are cited in this paper, we indicate the reported value and the corrected figure in square brackets [ ]. The values in brackets were used in our estimates of worker exposure.

Extended Work Periods

There is considerable evidence that the work week at the Pliofilrn facilities was often much longer than the modern 40-h schedule. Due to the nature of the process, Pliofilm typically was manufactured on a continuous basis. During the initial years of Pliofilrn production, Depression-era unemployment caused industry to use four 6-h daily shifts as a means of providing jobs for a greater number of people (Hanning, 1990). Employees typically worked 5- or 6-d work weeks. However, in the 1940s, with the beginning of U.S. involvement in World War II, production in the rubber industry greatly increased and labor was in short supply (Department of Labor, 1942). Employees began working 8-h shifts, and extended work periods were not uncommon (Hillman, 1942; Rothstein, 1932; Zimmer, 1931). Extension of the individual work week to 50 or more h and the payment of attendance bonuses were being considered in 1943 in an attempt to meet wartime needs (Flanick, 1943). Similar work patterns were used in St. Marys where employees worked 6 to 7 d a week (Hanning, 1990; Osborne, 1991).

In the late 1940s, employees continued to work more than 40 h per week. The typical Pliofilm production schedule at St. Marys involved operating for 19 d with a 2d shutdown for maintenance. People were expected to work one 8-h shift, 7 d a week, including weekends (Osborne, 1991). This information is consistent with the data in the personriel records. For example, a workman's compensation report for a person diagnosed with leukopenia indicated that he worked 49 h per week for an entire year (Industrial Commission of Ohio, 1944). The change in the average work week during the 1940s and early 1950s can be seen in the records of hours worked per week recorded in the accident and injury reports, see Table 1. The information shows that three out of four employees (75%) for whom data are available worked more than 40 hlwk during the period between 1940 and 1941, with an average work week of 46 h. The proportion of employees working overtime remained approximately constant through 1951, but the average work week increased to 49 h. In 1952–1956, the percentage of workers with long schedules dropped to 40%, and the average work week was decreased to 44 h. It is acknowledged that those who filed an accident or injury report may not

TABLE 1. Hours Worked per Week by Various Members of Pliofilm Cohort for 1940-1956

Period	40 h/wk	48 hlwk	56 hlwk	Average (h/wk)	Number of workers with > 40 hlwk
1940-1941	1	3	0	46	3/4 (75%)
1942-1946	3	6	3	48	9/12 (75%)
1947-1951	4	5	5	49	10/14 (72%)
1952-1956	6	3	1	44	4'10 (40%)

Note. Based on data obtained from applicable Coodyear "Foreman's accident and injury reports" (dated 1937-1956).

be representative of the entire work force. Nevertheless, these data, coupled with the testimony of workers and knowledge of the pressures on similar industries during the war years, give us confidence that long work weeks were common. The alternative to using the injury report data would be to use the worker interview data and set the work week at 51 h per week (see discussion on uncertainty analysis).

WWII Shutdown of St. Marys

Pliofilm was in great demand by the military for protecting equipment from dust and moisture during shipment to the war zones. However, with the beginning of hostilities in the Far East, supplies of rubber were decreased and the ability to produce Plioiilm was affected. For example, from 1942-1945, the St. Marys facility received little new rubber from Indonesia and relied on the recycling of old Pliofilm (Hanning, 1990). Although recycling efforts were intense, Pliofilm production at the St. Marys facility was reduced to 4-7% of capacity. Evidence for a decrease in production can also be seen in a report of the history of the St. hlarys facility published in an employee newsletter (Wingfoot Clan, 1983). In contrast with St. Marys, the Akron I plant continued to produce Pliofilm at or near capacity during 1942-1945.

The reduced production at St. Marys could have been satisfied by using one, rather than four, casters. Even this caster needed to operate only one shift, rather than three per day. The unused capacity in St. hlarys was devoted to the production of coated, waterproof tent fabric and paper/metal foil laminate (Hanning, 1990; Wingfoot Clan, 1983). Neither of these products used benzene as a solvent (Hanning, 1990). Worker's job histories do not reflect these changes. The records indicate only that workers were operating the neutralizers or casters. They do not specify what products the equipment was manufacturing (Hanning, 1991b).

The lack of availability of rubber for St. Marys from 1942-1945 is expected to have lessened worker exposure to benzene for several reasons, First, the time workers spent in the production of Pliofilm (and thus

were exposed to benzene) was reduced from three to one shifts per day. Second, the reliance on recycled Pliofilm eliminated the need for certain steps in its manufacture. For example, the mixers and the reactors were not operated since the chlorination step was not performed (scrap Pliofilm was added directly to the neutralizers). Third, the number of times the filter presses were cleaned and changed was reduced greatly since sodium carbonate was not necessary to neutralize excess hydrogen chloride. Based on this information, it was concluded that the background concentration of airborne benzene in the facility was relatively low and that many of the workers in the exposure categories, which would have had high levels of exposure, were exposed to relatively low concentrations (e.g., about 5–20 ppm).

Medical Evidence of Elevated Exposure in the Early Years

The major difference behveen the Crump and Allen (1984) and Rinsky et al. (1986) analyses was that the former concluded that worker exposure to benzene was significantly higher in the early 1940s than in the 1960s. Some scientists at OSHA who evaluated the Crump and Allen (1984) analysis believed that human exposure to airborne concentrations in excess of 150 ppm for 8 hd for weeks or months was very unlikely because these would have produced acute illness (Crump and Allen, 1983). At that time, Crump and Allen and OSHA were not aware of information that indicated that incidents of acute toxicity had been observed in the Pliofilm cohort. We have since found published accounts that demonstrate the existence of significant hematopoietic effects, including fatalities, in the Pliofilm workers in the 1940s. In addition, there is ample evidence in the industrial hygiene literature that some fraction of workers can be exposed to 100–200 pprn for long periods (6 h/d for several weeks) without developing clear signs of illness (Bloomfield, 1951; Greenburg, 1926).

In the proceedings from a 1932 Department of Labor Conference on Health Hazards in the Rubber Industry, Dr. Conn, Medical Director of the Goodyear Hospital at Akron, described the results of a study of Goodyear workers who routinely had exposure to high levels of benzene:

> In tests of 1,104 employees exposed to more than 100 [150] parts per million of benzol over any considerable period of time, 7.5 percent (83) showed a slight leukopenia. Two and two-tenths percent (25) (all men who had exposures of over 100 [150] parts per million showed marked blood changes. Nine of this 25 showed serious disturbances of the blood-forming organs that had a sufficiently severe aplastic anemia to require hospitalization. Of these nine, three died. Those surviving have returned to work. They are tested frequently and are apparently in good condition. (Two fatalities came from the spreader room: one from Pliofilm.)

Dr. Wilson, a physician with Goodyear, reported on the same group of workers, stating that while their exposures occasionally could reach 500–1000 [750–1500] ppm (such as when vapors were released while opening a drum of benzol or from the heating of benzol-containing media), routine concentrations varied between 50 (75) and 500 (750) ppni, with "average concentrations being about 100 (150) pprn" (Wilson, 1942).

It is clear trom the reference to a fatility that occurred in the Pliofilm department and from later references to Pliofilm operations in the transcript (Department of Labor, 1942) that some members of the Pliofilm work force were included among the 1104 workers exposed to benzene concentrations of 100 (150) ppm or greater. However, it is also clear that the survey included workers manufacturing other rubber products such as balloon fabric. Therefore, we cannot conclude that all cases occurred among the Pliofilm workers, nor imply that the reported incidence rates of hematopoetic effects apply to the Akron I Pliofilm workers.

A second incident where exposure to benzene during the 1940s is known to have produced hematopoietic effects in Pliofilm workers occurred at St. hlarys. Injury reports submitted to the Ohio Industrial Commission indicated that two neutralizer operators at the Pliofilm facility suffered from serious blood abnormalities in July 1946 (American Petroleum Institute, 1986). Both were hospitalized, and one eventually died.

The information in these reports suggests that the industrial hygiene program facilities in the Pliofilm in the 1940s was not sufficient to prevent acutely toxic exposures to benzene. In evaluating this information, it should be remembered that benzene workplace concentrations of 100–150 ppm were not uncommon in numerous industries during these decades (Cook, 1945).

The clearest evidence for high benzene exposure, however, is provided in the blood-monitoring records of the St. Marys workers that have been evaluated by Kipen et al. (1989a). These workers were monitored monthly (red and white blood cell counts) in order to manage the employee risk due to exposure to benzene. Figure 4 represents the average white blood cell (WBC) counts by year for the St. Marys Pliofilm workers. It shows that for the years 1940–1949, the workers' average WBC counts were suppressed. However, during the 1950s the counts remained stable. The implication of this finding is that benzene exposures at St. Marys in the 1940s were sufficiently high to suppress the WBC counts and that, based on other studies, this would be expected if workers were exposed to benzene concentrations in the range of 25–100 ppm. Apparently, airborne levels of benzene decreased throughout the 1940s such that by the 1950s the levels were low enough to suppression of WBCs no longer occurred.

25–100 ppm

The findings of Kipen et al. (1989a) have been questioned by Hornung et al. (1989). They suggested that the temporal trend in blood counts could also be explained by factors other than exposure to ben-

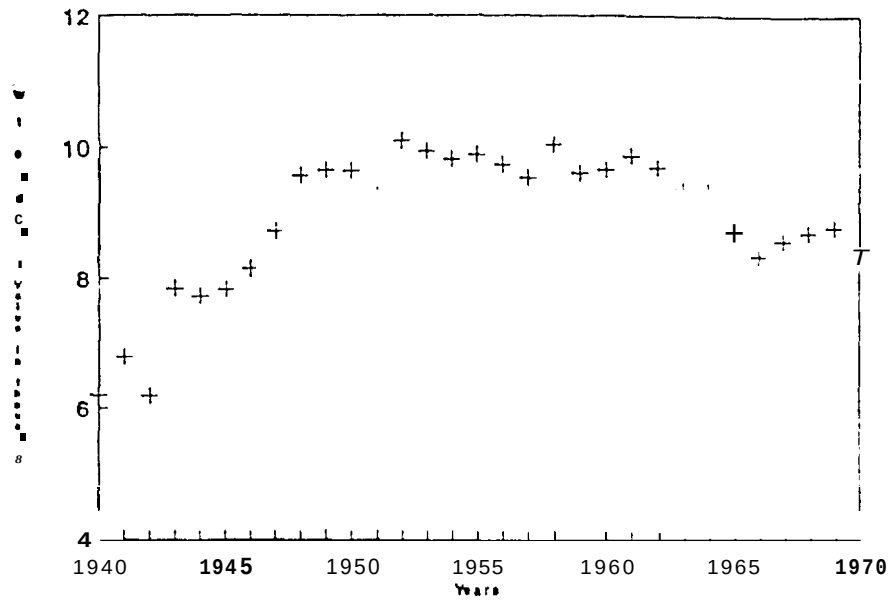

FIGURE 4. The average white blood cell count for Pliofilm workers at St. Marys during **the** years 1940-1970 (Kipen et al., 1989a).

zene, since preemployment measurements of blood counts were lower in the early 1940s than in later years. They also suggested that the test method used at that time could well have been flawed. Kipen et al. (1989b) published responses to these claims wherein they showed that the trend in preemployment data was insufficient to discount the dramatic change in the blood counts. Cody et al. (1991) have also shown that the preemployment data from the 1940s could be used to demonstrate a progressive suppression of blood counts during the first 6 mo of employment in the Pliofilm process.

Evidence for Improved Engineering Controls

Estimates of exposure by Crump and Allen (1984) and Rinsky et al. (1981) have been based on the assumption that the Pliofilm manufacturing process remained relatively unchanged from the time of its development in 1936 until its discontinuation in 1976. Our research indicates that although the chemical process probably remained relatively constant, the three facilities had different manufacturing equipment and industrial hygiene controls. Further, it is well known in the industrial hygiene community that employee exposures are not strictly a function of the operation but are also a function of work practices, room size, ventilation rate, building layout, and local exhaust ventilation (Mclnerney, 1977). These

characteristics are known to have differed from facility to facility and to have changed over time. The following describes the differences in the facilities and the known engineering changes in the manufacturing process at the two facilities for 1940–1970.

In 1936, the process for manufacturing Pliofilm was developed in Akron (Akron I). The location of the first production facility was a portion of the third and fourth stories of a multistoried building in which a number of rubber products were manufactured. Pliofilm production and balloon fabric manufacturing were on the same floor (Department of Labor, 1942; Hanning, 1990). Only general division ventilation was provided.

A second Pliofilm production facility was built in the early 1940s in a two-story building in St. Marys, Ohio. Unlike Akron I, this facility was designed explicitly for the purpose of manufacturing Pliofilm. While the processes and equipment were similar to Akron I, the building layout was significantly different. First, the ventilation for the building was provided by large ventilation fans located in the basement of the building that supplied filtered air (for dust removal) to each room of the building (Hanning, 1991b). Second, the finishing operations, which were located in a separate building in the Akron facility, were in a room between the wetside operations and the casters (Beebe, 1976).

In the early 1940s, a shortage of toluene caused many rubber operations throughout the industry to shift to benzene as a solvent. These changes resulted in widespread cases of leukopenia among Akron rubber workers (including Pliofilm cohort members). In response, benzene was replaced with other solvents in all of Goodyear's Akron manufacturing departments except Pliofilm and balloon manufacturing. In the balloon fabric area, the Akron management instituted engineering controls including improved local ventilation, and in both departments they maintained a program of monthly and, later, quarterly blood monitoring (Department of Labor, 1932).

In November 1946, following the cases of benzene toxicity observed at St. Marys, management apparently embarked on a major program to reduce airborne concentrations of benzene (Fluker, 1946). The engineering controls included local exhaust ventilation around manways at certain tanks and placement of the wetside filter presses within ventilated enclosures. Local exhaust ventilation was provided at the hatches of the mixer, reactor, and neutralizer units (Hanning, 1990). Pliofilm production required that rubber be added manually into the mixer. Scrap Pliofilm, plasticizers, additives, and sodium carbonate were added to the neutralizer vessels. While adding these materials, workers were exposed to relatively high concentrations of benzene vapors displaced from the tanks (Hanning, 1990). The plate-and-frame filter presses, which removed the sodium carbonate and sodium chloride from the rubber hydrochloride solution after the neutralization step, required regular cleaning. This cleaning involved the scraping of caked salts off the filter cloths. The

cleaning process placed the neutralizer operator directly over material saturated with warm (90°-120°F) rubber hydrochloride-benzene solution (95% benzene) for approximately 30 min each time the press was cleaned. The local exhaust ventilation was probably effective at pulling a substantial amount of the benzene vapors away from the workers, but typical airborne concentrations for such operations in other industries can be as high as 500–1000 ppm (see Table 9). Only a single air sample was collected at the filters before the engineering controls were installed, and the concentration was above 250 (375) pprn. Samples collected several years later (after engineering controls) showed levels of 19–50 (27–75) ppm (Rinsky et ai., 1981). The state of Ohio concluded that the filter-press ventilation system was sufficient to maintain benzene concentrations below 100 (150) ppm and typically below 35 *(52)* pprn (Fluker, 1946).

After 1946, additional ventilation improvements were made in the casting units at St. Marys in response to a series of flash fires within them (Allman, 1991; Hanning, 1991). The effect of the ventilation on the workplace concentration of benzene is not known. It is acknowledged, however, that testimony by members of the labor union indicates that local exhaust ventilation equipment was not always kept in repair (United Rubber Workers, 1977).

The general (dilution) ventilation system that was designed into the St. Marys process was the first engineering control measure installed at a Pliofilm facility (Hanning, 1990). it is not clear if such controls would have been installed at Akron I, since the Akron II facility was built 2 yr later. A limited industrial hygiene survey of the Akron I facility in 1948 did not allude to the use of ventilation, and the concentration of benzene reported in the area where the rubber hydrochloride solution was stored was 500 (750) ppm (Fluker, 1948). Engineering controls similar to those installed at St. Marys are believed to have been installed at Akron II (Hanning, 1991a).

The Akron II facility opened in 1948 and incorporated a significant change in the design of the casting unit. Casters at the Akron I and St. Marys factilities passed heated air over the Pliofilm *to* remove the benzene. The benzene-laden air then passed through an activated charcoal recovery system. Benzene concentrations in the casters were kept below the lower explosive limit by the large volumes of heated air that passed through them. Large exhaust fans kept the casters cinder negative pressure. At Akron II, the heating and removal of benzene were achieved by radiant heaters. Benzene concentrztions were maintained above the upper explosive limit, and an inert gas was introduced into the casters. Benzene was recovered by condensation on a refrigerated coil. This system was apparently more likely to leak benzene than the use of activated carbon, and the odor of benzene was reported to be detectable around the Akron II casters (Hanning, 1990). In contrast, the odor of benzene

was not reported to be detectable around the St. Marys casters (Hanning, 1990). The threshold of smell for benzene is somewhere between 25 and 100 ppm (ASTM, 1978; Dräger, 1980; Cerarde, 1963), depending on smoking status and other personal characteristics. This value is consistent with measurements of 35 (50) ppm benzene reportedly found near the Akron II casters (Rinsky et al., 1981).

Dermal Exposure

In addition to inhalation exposure, dermal contact by workers a p pears to have been common. The contribution of dermal exposure to benzene uptake was acknowledged but not quantitatively accounted for in the previous exposure estimates of Rinsky et al. (1987) and Crump and Allen (1984). Based on worker interviews and other records, we have been able to identify several points in the Pliofilm process that required employees to have significant dermal contact with benzene.

The available information indicates that Pliofilm workers rarely, if ever, used gloves (Allman, 1991). Even if they had, based on what is known about gloves used in such operations for the years 1940–1970, only a modest level of protection would have been afiorded the workers since nearly all gloves manufactured at that time were at least partially permeable to benzene. Recent work has shown that virtually all gloves available before 1985 had a very limited period during which they provided protection (Barnardinelli and Bender, 1990; Nelson et al., 1981; Weeks and McLeod, 1982).

The dermal uptake of benzene due to dermal contact has been studied by several researchers. Hanke et al. (1961) showed that liquid benzene passed through the arms of human volunteers at a rate of 0.4 mg/cm²/h. Research in animals has reached similar conclusions (Franz, 1984; Maibach and Anjo, 1981). The work by Hanke et al. (1961) is believed to be the best one to use to estimate the doses received from dermal exposure since the rate was determined in workers' forearms over a period of 1.5–2 h. Pliofilm workers were dermally exposed to benzene on the hands and forearms for periods of time up to 1.5 h.

Based on Hanke's et al. work, one can estimate the dermal uptake of benzene by considering the number of contacts and the duration of contact with benzene cement solutions:

$$\text{Dermal uptake} = P \times N \times A \times t \times R/W \qquad (1)$$

where dermal uptake is the absorbed dose (mg/kg/d), P the molar concentration of benzene in the benzene/cement solution, N the number of skin contacts per d, A the surface area of contacted skin (cm²), t the contact time (h/d), R the dermal absorption rate (mg/cm²/h), and W the body weight (kg).

Example Calculation Workers who were responsible for the neutralizers are believed to have had their hands and forearms in contact with liquid benzene for about 30 min per shift while cleaning the wetside filter press. The likely dermal uptake received during this task may have been approximately:

P = 0.95
N = 1 time/d
t = 0.5 h
A = 1980 cm^2 (surface area of hands and forearms)
R = 0.4 $mg/cm^2/h$
W = 70 kg
Dermal uptake = (0.95)(1)(1980)(0.5)(0.4)/70 = 5.3 mg/kg/d

An absorbed dose of 5.3 mg/kg/d of benzene is appreciable compared to the uptake due to inhalation. Accepting an overall average of 50% inhalation absorption over 8 h at concentrations of 10–100 ppm (Nomiyama and Nomiyama, 1974), an inhalation rate of 1.2 m^3/h, and a conversion factor of 3.2 mg/m^3 per ppm of benzene, the airborne concentration of benzene necessary to produce an equivalent dose over an 8-h shift would be about 25 ppm.

Table 2 presents estimates of uptake for those exposure categories believed to have had significant dermal uptake. The following equation estimates the airborne concentration of benzene that for an 8-h workday produces a dose equivalent to that of the dermal exposure:

$$\text{Airborne concentration (EAC)} = (W \times C)/(K \times R \times B) \qquad (2)$$

where W is the body weight (70 kg), U the dermal uptake (mg/kg/d), K the conversion factor (3.2 mg/m^3 equals 1 ppm benzene), R the respiratory rate (9.6 m^3/8-h d), and B the inhalation bioavailability (50%). In our assessment, the EAC was added to the estimate of concentration inhalation to calculate the total average daily equivalent airborne concentration.

The development of dermal exposure estimates involves considerable uncertainty. To evaluate the uncertainty in the estimates of the EAC values, a Monte Carlo model of the equation was developed. Variation in dermal exposures arises from the differing degree of absorption of benzene through the individual's skin, the extent of contac:, and the frequency of contact. Hanke et al. (1961) reported the mean intake and confidence limits for the rate of absorption based on the variation found in his test subjects. The variation in the extent of skin area in contact with the cement is based on our conclusion that the tasks would have involved contact of the hands and some portion of the forearm. The variation in the area of contact ranges from a minimum of the hands to a maximum of the hands and forearms. The frequency of performing the

TABLE 2. Assumption Used in Developing Equivalent Airborne Concentrations (EACs) for Selected Exposure Categories and Results of the Monte Carlo Model of Uncertainty in the EAC Estimates

Exposure category	Number of contacts with benzene (exposure/d)	Surface area of hands and arms (cm^2)	Exposure time (h/d)	Rate of liquid benzene absorption through the skin ($mg/cm^2/d$)	Body weight (kg)	Dermal uptake ($mg/kg/d$)	Equivalent airborne concentrations (ppm)	Results of the Monte Carlo model of EACs	
								5th percentile	95th percentile
Wetside filter press	1	1980	0.5	0.4	70	5	24	12	30
Dryside filter press	1	1980	0.2	0.4	70	2	8	4	10
Quencher	1	1980	1.5	0.4	70	16	73	38	91
Cleaning neutralizer	0.17	1980	1.0	0.4	70	2	8	4	10

activities that resulted in dermal contact (i.e., cleaning the filters and operating the quencher) varied from shift to shift. Based on worker interviews and information on the process, we concluded that the operations could have been performed from 1 to 1.5 times a shift. Table 3 presents the actual assumptions used in the Monte Carlo model.

The results of the model are presented in Table 2. These results show that the impact of the variations on the estimates of EACs in Table 2 is relatively small (a factor of 2) and the values used in this paper fall within the 95th and 5th percentiles of the estimated distribution. Based on the result of the model, we conclude that while there is some uncertainty in the estimates of dermal exposure, the contribution from this source is significant and should be included in the analysis.

Changes in Some Exposure Categories

Interviews of the workers and a reanalysis of the records indicated that certain jobs should be reassigned to different exposure categories than those assigned by Rinsky et al. (1986). In addition, these data allowed us to better relate the available air monitoring information to the exposure categories. For example, company monitoring data taken around the casters were reported by several subgroups using terms such as "behveen units" and "platform" (Rinsky et al., 1981). It is now clear that the workers in the exposure category called "knifeman" spent the majority of their time where the "platform" air samples were taken, and the workers in the category of "caster operator" were located where the "between units" samples were collected.

Our analysis indicates that exposure of the finishing workers to benzene has been underestimated in previous studies. These workers were involved in finishing operations that included rerolling, cutting, trimming, tensilizing (stretching the film to increase its strength and reduce its thickness), packing, and shipping. Management apparently did not monitor for benzene in finishing areas. Crump and Allen (1984), as well as Rinsky et al. (1986), believed that finishing workers had minimal expo-

TABLE 3. Sources of Uncertainty Considered in the Monte Carlo Model of Dermal Exposure

	Range	Distribution	Basis
Area of skin exposed	840-1980 cm^2	Uniform	Exposure was assumed to involve both hands and part of the forearm
Rate of absorption	0.35-0.41 mg/cm/d	Triangular (most likely value 0.38)	Hanke et al. (1961)
Frequency of exposure	1-1.5 times/shift	Uniform	Worker interviews on frequency of press cleaning and quencher operation

sure to benzene. Crurnp and Allen (1984) assigned finishing workers time-weighted average (TWA) concentrations of 1-5 ppm. Rinsky et al. (1986) assigned exposures of 0 pprn for the workers. Workers who were only employed in the finishing area were excluded from the Kinsky cohort (Rinsky *et* al., 1981).

Based upon the following evidence, we concluded that the workers in the finishing departments of St. Marys and Akron II were exposed to low but significant airborne concentrations of benzene. First, the floor plan of St. Marys (Fig. **2)** indicates that the finishing operations were located in rooms between the wetside and dryside operations. Thus the workers in such areas were almost certainly exposed to fugitive emissions of benzene from both operations, Second, the University of North Carolina (UNC) report (1974) indicated that odors from operation in one part of the plant were readily detectable in other portions of the facility, thus suggesting that air exchanges between rooms were significant. For example, in a discussion of the mixing operation, UNC reported that "This operation and the subsequent batch drop mill generates considerable smoke and a rather unpleasant odor which permeates the plant." When discussing the Prime Wrap process, a product produced in the Pliofilm department in St. Marys during the 1970s, UNC noted that "the distinctive odor of tetrahydrofuran (the solvent used in the Prime Wrap process) was quite evident at various levels throughout the [Pliofilm] building." Third, UNC took four time-weighted average samples from the finishing operation areas and reported values of 0, **12, 20,** and 30 pprn benzene. Interestingly, these levels are significantly higher than benzene concentrations measured by UNC in many of the wetside and dryside work areas (UNC, 1974).

In contrast with the finishing workers at St. Marys, Akron I workers were not exposed to fugitive emissions of benzene, since these operations were located in a separate building (Beebe, 1976). Therefore, the Rinsky et al. (1986) assumption of low exposure for this group is probably correct. The location of the finishing operations at Akron II *is* unknown. However, Akron II, like St. Marys, was designed for Plioiilm production. It is therefore plausible that Akron II used the integrated design of St. Marys and located the finishing operations in a room (or area) adjacent to the casting units.

The conclusion that fugitive emissions could result in significant background levels also led to the reconsideration of certain job titles that require that a worker move about in the facility or spend time in the facility in areas where monitoring data are unavailable. For such workers we developed three new exposure categories: general wetside, general dryside, and facility average. Estimates of exposures for these categories are based on averages of the background monitoring for the operations in the wetside, dryside, and facility as a whole. The finishing operations

for Akron II and St. Marys facilities were assumed to be in the general dryside exposure category.

One key finding from our investigation involves the estimated concentration of benzene in the dryside area at St. hlarys for the years prior to 1946. Crump and Allen (1984) concluded that workers in these areas were exposed to airborne concentrations of benzene in excess of 250 pprn. Their estimates were based on their understanding that the casting units were not enclosed and ventilated prior to 1936. Apparently, they confused the ventilating of the casting units with the improved ventilation of the wetside filter presses that occurred that year. Although it is true that additional local exhaust ventilation was installed at the St. Marys facility in 1946, the evidence is that the casting unit was always enclosed and vented to a solvent recovery unit (Hanning, 1990). It is highly unlikely that benzene concentrations around the casting units regularly approached or were in excess of 250 ppm.

ESTIMATING WORKER EXPOSURES

In this section, the key differencesin the Crump and Allen **(1984)** and Rinsky et al. (1986) assumptions are contrasted and the merit of these differences is discussed in light of the new data. Table **4** summarizes the differences in the hvo approaches and the analyses presented in this article.

Estimating Exposure for 1940–1970

The major difference among the estimates derived by the three r e search groups involves certain assumptions for the 1940s and 1950s. Crurnp and Allen (1984) assumed that the workpface concentrations for each job category were related directly to the increased knowledge about benzene's toxicity. Specifically, they believed that exposures steadily decreased as the ACGIH threshold limit values (TLV) decreased from the 1940s to the 1970s. During the years that Pliofilm was produced, there were six changes in the benzene TLV (Table 5). The TLVs ranged from a high of 100 ppm (before 1947) to a low of 10 ppm (1970 and after). Therefore, Crurnp and Allen (1984) divided the exposure estimates into six periods of time corresponding to when the various TLVs were in place, plus a seventh period for the years before the first occupational exposure guidelines were drafted (1946). If there were no reported measurements for an exposure category (E_i) during a specific time period (i), they estimated the airborne conccntration for that period based on measurements taken in a later period ($i + 1$) times the ratio of the period's TLVs ($S_i + S_{i+1}$). That is,

$$E_i = E_{i+1}(S_i/S_{i+1}) \quad (3)$$

TABLE 4. Comparison of the Primary Assumptions in the Three Approaches Used to Retrospectively Estimate the Airborne Concentrations of Benzene for Pliofilm Workers

Issue	Rinsky et al. (1986)	Crump and Allen (1984)	This analysis
Were the airborne concentrations of benzene for the years before routine air sampling was conducted similar to, or higher than, concentrations measured in the 1960s and 1970s?	In the absence of information indicating a change in manufacturing operations, it was assumed that worker exposures remained unchanged from 1940–1970.	Exposures to benzene decreased between 1940 and 1970 as the hazards of benzene were better understood and the threshold limit value (TLV) decreased.	Benzene exposure decreased from 1940–1970 as a function of improved engineering controls and as the TLV decreased from 100 to 25 ppm.
Did grab samples reflect short-term, high-level exposure or typical background exposure in the manufacturing facility?	In general, grab sample or length-of-stain measurements overestimated typical worker exposures. When exposed to levels above the TLV, workers used respiratory protection.	The average of grab sample measurements reflects both background and some peak exposures. Peak exposure, which occurred during certain tasks, needs to be added to estimate the 8-h TWA concentration.	Short-term measurements generally reflect background levels in the manufacturing building. Certain peak exposures must be accounted for to estimate the likely 8-h TWA concentration.
Did the three manufacturing plants use similar equipment and were the airborne concentrations of benzene similar?	Yes, the same process was used at all three locations.	Yes, the same process was used at all three locations.	No, the three facilities should be treated separately. Monitoring data indicate that Akron exposures were higher than St. Mary's. Some aspects of the manufacturing processes were different.
Should measurements from separate years be averaged together or is it more appropriate to assume workplace concentrations remained constant (unless contrary industrial hygiene data were available)?	Industrial hygiene data should be separated by year.	Data from various years can be averaged together to estimate "representative" concentrations.	Data from various years can be averaged together to estimate "representative" concentrations.

TABLE 5. Changes in the Threshold Limit Value (TLV) for Benzene for the Years of Pliofilm Production

Year(s)	TLV (ppm)
≤1946	100
1947	100
1948	50 TWA
1949–1957	35 TWA
1958–1963	25 TWA
1964–1969	25 Ceiling
≥1970	10 TWA

For example, the exposure category "quencher" had no reported measurement for the year 1948. The TLV at that time was 50 ppm. The average measurement for the period of 1949–1957 was 39 ppm and the TLV was 35 pprn. Therefore, Crump and Allen (1984) estimated that the exposures for the year 1948 were

$$E_{(1948)} = 39 \text{ ppm } (50 \text{ ppm}/35 \text{ ppm}) = 56 \text{ ppm}$$

Using a similar analysis, the exposures in 1947 were estimated to be 111 ppm.

In contrast, Rinsky et al. (1986) assumed that no change in workplace concentrations occurred unless specific information was available to show otherwise. They used only time-weighted average airborne samples for the year in which the measurement was taken to determine if any change had occurred. For the years in which no data were available, exposures were interpolated from previous and subsequent values. For the years before data were available, they assumed that the value of the earliest year was applied to all years before it. For example: reported measurements for the mixer exposure category were available for the years 1949 (45 ppm) and 1956 (10 pprn). Based on these values, Rinsky et al. (1986) interpolated exposures for the years 1950–1955 and set all years before 1949 equal to 45 ppm. Thus the estimates of the exposure for the mixer operator were:

1956	10 ppm	1951	35 ppm
1955	15 ppni	1950	40 ppm
1954	20 ppm	1949	45 ppm
1953	25 pprn	<1948	45 ppm
1952	30 ppm		

As we have discussed, there is medical, engineering, and general historical evidence to support Crump and Allen's (1983) assumption that worker exposure in the 1940s was higher than during the 1950s and

1960s. The question, however, is whether it is likely that workplace concentrations of benzene decreased at the rate that corresponds to changes in the TLV. There are several reasons why this approach is reasonable. First, data from industrial surveys of the St. Marys Pliofilm department (the so-called "112 Surveys") clearly indicate that workplace concentrations were consistent with the 1969 change in !he benzene TLV (Rinsky et al., 1981). That is, samples collected in the areas where workers spent much of their time averaged 13 pprn for the years 1963 to 1967: a value about half of the prevaiiing TLV of 25 ppm. The surveys taken from 1969-1973, in the same areas, averaged 5 ppm (again about half the prevailing TLV). Second, it is clear that some degree of compliance with the TLVs was important to the managers of the Pliofilm operations. For example, Fluker (1948) and Sefarian (1956), both with the State of Ohio Department of Industrial Safety, make reference to TLVs in their reports and letters on Pliofilm operations. Third, the "112 Surveys" were begun in 1963, the year that the ACGIH TLV for benzene changed from a time weighted average value of 25 ppm to a "ceiling value" of 25 ppm. Ceiling valves were defined as concentrations never to be exceeded during the work day. We believe that the decision to conduct a large survey of workplace exposures at the time the TLV changed to a ceiling value is not coincidental, but rather was a practice frequently undertaken by major firms concerned about meeting occupational standards. Finally, evidence that the Crump and Allen (1984) approach is reasonable is that these estimates are consistent with the limited measurements taken in the 1940s and 1950s (see Table 6).

One shortcoming of using the TLV ratio technique to estimate exposures during the 1940s is that it can produce unlikely estimates for certain years. For example, in 1948 the TLV for benzene dropped by a factor of 2, so our estimates of concentration for the dryside workers in St. Marys dropped in a similar factor. This drop in workplace concentration may or may not have occurred that rapidly. interviews of workers from this period do not indicate that any significant changes in benzene controls were installed on dryside equipment (Allman, 1981; Hanning, 1990; Crisrner, 1991). A more reasonable view is that sometime during the 1950s, the airborne concentration benzene levels in the Pliofilm operations decreased to meet the 1948 TLV. As with any major undertaking, several years would be needed to install engineeiing controls to reduce workplace concentrations.

Evidence That Monitoring Data Do Not Reflect Peak Exposure

The second major question about how to retrospectively estimate employee exposure is whether the grab samples (which make up the bulk of the available data) adequately reflect the short-term peak expo-

TABLE 6. Measured concentrations of Benzene Vapor and Concentrations Estimated Using the **TLV** Ratio Technique

Year	Location in plant'	Reponed concentration[b] (ppm)	Concentration adjusted for analytical **bias'** (ppm)	Background concentration (ppm) based on the 112 Surveys data multiplied **by** the **TLV** ratio[d]	Reference
1941-1942	**All** areas	>100	[>150]	60-114	Depanment of Labor (1942)
1946	Wetside filter presses	>35	[>52]	58	Fluker (1946)
1947	Storage	19	[29]	**25**	Rinsky et al. (1981)
1949	Storage	10	[15]	**25**	Rinsky et al. (1981)
	Mixers	**45**	[67]	60	Rinrky et al. (1981)
1950	Storage	35	[52]	25	Rinrky et al. (1981)
1956	Mixer	**0**	[0]	15	Sefarian (1956)
	Reactor	0-35	[0-52]	1	Sefarian (1956)
	Neutralizer	**0-35**	[0-52]	20	Sefarian (1956)
	Storage	0-15	[0-26]	25	Sefarian (1956)

'Location in St. ***hlarys*** facility where value was measured.
'Results of industrial hygiene samples of benzene at St. **Marys.**
'Measured airborne concentration of benzene multiplied **by** 1.5 to correct for inaccurate instrumentation.
[d]Background **values** determined by taking the average of the 112 Surveys data from the **years** 1963-1967 and multiplying by the ratio of the **TLVs.** These **valves have** not been adjusted for peak exposure, dermal exposure, or extended work weeks.

sures of the workers. Crump and Allen (1984) did not account for peak exposures but believed that some effort should be made to address them, especially for the casting operators. In contrast, Rinsky et al. (1986) believed that grab samples were representative of the peak concentrations and claimed that these measurements were collected selectively in those areas where benzene exposure was the highest. Therefore, they believe that these samples overestimated the background concentrations within the building.

While it is acknowledged that the St. Marys industrial hygiene program probably focused on those activities that were likely to produce the highest concentration of benzene, it is not clear that the samples were taken at times when benzene exposure would have been at its highest. Colorimetric tubes used in the "112 Surveys" and Akron II surveys only reflect the concentration of vapor over a time period of 30 s to 2 min. For the results of surveys using these tubes to accurately reflect the 8-h TWA workplace concentrations, a careful sampling program based on time-weighted worker activity patterns would have been necessary. There is no evidence of such a program. It is unlikely that samples were collected during the period of greatest exposure, since during the 1977 OSHA

hearing on the revised benzene standard, Pliofilm workers testified that they were instructed not to enter areas where respirators were required when wearing sampling devices (United Rubber Workers, 1977).

Additional support for concluding that the grab sample data fails to adequately reflect peak exposures can be found by comparing "112 Surveys," estimates with the 4- and 8 h TWA measurements (Rinsky et al., 1981). For example, the "112 Surveys" data for the reactor operators in 1973–1974 indicate that the TWA airborne benzene concentration was less than 1 ppm, whereas the 8-h TWA data indicate that concentrations were 9 pprn in 1976. Similarly, the "112 Surveys" estimate for neutralizer operators in 1973–1974 indicate a concentration of approximately 3 ppm, while the 8-h TWA data for the same years suggest 25 ppm.

Finally, samples collected at St. Marys in the 1970s at the employees work station found concentrations of 98 and >200 ppm at the dryside plate and frame filters during cleaning, and 100 and 200 pprn during the gauging and inspection of tanks (Rinsky et al., 1981). The levels found in the "112 Surveys" for areas near tanks assumed to be closed averaged 1.7–15 ppm, and at the dryside presses the values averaged about 70 ppm. Based on these data, we concluded that the Akron II and "112 Surveys" were taken in the areas of high potential benzene exposure but not necessarily during the time when benzene exposures were at their highest (such as during sampling and loading tanks). Therefore, we believe there is sufficient evidence that grab sample results are representative of the general background levels of benzene in the building and usually do not reflect short-term peak Concentrations.

Evidence That Akron I, Akron II, and St. Marys Had Different Workplace Concentrations

Both Rinsky et al. (1981) and Crump and Allen (1984) concluded that the similarities of the processes at the St. Marys and the two Akron facilities allowed air sampling data from any site to be used to estimate exposure at all three facilities (Table 4). For example, Rinsky et al. (1987) noted that "Processes and joh assignments were essentially identical at both [Pliofilm] locations, so benzene exposure levels measured at [St. Marys] were assumed to be naturally occurring simulations of exposure levels in corresponding areas at [Akron], when actual exposure measurements did not exist." Based on the available information, this assumption no longer appears plausible. First, as discussed above, there were significant differences behveen the three facilities as far as room size, layout, and design of machinery. Second, a review of the two largest sets of air sampling data, the "112 Surveys" at St. Marys and the survey taken at Akron II, shows that the data from Akron II are appreciably higher than those of St. Marys.

Finally, there is biological evidence for suspecting that the employees

at the three sites had different levels of exposure. Lamm et al. (1989) reported that the leukemias observed in workers at the Akron facilities were of a significantly different nature than those at St. Marys. More importantly, Rinsky et al. (1981) reported that the standard mortality ratio (SMR) for the cohort at Akron I and II was about double that of St. Marys (*746* vs. 345). This difference is still apparent in the 1990 update by NIOSH (Paxton, 1992).

Justification for Averaging Years

The Crump and Allen (1984) approach for estimating workplace concentrations was dictated by their belief that "benzene exposure would be approximately the same unless standards (e.g., TLVs) were changed." Therefore, these authors averaged the air sampling data collected over the period during which the TLV was constant. The approach used by Rinsky et al. (1986) to estimate exposure was to assume that measurements of benzene primarily applied to the year in which they were taken. We chose to adopt Crump and Allen's (1984) TLV ratio approach in our analyses.

Description of Our Approach

Based on new information collected and the above discussion, we have developed revised estimates of the airborne concentrations of benzene for the various exposure categories at the three facilities. In developing the estimates, the assumptions were made:

1. The Akron I, Akron II, and St. Mary's facilities were different. We estimated the airborne concentrations at Akron II based on the 400 air samples actually collected at the Akron II facility. The "112 Surveys" data collected at St. Marys were used to estimate exposures at that site. However, because of the virtual absence of monitoring data at the Akron I facility, the "112 Surveys" data were also the basis for the Akron I estimates.
2. The ratio of the workplace concentration of benzene to the prevailing TLV was assumed *to* be constant. Worker exposures at St. Marys were estimated by calculating the mean of the "112 Surveys" results for the years 1963–1968 and dividing by the TLVs for those years. For example, the estimate of the background concentration for the workers in the neutralizer category for the 1950s was estimated as follows. The mean value of the "112 Surveys" for these workers was 15 pprn for the years 1963–1968. This value was multiplied by 1.4 [the TLV during the 1950s (35 pprn) divided by the TLV for 1963 (25 ppm)]. Thus our back-calculated estimate of the benzene vapor concentration around the neutralizer for the 1950s was 21 ppm. The ratio of 1.4, with the exceptions discussed below, was assumed to be consistent for the years

between 1949 and 7957 for all jobs at St. Marys. This approach was not used to estimate airborne concentrations at Akron II because the exact year(s) in which the measurements were made are unknown.

3. The Akron and St. Marys "112 Surveys" provide plant-wide averages rather than peak exposures. As discussed previously, the averages of the "112 Surveys" and Akron II survey were assumed to be generally representative of background concentrations, that is, the prevailing building concentrations at the work station rather than peak exposures. The approach used in this paper was to reconstruct the duration and frequency of peak exposure activities based on interviews of workers, and *to* add these to the background concentration. Tables 7 and 8 present a summary of our estimates.

   The benzene concentrations that occurred during high exposure activities were estimated using one of two approaches: (a) the upper end of the distribution of concentrations reported in the "112" and Akron II surveys, and (b) monitoring information on peak exposures from similar industrial processes (see Table 9). The survey data were used to estimate the peak concentrations at St. Marys for the years after 1946, and at the Akron II facility when local ventilation was in place to control peak concentrations. 'The Akron I facility was assumed to have similar exposures to St. Marys for 1940–1948. Estimates from similar processes were used for Akron I and St. Marys for the years before 1946. A factor to account for the use of gas canister masks (respirators)was also included in the analyses. The masks when worn were assumed to be able to reduce the inhaled concentration by a factor of 4 (see discussion that follows). Table 10 and Table 11 present the estimated duration and concentrations for each of the peak exposures.

4. Adjustment of early monitoring data for analytical biases. Measurements of airborne concentrations *of* benzene taken before 1963 were underreported by the instrumentation. The values were therefore adjusted upward bv a factor of 1.5.

5. Airborne concentrations of benzene at St. Marys in the 1940s were affected by the shortage *of* natural rubber and the installation of significant local exhaust ventilation. During the years 1942-1945, Pliofilrn production at St. Marys was dependent predominantly on the use of recycled Pliofilm, and production was limited to 4–7% of capacity. This implies that, on average, workers were exposed much less frequently and that the background concentrations were fairly low. However, due *to* uncertainty as to whether the total number of workers in the Pliofilm department was less during the war years, we assumed that exposures occurred during onefourth of the work week.

   The use of recycled Pliofilm eliminated the need for operators in the mixing, mill, and reactor jobs (Hanning, 1990). We assumed that workers in these areas received only minimal exposure to benzene,

TABLE 7. Estimated Airborne Concentrations of Benzene Used to Calculate Uptake by Pliofilm Workers in Akron I or II

Exposure categoryldate	Concentration (ppm)				
	Background	Peak 1	Peak 2	Peak 3	Peak 4
Mill					
1936-1946	53	NA[a]	NA	NA	NA
1947	27	NA	NA	NA	NA
1948	19	NA	NA	NA	NA
1949-1965	38	NA	NA	NA	NA
Mixer					
1936-1946	53	200	NA	NA	NA
1947	27	150	NA	NA	NA
1948	19	105	NA	NA	NA
1949-1965	38	75	NA	NA	NA
Reactor					
1936-1946	4	200	225	NA	NA
1947	2	10	NA	NA	NA
1948		7	NA	NA	NA
1949-1965	24	75	NA	NA	NA
Neutralizer					
1936-1946	53	250	200	225	NA
1947	29	15	120	NA	NA
1948	20	10	04	NA	NA
1949-1965	30	150	150	NA	NA
Quencher					
1936-1946	113	300	200	200	40
1947	57	300	120	140	20
1948	40	300	04	98	14
1949-1965	59	300	150	150	38
Knifeman					
1936-1946	79	120	250	250	NA
1947	40	120	250	250	NA
1948	28	120	250	250	NA
1949-1965	59	120	250	250	NA
Spreader					
1936-1946	76	250	750	NA	NA
1947	33	250	750	NA	NA
1948	27	250	750	NA	NA
1949-1965	54	250	62	NA	NA
Still house					
1936-1946	40	NA	NA	NA	NA
1947	20	NA	NA	NA	NA
1948	14	NA	NA	NA	NA
1949-1965	38	NA	NA	NA	NA

[a] NA = Not applicable

TABLE 8. Estimated Airborne Concentrations of Benzene Used to Estimate Uptake by the Pliofilm Workers in St. Marys

Exposure categoryldate	Concentration (ppm)				
	Background	Peak 1	Peak 2	Peak 3	Peak 4
Mill					
1940–1941	53	NA[a]	NA	NA	NA
1942–1945	0	NA	NA	NA	NA
1946	53	NA	NA	NA	NA
1947	27	NA	NA	NA	NA
1948–1956	19	NA	NA	NA	NA
1957–1968	13	NA	NA	NA	NA
1969–1972	6	NA	NA	NA	NA
1973–1976	9	NA	NA	NA	NA
Mixer					
1940–1941	53	200	NA	NA	NA
1942–1945	0	0	NA	NA	NA
1946	53	200	NA	NA	NA
1947	27	150	NA	NA	NA
1948–1956	19	105	NA	NA	NA
1957–1968	13	75	NA	NA	NA
1959	6	75	NA	NA	NA
1970–1972	6	0	NA	NA	NA
1973–1976	9	NA	NA	NA	NA
Reactor					
1940–1941	53	200	225	NA	NA
1942–1945	0	0	0	NA	NA
1946	53	20	NA	NA	NA
1947	27	10	NA	NA	NA
1948–1956	19	7	NA	NA	NA
1957–1968	1	5	NA	NA	NA
1969–1972	2	5	NA	NA	NA
1973–1476	7	NA	NA	NA	NA
Neutralizer					
1940–1941	58	250	200	225	NA
1942–1945	58	250	200	0	NA
1946	58	250	200	225	NA
1947	29	15	120	NA	NA
1948–1956	20	10	84	NA	NA
1957–1968	15	7	60	NA	NA
1969	5	7	60	NA	NA
1970–1972	5	3	25	NA	NA
1973–1976	10	NA	NA	NA	NA
Quencher					
1940–1946	113	300	200	200	40
1947	57	300	120	140	20
1948–1956	40	300	84	99	14
1957–1968	28	300	60	70	10
1969	14	300	60	70	5
1970–1972	14	300	25	200	5
1973–1976	9	NA	NA	NA	NA

[a] NA = Not applicable

TABLE 8. Estimated Airborne Concentrations of Benzene Used to Estimate Uptake by Pliofilm Workers in St. Marys (*Continued*)

Exposure category/date	Concentration (ppm)				
	Background	Peah 1	Peak 2	Peak 3	Peak 4
Knifeman					
1940-1946	79	120	250	250	NA
1947	40	120	250	250	NA
1948-1956	28	120	250	250	NA
1957-1468	20	120	250	250	NA
1969-1972	5	120	250	250	NA
1973-1976	18	NA	NA	NA	NA
Spreader					
1940-1946	76	250	250	NA	NA
1947	38	250	35	NA	NA
1948-1956	27	250	25	NA	NA
1957-1968	19	250	18	NA	NA
1969-1972	2	250	10	NA	NA
1973-1976	9	NA	NA	NA	NA
Still **house**					
1940-1942	40	NA	NA	NA	NA
1943-1945	10	NA	NA	NA	NA
1946	40	NA	NA	NA	NA
1947	20	NA	NA	NA	NA
1948-1956	14	NA	NA	NA	NA
1957-1968	10	NA	NA	NA	NA
1969-1972	5	NA	NA	NA	NA
1973-1976	9	NA	NA	NA	NA

Finally, the frequency of wetside filter press changing was also reduced. Exposure estimates for Akron I were not reduced since production information indicates that the Akron facility operated near capacity throughout World War II (Crismer, 1991).

The engineering improvements installed at St. Marys in 1946 included local exhaust ventilation at the wetside operations of mixer, reactor, neutralizer, and filter press. Estimates of peak exposure for the years before such controls were installed were based on data from similar processes. Estimates of the concentrations in the storage room were also adjusted to reflect the single measurement taken before 1946. We have made the assumption that Akron I also installed controls in 1946.

6. As discussed above, certain jobs have been assigned to different exposure categories than in earlier studies. Table 12 presents the revised assignments.
7. Dermal exposure should be accounted for in the estimate of the workers' total absorbed dose. As discussed, the contribution of dermal exposure to worker uptake can be estimated from the frequency and

TABLE 9. Approximate Breathing Zone Concentrations of Benzene for Various Tasks Frequently Performed in the Chemical Manufacturing, Pharmaceutical. and Rubber Industries

Task	Breathing zone concentration (ppm)		Reference
	Without LEV[a]	With LEV	
Sample reactor contents with ladle through a manway	80–120 (100 ppm)[b]	10–30 (20 ppm)	Bond (1991) Paustenbach (1977)
Cleaning a filter press	100-1000 (250 ppm)	10–Boppm (40 ppm)	Bond (1991)
Operating a centrifuge	150-500 ppm (300 ppm)	25-50 ppm (35 ppm)	Paustenbach (1977) Schoch (1991)
Loading a reactor through the manway	100-300 ppm (200 ppm)	20–60 ppm (40 ppm)	Paustenbach (1977)
Pouring from one drum into another	100–200 ppm (100 ppm)	10–40 ppm (20 ppm)	Dorsey (1973)

Note. The temperature of benzene was assumed to be 20°C. Higher temperatures would necessitate correcting the data. Data in this table were obtained from various industrial hygienists who have collected samples during these tasks or unit operations.

[a]LEV, local exhaust ventilation.

[b]Values in parentheses represent the author's best estimate of the most likely concentration in the Pliofilm operation.

TABLE 10. Estimated Duration of Background and Peak Exposures for Workers at Akron I and II

Exposure class/date	Background (h/d)	Peak 1 (h/d)	Peak 2 (h/d)	Peah 3 (h/d)	Peak 4 (h/d)
Mill					
1936-1965	8	NA[a]	NA	NA	NA
Mixer					
1936-1965	7.08	0.92	NA	NA	NA
Reactor					
1936–1946	4	2	2	NA	NA
1947-1965	6	2	NA	NA	NA
Neutralizer					
1936–1946	-4.20	0.50	1.30	2	NA
1947–1%5	6.20	0.50	1.30	NA	NA
Quencher					
1936-1965	3	1.33	1	1.67	3
Knifeman					
1936-1965	7.62	0.13	0.17	0.08	NA
Spreader					
1936-1%5	7	0.06	0.92	NA	NA

[a]NA = Not applicable

TABLE 11. Estimated Duration of Background and Peak Exposures for Workers at St. Marys

Exposure class/date	Background (h/d)	Peak 1 (h/d)	Peah 2 (h/d)	Peak 3 (h/d)	Peak 4 (h/d)
Mill					
1940–1976	8	NA[a]	NA	NA	NA
Mixer					
1940–1972	7.08	0.92	NA	NA	NA
1973-1976	NA	NA	NA	NA	NA
Reactor					
1940–1946	4	2	2	NA	NA
1947-1972	6	2	NA	NA	NA
1973-1976	NA	NA	NA	NA	NA
Neutralizer					
1940-1946	4.2	0.50	1.30	2	NA
1947–1972	6.2	0.50	1.30	NA	NA
1973-1976	NA	NA	NA	NA	NA
Quencher					
1940-1972	3	1.33	1	1.67	3
1973-1976	NA	NA	NA	NA	NA
Knifeman					
1940-1972	7.62	0.13	0.17	0.08	NA
1973-1976	NA	NA	NA	NA	NA
Spreader					
1940-1972	7	0.08	0.92	NA	NA
1973-1976	NA	NA	NA	NA	NA

[a]NA = Not applicable.

duration of dermal contact. The 8-h equivalent airborne concentration of benzene was calculated and added to the estimates of background and peak concentrations to obtain the total dose (uptake).

8. Exposure estimates should be normalized to an 8-h day, 5-d work week. The average length of the Pliofilm work week was approximately 36 h from 1936 to 1940 and then between 40 and 56 h until the mid 1950s. The impact of this finding is that the employee was absorbing a much greater dose in the mid 1940s than the airborne concentrations would indicate. In order to account for this factor, estimates of exposure were normalized to a 40-h work week.
9. Exposure estimates for 1974–1976 should be estimated based on the availability of higherquality data. In these years, three surveys of workers were made using either 4-h or 8-h TWA samples. Unlike the grab samples, these samples would be expected to include peak exposures. Therefore, these results were used where possible to determine uptake via inhalation.

Exposure Calculations The estimates of airborne concentrations were based on the following equation:

TABLE 12. Estimates of the Time-Weighted Average (TWA) Uptake (Presented as Equivalent 8-h/d Vapor Concentration) of Benzene for Pliofilm Workers for Akron I and Akron II Facilities

		Airborne concentration (ppm equivalent)							
		Akron I					Akron II		
Job code	Exposure category	1936–1939	1940–1941	1942–1946	1947	1948	1949–1951	1952–1956	1957–1965
7, 8, 10, 27, 30	Knifeman	80	100	110	65	50	85	80	70
28, 35, 44, 54, 57	Spreader	100	130	140	100	85	80	70	65
19, 32, 63	General dryside[a]	70	90	95	45	35	70	60	55
14	Dryside head operation	80	100	110	65	50	75	70	60
11	Mill	50	60	65	35	25	45	40	40
18, 31	Mixer	60	75	75	45	30	50	45	40
56	Mixer mill operator[b]	55	65	70	40	25	45	40	40
16, 47	Reactor	75	95	100	5	5	40	35	30
21	Neutralizer	130	160	170	85	75	100	90	80
22	Quencher	190	250	260	210	190	220	200	180
5	Wetside head operator	120	130	130	65	20	45	45	40
34	Still house	35	45	50	25	15	45	40	40
12, 37, 61	General wetside[c]	50	60	65	35	25	45	40	40
6, 36, 7, 13, 15, 20, 23, 24 25, 26, 29, 38, 39, 41, 49, 50, 51, 53, 55, 59, 60	Minimal/zero 1	0	0	0	0	0	75	70	60
46, 52	Minimal/zero 2	50	60	65	35	25	0	0	0
4	Minimal/zero 3	0	0	0	0	0	0	0	0
1, 2, 3, 9, 33, 43, 45, 62	Facility average[d]	55	70	75	40	25	60	50	45

[a]Mean of all dryside measurements.
[b]With 50% of time spent at mixer and 50% at mill.
[c]Average of all wetside measurements other than still house.
[d]Average wetside plus average dryside divided by 2.

TABLE 13. Estimates of the Time-Weighted Average (TWA) Uptake (Presented as Equivalent 8-h/d Vapor Concentration) of Benzene for Pliofilm Workers at the St. Marys Facility

		Airborne concentration (ppm equivalent)									
Job code	Exposure category	1940–1941	1942–1945	1946	1947	1948–1951	1952–1956	1957–1968	1969	1970–1972	1973–1976
15, 31	Knifeman	100	25	110	65	50	45	35	20	20	10
1, 5	Spreader	110	35	110	60	45	40	30	15	15	20
21, 22, 26, 28, 30, 18, 24, 20, 23, 25, 34	General dryside[a]	90	25	95	45	35	30	20	5	5	15
8	Dryside head operation	100	5	110	55	40	35	25	10	10	15
19	Mill	60	0	65	35	25	20	15	5	5	10
10, 11	Mixer	75	0	75	45	30	30	20	10	5	10
7	Reactor	120	0	130	25	20	15	5	5	5	5
6, 33	Neutralizer	160	30	170	85	75	65	50	45	40	40
4	Quencher	250	65	260	210	190	170	140	130	150	80
12	Wetside head operator[b]	110	10	110	30	25	20	10	5	5	10
27	Still house	45	10	50	25	15	15	10	5	5	10
3, 16	General wetside	60	15	65	35	25	20	15	5	5	10
2, 9, 13, 14	Facility average[c]	70	20	75	40	25	25	15	10	10	5
17, 29, 32, 35	Minimal zero	0	0	0	0	0	0	0	0	0	0

[a]Mean of all dryside measurements.
[b]Average of all wetside measurements other than still house.
[c]Average of all wetside measurements plus average dryside measurements divided by 2.

Exposure

$$= \frac{\{[(\{[1 - (R \times U)] \times \Sigma D_i \times C_i\} + D_b \times C_b)/8\ \text{h}] + \Sigma \text{EIU}\} \times H}{40\ \text{h per week}} \quad (4)$$

where D_i is the duration of the ith peak exposure, D_b the duration of the background exposure, C_i the vapor concentration for the ith peak activity, C_b the vapor concentration for the background activity, R the respirator effectiveness, U the fraction of time the respirator is used during peak exposure, EIU the equivalent inhalation uptake from the ith dermal exposure, and H the hours worked per week. This formula accounts for the workers' uptake due to background levels, short-term peak exposures, dermal exposure, and for workweeks that varied in length.

An example calculation is presented below for the neutralizer at St. Marys in 1936. Based on interviews and historical records, workers in this category are believed to have performed several tasks that involved short-term, high-level inhalation exposures and to have performed two tasks with significant potential for dermal contact. To estimate the equivalent daily airborne concentration of benzene vapor, the following approach was used:

D_1	= 1.33 h	C_1	= 200 ppm
D_2	= 0.5 h	C_2	= 250 ppm
D_3	= 2 h	C_3	= 250 ppm
D_b	= 4.16 h	C_b	= 58 ppm
R	= 0.75	U	= 0.33
EIU_1	= 24 ppm	EIU_2	= 8 ppm
H	= 48		

Airborne concentration

$$= \{[1 - (0.75 \times 0.33)) \times [1.33 \times 200) + (0.5 \times 250) + (2 \times 225) + (4.16 \times 58)]/8 + (24 + 8)\} \times 48/40$$

= 170 ppm (rounded to two significant figures)

The estimates should be viewed as the average daily airborne concentrations of benzene vapor that would have to be inhaled for 8 h/d, for a 40-h work week, to be equal to the amount of benzene absorbed by these workers under the conditions of exposure. Tables 12 and 13 present our estimates for the workers at the two locations.

UNCERTAINTY ANALYSIS

It is not possible to develop confidence limits or specific quantitative estimates of uncertainty for the airborne concentrations developed in this paper. The available analytical data are too limited and the estimates are too dependent on inference and indirect evidence to use techniques

such as Monte Carlo or error propagation. However, it is possible to test the impact of the major assumptions on the estimates to identify those assumptions and factors that drive the analysis. This section presents an evaluation of the impact of slight and major changes in the key exposure factors and their effect on the final estimates. The exposure factors examined include:

- The Crump–Allen TLV ratio approach
- Lengthened work weeks
- Possible analytical biases
- Use of protective equipment
- Uncertainty in the estimates of dermal exposure

The relative impact of selecting various exposure factors was evaluated in the following manner. First, the estimated concentrations of each of the major exposure categories (knifeman, spreader, mixer, reactor, neutralizer, quencher, still house, and facility average) were averaged to yield a plant-wide background average. This plant-wide average was calculated each year. Second, these yearly values were then averaged for the years Pliofilm was manufactured at the facilities in the two locations, Akron and St. Marys. The Akron I and II facilities were combined in the analysis since the work force at Akron I was transferred to the Akron II facility. Thus, the workers remained the same. The resultant location averages provide a useful measure of how each factor affects the worker exposure at each of the locations. In addition to these location averages, an additional set of averages were calculated for the years 1940-1949. The purpose of this second set was to illustrate the effect of the factors on the years when the least amount of data were available and when exposures were believed to be the greatest. The results of the analyses are presented in Table 14.

RESULTS

The airborne concentrations predicted in this paper ranged from a few parts per million to several hundred parts per million, depending on the exposurs category, location, and year. The facility average exposures at the two Akron facilities were higher than at St. Marys and were higher in the 1940s than at later periods. Our concentrations differ from both the Rinsky et al. (1986) and Crump and Allen (1984) estimates. Table 14 presents a comparison of the average concentrations estimated by the three investigators. Our estimates are, depending on location in the facilities, three to five times higher than those of Rinsky et al. (1986). However, our estimates are quite similar to those of Crump and Allen (1984) for the St. Marys facility and about 25% higher for the two Akron facilities. Figure 5 is a set of graphs of the three estimates for three different

TABLE 14. Estimates of the Equivalent 8 h/d Concenlration (ppm) of Benzene for the Ohio Pliofilm Workers,' Cornparison to Previously Published Estimates, and the Effect of Using Alternative Exposure Factors

	Akron I, II (1936-1966)	Akron I, II (1940-1949)	St. Marys (1940-1976)	St. Marys (1940-1949)
Our estimates	86	106	45	63
Comparison to published values				
Rinsky et al. (1986)	23	25	19	25
Crump and Allen (1984)	63	103	44	103
Relative contribution of background peak, and dermal components				
Bachground only	54	67	23	43
Background and peak	69	87	30	50
Background, peak, and dermal	06	106	45	63
Sensitivity analysis				
TLV approach				
No adjustment for TLV[b]	71	74	38	43
Adjustment for TLV	86	106	45	63
Length of work week				
40 h	78	88	41	53
51 h[c]	90	113	47	68
Analytical[d]				
ho adjustment for possible bias	78	104	45	63
Maximum bias reported (2 0)	93	107	45	63
Respirator use[e]				
Use of respirators during all tasks[e]	77	93	41	57
No use of respirators	94	118	49	69
Dermal contact[f]				
5th Percentile	77	96	37	56
95th Percentile	89	110	48	66

'An average of the exposure categories, knifeman (platform), spreader (between units), mixer, reactor, neutralizer. quencher. still house, and facility average.

[b]TLV ratio approach (see text) is not used. Background levels reported in 1963-1967 were applied to all years before 1463 (Akron I and St. Marys facility only).

[c]Longest reported work week (Osborn, 1991).

[d]Correction of pre-1963 analytical measurements for analytical biases.

'Respirators are assumed to be worn whenever the worker is exposed to airborne concentrations in excess of the prevailing TLV. Respirators assumed to be 75% effective when worn.

'Results of the Monte Carlo model for dermal uncertainty (see Table 2 and 3).

exposure categories at the two different locations. In general, our estimates tend to follow Crump and Allen's estimates more closely than Rinsky et al. (1986), and both are about fivefold greater than those of Rinsky et al. (1986) for most of the job titles. However, we differ from Crump and Allen's estimates in two ways; first, we found that the average concentrations at the two Akron facilities were higher than their estimates, and second, we concluded that wetside exposures, represented in Figure 5 by the neutralizer, were higher than for the dryside workers, represented by the spreader operator.

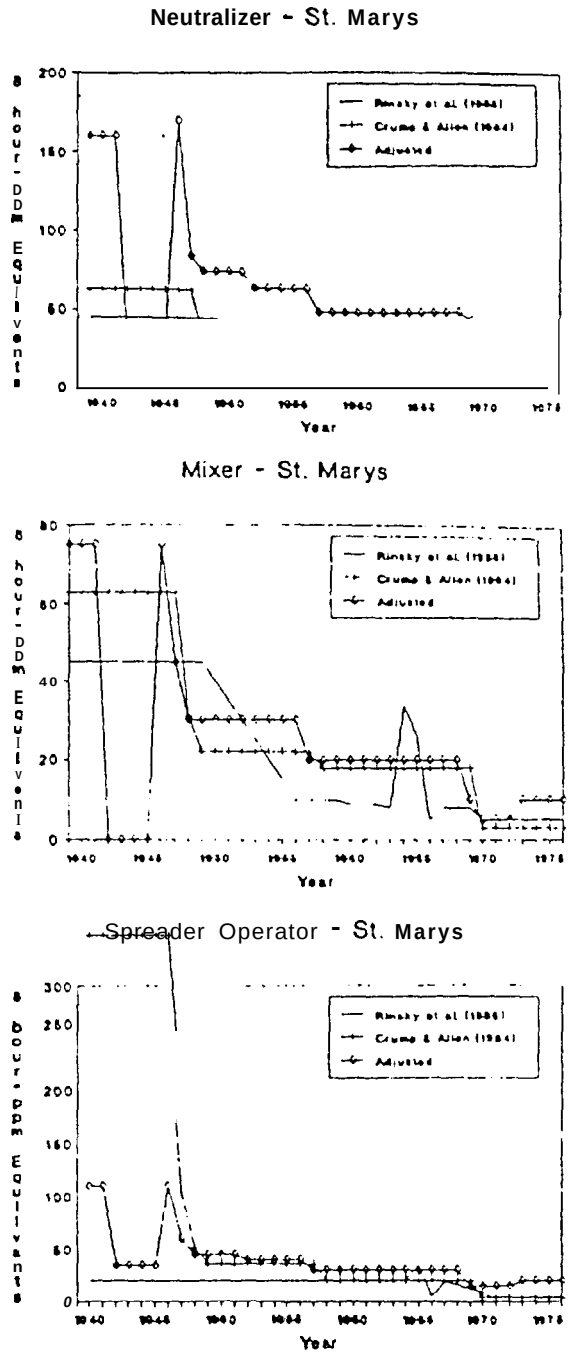

FIGURE 5. Comparison of the predicted exposure profiles for three different jobs using the method of Rinsky *et al.* (1986), Crump and Allen (1984), and ourselves

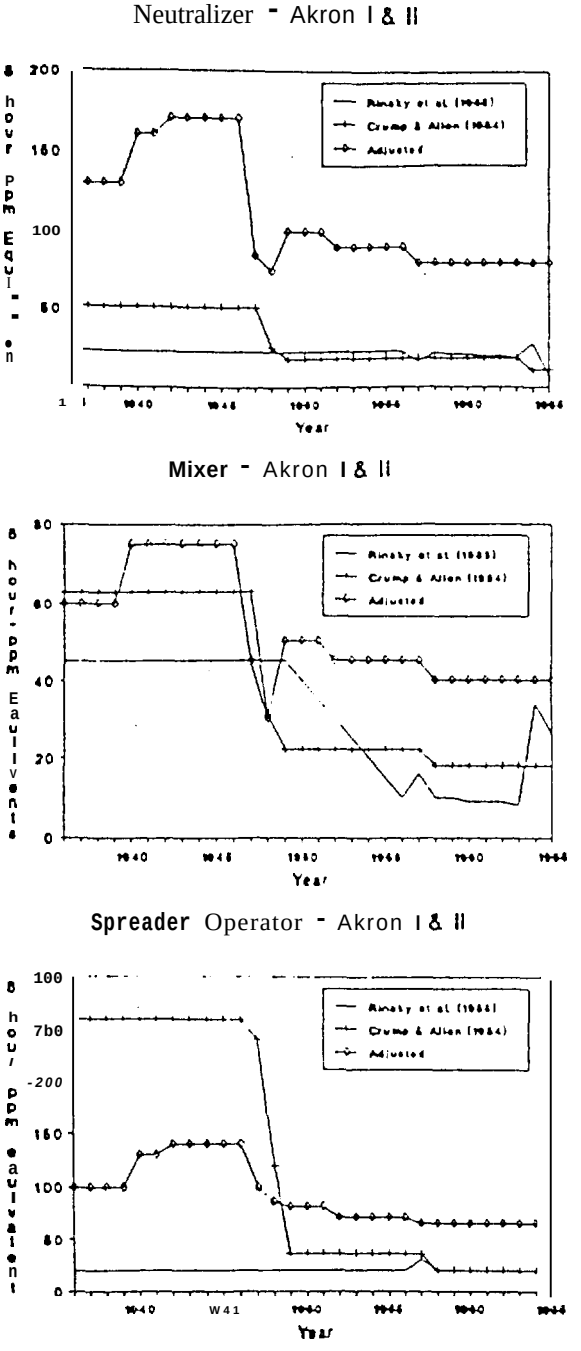

FIGURE 5. Comparison of the predicted exposure profiles for three different jobs using the methods of Rinsky et al. (1986), Crump and Allen (1984), and ourselves.

Our estimates indicate that the highest exposures to benzene occurred in Akron I during the 1940s. Before the 1940s, the shorter work week (about 36 h) mitigated the high workplace exposures and kept the weekly absorbed dose relatively low. After the 1940s, the improved engineering controls and the increasing concerns about the toxicity of benzene (as reflected in the decreasing TLVs) reduced the workplace concentrations. The lack of significant Pliofilm production in St. Marys in the 1940s had the effect of greatly reducing the exposures of these workers (compared with Akron I) during this period of time.

The workers with the highest potential for exposure were those in the quencher and neutralizer exposure categories. The 8-h daily equivalent exposures for those people working near the quenchers in the Akron facilities was estimated to exceed 200 ppm for most of the 1940s and early 1950s. In the Akron facilities, we estimated that the neutralizer operators may have been exposed to concentrations in excess of 150 ppm for much of the same period. About 50 ppm equivalents or one-third of the total exposure to the neutralizer was due to dermal uptake.

Our exposure estimates systematically incorporate contributions due to peak airborne concentrations and dermal contact into a single equivalent TWA airborne concentration of benzene. Table 14 presents the contribution of the three sources of exposure to the final estimates. On average, benzene concentrations due to fugitive emissions (background) contributed 50–60% of the total exposure, depending on location. Peak exposures represented approximately 20% and dermal uptake constituted 30% of the dose. The relative contributions from the three sources varied greatly over the different job categories and for different years. The contribution of peak exposure to the workers' total exposure for certain job classifications such as mixer was less than 20%, while other jobs such as the reactor, neutralizer, and quencher were doubled as a result of peak exposures. The contribution to total exposure from dermal contact was high for two categories: quencher and neutralizer. The quencher job classification was estimated to have had the highest potential for dermal uptake. Workers in the category received a dermal dose of 14.5 mg/kg/d, which is equivalent to that received during 8 h of inhalation exposure to 65 ppm.

Our estimates indicate that, on average, exposures for the different job categories at the Akron facilities were from one to eight times higher than the corresponding categories at St. Marys. There are two reasons for this difference. First, the finding that the St. Marys facility was operating at only 4–7% of its capacity during the war years, 1942–1945, greatly reduced our estimate of exposure during this period (yet this is when levels at Akron I are believed to be at their highest). Second, the use of the Akron II survey data to predict exposure at the Akron II facility (rather than to the St. Marys data) results in higher estimates of workplace concentrations for the years this facility operated (1948–1966).

The sensitivity analysis (Table 14) showed that no single factor produced a major change in the overall estimate of exposure. For example, the assumption of high workplace concentrations during the early years of production had the greatest effect of all the factors in raising the estimates of exposures by 20%. The assumptions of an increased work week, analytical biases, use of personnel protection devices, and uncertainty in dermal estimates each changed the average estimates by less than 15%. Estimates for the years 1940–1949 presented similar results. The assumption of increasing workplace concentrations during the early years of production raised estimates of exposures by 30%. All other factors again affected the estimates by less than 15%. The role of erroneous analytical measurement had only a minor impact on the estimates of exposure at either location.

Our assumption that respirators only had a protection factor of 4 and were used only 33% of the time that workers were involved in tasks where short-term concentrations exceeded the TLU proved not to have a dramatic effect on our estimates. For example, even if it is assumed that workers always wore their respirator when doing tasks with high exposure, and even if the respirators were 75% effective, our dose estimates drop by 10% in the Akron facilities and 9% at St. Marys. However, if we assume that workers never wore respirators or that they probably offered little or no protection, our estimates would be only about 9% too low at either location. Lastly, dermal contact had contributed from 9–21% of the total average estimates, but for some exposure categories, dermal uptake results in doses twice as high as predicted by air sampling alone.

DISCUSSION

Some of the methods used to conduct retrospective exposure assessments can be questioned, and it is true that the results contain a significant degree of uncertainty. As discussed previously, only a handful of workplace measurements of benzene vapor are available for any of the plants for the years before the 1950s (Fig. 3). In the absence of analytical measurements, indirect evidence of exposure must be used. Such information includes later industrial hygiene surveys, production information, plant records, and worker interviews. We are aware of the potential pitfalls of relying on worker memories in reconstructing exposure; however, in the absence of adequate written records, we believe that if recollections of different workers are relatively consistent, they provide a valid source of information. For example, the four employees interviewed for the paper had worked from 25–30 yr at the plant.

The uncertainty analysis indicated that while no single assumption dominated the estimates, the factor that had the highest effect was the assumption of increasing workplace concentrations as one went backward from 1976–1940. Our belief that exposures during the early years of

Pliofilm manufacture (pre-1950) were relatively high is based on four factors: (1) medical and clinical evidence of toxicity in Akron and St. Marys workers (Department of Labor, 1942; Kipen et al., 1989a; Lamm et al., 1989; Wilson, 1942); (2) evidence of significant engineering changes in St. Marys in 1946 and at Akron I in 1946; (3) industrial hygiene experience in other industries (Table 9); and (4) the higher TLVs that were in place in the 1940s and 1950s.

We agree with Crump and Allen (1984) that the commitment of management to control workplace exposure to benzene to meet the prevailing TLV can be used to predict airborne levels before 1960. Crump and Allen (1984) relied on a logical assumption that workplace exposure would be expected to have decreased as the occupational exposure limits (e.g., the TLVs) decreased. Their estimates are consistent with the reports in the industrial hygiene literature, for example, that workplace concentrations of benzene vapors in most industries declined between 1939 and the 1960s. Our analysis provides significant additional evidence to support Crump and Allen's contention that worker exposures to benzene were higher in the 1940s and 1950s than in the 1960s and 1970s.

The second most important factor, according to the uncertainty analysis, was the length of the workweek. The length of work week was based on records of personnel injury reports. Our estimates, while greater than 40 h, are less than the estimates from worker interviews. Workers consistently indicated that 6- and 7 d workweeks were the norm for all years after the 1940s. Had such estimates been included, exposure estimates would have been increased by 5%. Although it is possible that the database is not robust and may not be representative of all workers, the data seem reasonable in light of what is known of other industries for that time period.

Correction of analytical biases (in measurements taken before 1963) have a smaller effect on the final estimates then would have been expected. The reason for this lack of impact is our use of the St. Marys data taken after 1963 (and thus unaffected by the analytical measurement bias) to estimate early exposures at St. Marys and Akron I. While there were some measurements taken at St. Marys and Akron I before 1963, the data were so scattered that they were only used to confirm the estimates based on the post-1963 data (see Table 6). The impact of the analytical bias assumptions is limited to the exposure estimated at the Akron II facility, where estimates of background airborne concentrations were increased by 50%. The contribution to total estimated exposure at the Akron II facility was less than 50% since the contribution from dermal contact was unaffected by the analytical bias.

Both Crump and Allen (1984) and Rinsky et al. (1986) assumed that the available industrial hygiene data reflected the time-weighted average (8 h) daily exposure, including peak exposures. Crump and Allen (1984) did attempt to incorporate peak exposures for workers who entered the dry-

ers and casting units. In contrast, Rinsky et al. (1986) concluded that short-term, high-level exposures (even if they did exist) would not contribute significantly to the workers' total uptake (absorbed dose of benzene) because of the alleged use of personal protective equipment (PPE)—gloves and respirators.

In our analysis, we assumed that respirators used during the years 1936–1976 had only a limited impact on exposure because of its limited effectivenessand inconsistent usage. We estimated that the half-face respirators used by the Pliofilm workers were no greater than 75% effective. This assumption is based on the following lines of reasoning. First, it was recognized in the 1970s that only under ideal conditions would half-mask respirators provide a fit that ensures that more than 80% of the inhaled vapors pass through the charcoal (20% enters uncleaned through the leaks in the facial skin/rubber gasket interface). Based on the experience of the industrial hygiene community in implementing fit tests during the 1970s and 1980s, we would expect that the respirators of the 1940s and 1950s would not be able to reduce exposure concentrations to levels below 25% of the ambient levels due to the poor fit of the mask.

Second, the records indicate that these workers used Mine Safety Appliance (MSA) "comfo" half-mask respirators equipped with a charcoal cartridge (Mclnerney, 1977). Prior to 1975, charcoal cartridges were thought to effectively collect nearly all organic vapors. However, beginning with the classic studies of Nelson et al. (Nelson and Harder, 1372, 1974, 1975; Nelson and Hodgkins, 1972; Nelson et al., 1972, 1974, 1975; Ruch et al., 1972), it was recognized that at concentrations of 1000 ppm benzene, the time for 10% breakthrough occurs after about 2 h of use (Nelson and Harder, 1976). It also was recognized in the 1970s that for charcoal respirators to be effective they needed to be stored properly prior to and after initial use; othenvise the charcoal would soon be exhausted due to passive uptake of airborne organics (NIOSH, 1976). Worker interviews indicate that it was common practice for workers to wear their masks around their necks when not in use; therefore, due to passive uptake and humidity effects, it is unclear how effective the charcoal was at remcving benzene vapor (Allman, 1991). This is important considering the poor warning properties of benzene.

Third, respirators offer only a modest level of protection for chemicals that have an odor threshold greater than or equal to the occupational exposure limit. Such a warning property is necessary; otherwise, the worker could be exposed to harmful levels while believing himself protected by the respirator. In the case of benzene, the odor threshold reported in the literature varies from 8 to 31 ppm (ASTM, 1978), 40 ppm (American Petroleum institute, 1985), and 100 ppm (Gerarde, 1963). Most hygienists believe it is about 25 ppm for most people and about 50 ppm for those people who routinely work with it. However, since 1958, the TLV has been 25 ppm (a value less than most estimates of the odor

threshold). It is also possible that workers would not have recognized that the respirators were not protecting them until concentrations within the respirator exceeded 100 ppm. It has been observed that due to central nervous system depression and the onset of olfactory fatigue, employees have been unable to detect benzene's characteristic odor at concentrations as high as 200 ppm. In addition, smoking (which was at its highest prevalence in U.S. males in the 1940s-1970s) can significantly raise the threshold of smell for benzene and other chemicals. Based on the available evidence, even if one were to accept that workers diligently wore respirators, it is likely that they offered only modest protection.

The record on respirator usage by the Pliofilm workers is mixed. Rinsky et al. (1981) indicated that respirators were worn whenever the TLV was exceeded. However, such a policy must have been difficult *to* implement in light of the analytical shortcomings during much of the 1940s and 1950s and the lack of a clear olfactory warning. In contrast, worker interviews indicated that while respirators were available and workers were expected to use them, they rarely wore them. This is no surprise since benzene is not an irritant and respirators at that time were most uncomfortable. As in many industries, workers often wore respirators around their neck but rarely put them on (Allman, 1991. Mclnerny (1977) testified at the OSHA hearing on the benzene standard that respirator usage ranged from 25% in the 1940s and 1950s to 60% in the 1970s. Given this mixed testimony and the experience of industrial hygienists in other industries, we assumed that workers used respirators approximately 33% of the time they were exposed to peak concentrations.

Although some of our estimates of the likely TWA airborne concentrations (150-250 ppm) appear high by today's standards, an examination of the occupational medicine literature (Table 15) indicates that exposures to these and higher levels can be tolerated for various lengths of time. For example, workplace exposure to benzene for periods of 1-2 h in the vicinity of 300-400 ppm was not uncommon prior to 1946, and exposure to levels from 100 to 200 pprn (8-h TWA) could he tolerated for weeks by some persons without apparent significant adverse effects (Hamilton, 1929; Aksoy, 1980).

Greenburg (1926) studied people repeatedly exposed to benzene at 18 different work areas in a variety of facilities and showed that humans, if acclimated, could tolerate levels of exposure ranging from 100-1000 ppm. Table 16 presents some of the results of this study.

Concentrations in work areas in which benzene was the only solvent present ranged from 0 to more than 4000 ppm. The values reported by Greenburg (1926) represent time-weighted averages over several hours, and the concentrations given are "representative of general room air and/or air at a worker's station." Elkins (1950) found that exposure to levels ranging from 200 to 700 ppm over several years resulted in some fatalities (cause of death not stated) in the leather processing industry,

TABLE 15. Acute Adverse Effects Associated with Shod-Term Exposure to Benzene Vapor

Benzene concentration (ppm)	Duration of exposure (h)	Effects observed	Reference
25	a	None	Cerarde (1960)
38	Unknown	Olfactory threshold	API (1985)
50-150	5	Headache, lassitude, weariness	Cerarde (1960)
500	1	Symptoms of illness	Cerarde (1960)
1500	1	Serious symptoms	Cerarde (1960)
1500-3000	Several hours	Moderate symptoms	Bloomfield (1951)
1550-3100	6	No serious effect	Herbert (1939)
1570-3130	Several hours	Slight symptoms	Drowning (1937)
3000	1/2	Endurable	Cerarde (1960)
3000	1/2-1	Dangerous	Browning (1937)
3000–4700	1	Maximum concentration without serious CNS effects	Bloomfield (1951); von Oettingen (1940)
3130-4700	1/2-1	Maximum concentration without serious CNS effects	Browning (1937)
4650	1/2	Listlessness, confusion, and some dizziness	Hamilton (1929)
4700	1/2	Confusion and some dizziness	Greenburg (1926)
6190-9300	Few hours	Definite symptoms of poisoning	Greenburg (1926)
6200-9300	1/2-1	Immediate or subsequent death	Herbert (1939)
7500	1/2-1	Immediately dangerous to life	Bloomfield (1951); von Oettingen (1940); Gerarde (1960)
6200-9300	2-4	Loss of consciousness	Hamilton (1926)
19,000-20,000	Short exposure	Rapidly fatal	Erowning (1937); Bloomfield (1951); von Oettingen (1940); Gerarde (1960)

although dermal exposure in these cases was probably significant. These findings are not surprising given the clear differences in susceptibility of the hematopoietic system among persons exposed to benzene.

Individual case reports of acute benzene intoxication have appeared in the literature since the early 1900s (Greenburg, 1926; Hamilton, 1929; Sappington, 1950). In certain studies, concentrations either were measured or estimated (Cook, 1947). Table 15 presents some of the published case reports which contain exposure information. Due to the likely underreporting by the analytical methods, much higher ,concentrations than those reported may have been present. The data indicate that concentrations of benzene up to 1000 pprn are tolerable for short periods and that concentrations between 250 and 700 ppm are not self-limiting if workers are acclimated *to* the smell. The data also indicate that airborne concentrations of benzene in the rake or 200-250 ppm (8-h TWA) may not necessarily cause obvious acute or subchronic toxicity. Often, in the

1940s and 1950s there was a "selection process" where only those individuals who could tolerate the acute effects of benzene exposure remained on the job. For these reasons, we believe that our exposure estimates for the 1940s are not unreasonable.

The finding that Pliofilm was not manufactured at St. Marys during 1942–1945, and therefore worker exposure would be less, raises a potential contradiction with the findings of Kipen et al. (1989a) regarding the effects on blood. In the Kipen et al. study, the worker's blood counts show some indication of an improvement in blood counts in 1943; however, they indicate a significant suppression in blood counts. Further, in 1946 when rubber again became available and St. Marys returned to full production, blood counts showed no sign of renewed suppression. A

TABLE 16. Incidence of suppression[a] of White Blood Cell Counts in Various Jobs as Compared to Range of Workplace Concentrations of Benzene (Greenburg, 1926)

Process	Ventilation	Benzene concentration[b] (ppm) Average	Min	Max	Incidence of suppression
Cement mixing[a]	None	150	100	190	0/1
Slickering[c]	General room	700	500	890	0/2
Coating[c]	Local exhaust	580	180[d]	1020[d]	1/4
Mixing[c]	Enclosed process	430[d]	410[d]	450[d]	1/3
Cement mixing[a]	None	150	100	190	*Oil*
insulating wire[a]	None	130	50	210	6/12
		210[d]	40[d]	460[d]	
Compound mixing[a]	None	1360	80	2640	1/1
		580[d]	220[d]		
Coating[c]	General local exhaust	130	30	410	1/10
		330[d]	130[d]	480[d]	
Compound mixing[a]	Enclosed process	100	100	100	1/3
Core painting	None	220	113	340	2/5
Tire making	None	150	140	160	119
		210[d]	50	340	
Lining	Local exhaust	70	50	110	0/0
		90[d]	0[d]	350[d]	
Compound mixing	None	340	280	390	0/1
Cement mixing	None	620	310	860	6/9
Lining	Local exhaust	180	20	360	0/5
		400[d]	280[d]	500[d]	
Dry cleaning	None	1800	230	4140	2/3
Coating	Local exhaust	90	40	130	1/1
Cementing	None	100	60	120	2/9

[a]Suppression is defined as a 25% decreare in the individual's white blood count.

[b]Measurement of airborne benzene were collected within the workers' breathing zone during summer months.

[c]Workers were exposed to other solvents.

[d]Measurements were taken in the winter months.

plausible reason for this absence of a clear production-related improvement may be the way records were kept at St. Marys. Assignment to a job category was a function of the machine the worker operated, not the product manufactured or the solvents used. Therefore, a caster operator who manufactured tent fabric or foil products was identified as a caster operator.

Since blood measurements were both invasive and expensive, it can be expected that they were performed only on workers who were exposed to benzene (Hanning, 1991b). Consequently, it seems likely that the blood data for St. Marys during the war are only for those employees who were involved in the reworking of Pliofilm. Some indication of this can be seen in the decline in the number of workers tested in the war years. For example, only 6 workers' blood counts were reported for a 17-month period starting in February of 1942 (Kipen, 1992). Such workers would have had exposures greater than the estimates developed in Table 13. The estimates in this table assume that all workers at St. Marys had an equal probability of manufacturing Pliofilm during the war years. A second possible explanation is that monitoring of blood continued during the war for those workers who had previously developed dyscrasias. It is known that some workers exposed to benzene never returned to preexposure levels and yet remain asymptomatic.

During our investigation, we identified a significant difference between the medical monitoring programs of the two Akron facilities and St. Marys. Red and white blood cell counts were performed on a monthly basis at St. Marys from the 1940s to 1976 (Department of Labor, 1942; Hanning, 1990; Rinsky et al., 1981). In Akron, the blood monitoring, initially was conducted each month, but was relaxed to quarterly about 1943. The impact of this decreased monitoring frequency is that a worker could continue to be exposed to benzene for nearly 3 mo before a blood dyscrasia could be identified. At St. Marys, the worker could have continued to be exposed for only 1 mo, thus reducing the possibility of developing serious blood dyscrasias. Beyond the evidence for higher airborne concentrations, we believe that this may help explain the apparent increase in leukemias observed at the Akron facilities.

For a number of reasons, some caution should be used in interpreting the data from the Pliofilm cohort. The first is the efiect of "selecting for tolerance." It appears that there can be significant differences in interindividual susceptibility to the effects of benzene. As such, it is unclear whether the information on this cohort is biased since persons susceptible to the hematopoietic effects of benzene may have left the workplace prematurely as a result of the program of systematic testing and removal of workers. Whether this selection for tolerance would bias the cohort's response to the lukemogenic effect of benzene is not known. A second uncertainty is that some workers may have had additional exposure to benzene due to work in other settings. For example,

at the Akron I facility, benzene was used in the same building and on the same floor as the Piiofilm operations in the manufacture of balloon fabric (Department of Labor, 1942; Hanning, 1991; Krisman, 1991). It is known that some workers in the Akron facilities were transferred to Pliofilm from other departments where benzene was in use. In contrast, the St. Marys Pliofilm operation was the only department that used significant amounts of benzene. This suggests that the lifetime estimates of benzene exposure for the Akron workers may not be fully understood.

Although this analysis is based primarily on exposure data which were considered in the OSHA hearings on the benzene workplace standard, it is inaccurate to suggest that all of the pertinent data were considered or that they were properly integrated or interpreted (Infante, 1992). As discussed throughout this article, no prior assessment has attempted to quantitatively account for the five important exposure factors we addressed. Further, some cited information, such as the virtual shutdown of production of Pliofilm at St. Marys during the war and the exceedingly long workweek in Akron and St. Marys, were not considered by OSHA. Last, we believe that the blood data and the acute toxicity observed in some workers are inconsistent with the exposures suggested in the analysis of Rinsky et al. (1986). Like OSHA, we agree that the Crump and Allen ratio approach is likely to be the best way to retrospectively estimate dose and have adopted this approach in our assessment.

Although additional data regarding the exposure of the Pliofilm cohort would give us greater confidence in our analysis, we believe that our estimates are more plausible than those of earlier studies. Our results predict exposures that are much like those in other industries at that time and are consistent with those known *to* cause blood suppression. By considering the differences between the facilities at the two locations, we determined that prior studies probably overestimated exposures at St. Marys and underestimated exposures at Akron. We also concluded that dermal uptake was likely to contribute at least an additional *20%* to the dose absorbed via inhalation. We suggest that these exposure estimates for the various classes of workers be compared with the incidence of disease information to see if there is a doseresponse relationship. If it is present, we recommend that these estimates be combined with the most recent epidemiology data on the Pliofilm workers to derive a cancer potency factor for humans. We also suggest that when additional or better information on the Pliofilm workers becomes available, it be incorporated into the analysis.

REFERENCES

Agency for Toxic Substances and Disease Registry 1989 *Toxicological Profile for Benzene.* Atlanta Ga.: U.S. Public Health Service.

Aksoy, M. 1980. Different types of malignancies due to occupational exposure to benzene: A review of recent observations in Turkey. Environ. Res. 23:181-190.

Albert, R. E. 1979. Carcinogen Assessment Group's Final Report on Population Risk to Ambient Benzene Exposures. U.S. Environmental Protection Agency, Officeof Air Quality and Planning Standards. EPA-450/5-80-004. Research Triangle Park, N.C.

Allman, C. 1991. Personal communication with R. Bradshaw, ChemRisk, and W. Ollison, American Petroleum Institute, January 3.

American Conference of Governmental Industrial Hygienists. 1991. Notice of intended changes—Benzene. *Appl.* Occup. Environ. *Hyg.* 5(7):453–463.

American Petroleum Institute. 1985. Review of Published *Odor and Taste* Threshold *Values* of *Soluble Gasoline Components*. Health and Environmental Sciences Depanment. API publication no. 4419, December.

American Petroleum Institute. 1986. OSHA Hearing Docket H-059c, Exhibition 216, Tables 12 and 15. Washington, D.C.

American Society for Testing and Materials. 1978. *Compilation of* Odor *and Taste* Threshold *Values* Dara. ed. F. A. Fazzslari, p. 17. Philadelphia: American Society for Testing and Materials.

Austin, H., Delzell, E, and Cole, P. 1988. Benzene and leukemia: A review of the literature and a risk assessment. *Am. J. Epidemiol.* 127:419–439.

Beebe, P. 1976. Letter to J. A. Brown, Director of Film, Flooring and Molded Products Manufacturing from P. Beebe, Jr., Manager Industrial Hygiene and Safety. Re: Pliofilm Operations at St. Marys. September 20.

Bernardinelli, S. P., and Bender. T. R. 1990. Selection of chemical protective clothing. In *Exogenous Dermatoses: Environmental Dermarifrs*, chapter 36. eds. T. Menne and H. I. Maibach. Boca Raton, Fla.: CRC Press.

Bloomfield. C. D. 1951. Studies of health hazards in industry. Chemical hazards: Benzol vapor. *Ind.* Health *Monthly* 11:62-64.

Bond, C. 1991. Survey *of Various Concentrations of* Benzene hfeasured *During Various* Chemical *Manufacturing* Operalions *Between 1944-1965*. Midland, Mich.: Dow Chemical Company.

Brett, S. At., Rodricks, J. V., and Chincilli. V. M. 1989. Review and update *of* leukemia risk potentially associated with occupational exposure to benzene. *Environ. Health Perspect.* 82:267-281.

Browning. E. 7937. Toxicity of Industrial Organic Solvents: Summaries of Published Work. Report No. 80. Committee on the Toxicity of Industrial Solvents. Medical Research Council, Industrial Health Research Board. London.

Cody, R. P., Strawderman, W. W., and Kipen, H. M. 1991. Hematologic effects of benzene: Job specific trends during the first year of employment among a cohort *of* benzene-exposed rubber workers. in preparation.

Cook, W. 1945. Maximum allowable concentrations of industrial contaminants. *Br. J.* Ind. *Med.* 14(11):936-946.

Cook, W. A 1947. Review of automatic indicating and recording instruments for determination of industrial atmospheric contaminants. *Am. Ind. Hyg* Arsoc. Q. 8:42-48.

Crisman, H. 1991. Personal Communication with D. Paustenbach, ChemRisk—A Division of McLaren/ Hart Engineering, Alarneda, Calif., January 3.

Crisman, H. 1991. Personal communication with D. Paustenbach, ChemRisk, December 27.

Crump, K., and Allen, B. 1984. Quantitative Estimates of Risk of Leukemia from Occupational Exposure to Benzene. OSHA Docket H-059b, Exhibit 152 (Appendix B). Washington, D.C.

Depanment of Labor. 1942. Condensed Proceedings of the Conference on Health Hazards in the Rubber Industry. U.S. Department of Labor, Division of Labor Standards. Akron, Ohio. May 29.

Dorsey, C. P. 1973. Industrial Hygiene Report of Benzene Samples Collected During Various Pharmaceutical Operations. Eli Lilly and Company, Indianapolis, Indiana.

Dräger. 1980. The *Handbook lor Dräger Tubes: Air Investigations and Technical* Cas *Analysis with Dräger* Tubes, 3rd ed. (August 1976). New York: Dräger.

Elkins, H. B. 1950. The *Chemistry of Industrial Toxicology*, pp. 101-107. New York: John Wiley and Sons.

Flanick, H. L. 1943. Memorandum to H. L. Flanick from H. Slomin. Re: Employment and Labor Requirements in the Rubber Manufacturing Industry, June 21.

Fluker, J. H. 1946. Letter to J. H. Fluker, Assistant Superintendent, Division of Safety and Hygiene from W. E. Obetz, Medical Investigator for The Industrial Commission of Ohio. Re: Site visit to Coodyear Tire and Rubber Company, St. Marys, Ohio to check the effectiveness of the new ventilation equipment. November 21.

Fluker, J. H. 1948. Letter dated May 4. Re: Results of an industrial hygiene survey on The Goodyear Tire & Rubber Co. Plant, Akron, Ohio.

Foreman's Personal Injury Reports. 1940-1956. St. Marys, Ohio. Obtained via Goodyear's worker history files.

Franz. T. J. 1984. Percutaneous absorption of benzene. In Applied Toxicology of Petroleum Hydrocarbons, ed. MacFarland, H. N.. Holdsworth, C. E., MacGregor, I. A.. Call, R. W., and Lane, M. L., pp. 51-70. Princeton, N.J.:Princeton Scientific.

Cerarde, H. W. 1960. *Toxicology and Biochemistry of* Aromatic Hydrocarbons. London: Elsevier Publishing.

Cerarde, H W. 1963 The aromatic hydrocarbons In *Industrial Hygiene* and *Toxicology*, vol. 2 ed *f.* A. Patty. New York: John Wiley and Sons.

Coldstein. B. D. 1977. Hematotoxicity in humans. *J. Toxicol. Environ Health* (Suppl.) 2:69-105

Coldstein, B. D. 1983. Benzene: Review of Recent Literature. Prepared for the American Petroleum Institute. February 3.

Greenburg. L. 1926. Benzol poisoning as an industrial hazard VI. Intensive study of selected industries with respect to factor conditions and pollution of the atmosphere by benzol. *Public Healrh Rep* 41:1516-1539.

Hamilton, A 1929. *Industrial Poisons in the* United *States*, pp. 453-481 New York: Macmillan

Hamilton. A. 1931. Benzene (benzol) poisoning. Arch. *Pathol.* 11:434-601.

Hanke, J., Dutkiewicz, T., and Piotrowski, J. 1961. The absorption of benzene through the skin in man. *Med Pract.* 12 413-426.

Hanning. R 1990. Personal communication with R. Bradshaw, ChemRisk, and W. Ollison. American Petroleum Institute

Hanning. R. 1991a. Personal communication with D. Paustenbach, ChemRisk. and W. Ollison, American Petroleum Institute, May 1.

Hanning, R. 1991b Personal communication with W. Ollison, American Petroleum Institute, June 6

Hay. E. B. 1964. Exposure to aromatic hydrocarbons in a coke oven by-product plant. *Am. Ind Hyg Assoc. J.* 25:326-391.

Hay, E. B. 1990 Personal communication by W. Ollison.

Herbert. E. Q. 1939. Dangerous gases in distillation and refining processes. *J. Inst Petrol. IS* 323-346.

Hillman, S. 1942. Letter to S. Hillman, Associate Director. General Office of Production Management from the Secretary of Labor. Division of Labor Standards, National Archives. Washington, D.C.. January 10.

Hornung, R. W., Ward, E., Morris, J. A., arid Rinsky, R. A. 1989. Letter to the editor. *Toxicol Ind* Healrh 5:1153-1155.

IARC. 1982. Discussion on benzene, *IARC Eval. Carcinogen. Risk* Chem. *Hum.*, pp. 95-14: IARC Monograph no. 29. Lyon, France.

Industrial Commission of Ohio. 1944. Self-Insuring Employer's Report of Occupational Disease. Columbus, Ohio. Obtained from worker records; this is Rinsky worker number 683.

Infante, P. F. 1992. Benzene and leukemia: The 0 1 ppm ACGIH proposed threshold limit value for benzene. Appl. Occup. Environ. Hyg. 7(4):253-262.

Infante, P. F, Rinsky, R. A., Waggoner, L. R.. and Young, R. J. 1977. Leukemia in benzene workers. lancer 2:76-78.

Infante. P. F., and White, W. C. 1983. Benzene: Epidemiologic observations of leukemia cell type and adverse health effects associated with low-level exposure. Environ. *Health Perspect* 52:75-82.

Kipen, H. Ai. 1992. Personal communication with P. Price. ChemRisk—A Division of McLaren/Hart Engineering. Portland, Maine, January,

Kipen, H. M., Cody. R. P, Crurnp. K. S., Allen, B. C.. and Coldstein, B. D. 1988 Hematologic effects of benzene: A thirty-five year longitudinal study of rubber workers. *Toxicol* Ind. *Health* 4:411-430.

Kipen. H. *M.,* **Cody,** R. P., and Goldstein, B. D. 1989a. Use of longitudinal analysis of peripheral blood counts to validate historical reconstruction of benzene exposure. *Environ.* Healrh *Perspect.* 82:199-206.

Kipen. H. M., Cody, R. P.. and Coldstein, B. **D.** 1989b. Letter to the editor. *Toxicol.* Ind. *Health* 5:1156-1158.

Kodak. 1991. Memo to Dennis Paustenbach, ChemRisk—A Division of McLaren/Hart Engineering, Alameda, Calif.

Kusnetz, H. L., Saltzman, B. E,, and Lanier, M. E. 1960. Calibration and evaluation of gas detecting tuber. Am. *Ind. Hyg Assoc. J.* 21:361-373.

Lamm, S. H., Walters, A. S., Wilson, R.. Burd, D. **M.,** and Grunwald, H. 1989. Consistencies and inconsistencies underlying the quantitative assessment of leukemia risk from benzene exposure. *Environ.* Healrh *Perspect.* 82:289-297.

htaibach, H. I.. and Anjo. D. **M.** 1981. Percutaneous penetration of benzene and benzene contained in solvents used in the rubber industry Arch *Environ. Health* 36(5):256-260.

McInerney. H. M. 1977. Testimony of July 28. Submitted to OSHA Hearing Docket H059, Exhibit 121. NIOSH, Washington, D.C.

National Institute for Occupational Safety and Health. 1976. *A* Curde *for Industrial Respiratory Protection* John A. Pritchard, Los Alamos Scientific Laboratory, under interagency agreement nos. IA-74-23, IA-75-25, and IA-76-9 lor U.S. Department of Health. Education. and Welfare, Public Health Service. Center lor Disease Control and National Institute for Occupational Safety and Health. Cincinnati, Ohio: **NIOSH.**

h'elson, C. O.. Correia. A. M., and Harder, C. A. 1975. Respirator Cartridge Efficiency Studies VII. Effect of Relative Humidity and Temperature Lawrence Livermore Laboratory, report UCRL-77390, August

Nelson. C. O.. and Harder, C. A. 1972. Respirator cartridge efficiency studies. IV. Effects of steady state and pulsating flow. Am. Ind *Hyg. Assoc. J* 33 797

Nelson. G. O., and Harder, C A. 1974. Respirator cartridge efficiency studies. V. Effect of solvent vapor. Am. Ind. *Hyg Assoc. J.* July.391-410.

Nelson. C. O., and Harder, C. A. 1976 Respirator cartridge efficiency studies VI. Effect of concentration. *Am. Ind. Hyg. Assoc. J.* April: 205-216.

Nelson, C. O., Harder, C.A.. and Bigler, B. E. 1974. Respirator Cartridge Efficiency Studies VI. Effect of Concentration. Lawrence Livermore Laboratory, report UCRL-76184, November.

Nelson. C. O., and Hodgkins. D J. 1972 Respirator cartridge efficiency studies II Preparation of test atmospheres *Am* Ind *Hyg Assoc. J.* 33:110.

h'elson, C O., Johnson. E. R.. and Lindeken, C. L., and 'Taylor. R. D 1972 Respirator cartridge efficiency studies III. A mechanical breathing machine to simulate human respiration. *Am Ind. Hyg. Assoc. J.* 33:745.

Nelson, C O., Lum, B. Y., Carlson, C. I., Wong, C. M., and Johnson, J. S. 1981. Glove permeation by organic solvents. *Am.* Ind *Hyg Assoc. J.* 42:217-225.

Nomiyama. K., and Nomiyama, H. 1974. Respiratory retention, uptake, and excretion of organic solvents in man. Benzene, toluene, *n*-hexane, trichloroethylene. acetone, ethyl acetate, and ethyl alcohol. *Int.* Arch. *Arbeitsmed.* 32:75-83. (As cited in IARC. 1982.1

Occupational Safety and Health Administration. 1985. Occupational exposure to benzent.; Pro posed rule and notice of hearing. Fed. Reg. 52:50512-50586.

Occupational Safety and Health Administration, 1987. Occupational exposure to benzene; Final rule. Fed. *Reg.* 52:34460-34578.

Osborne, C. 1931. Personal communication with R. Bradshaw, ChemRisk, and W Ollison, American Petroleum Institute. January 3.

Ott, M. G., Townsend, J. C., Fishbeck, W. A., and Largner. R A. 1978 Mortality among individuals occupationally exposed to benzene. Arch. Envtron. *Health* 33.3-10.

Pagnotto, L. D. ,Elkins. H. B., Brugsch, G., and Walkley, J. E. 1961. Industrial benzene exposure from petroleum naphtha I. Rubber coating industry. Am. *Ind. Hyg Assoc J.* 22:217-245.

Paustenbach, D. I. 1977. Industrial Hygiene Report of Benzene Samples Collected during Various Chemical Manufacturing Activities. Eli Lilly and Company, Clinton, Ind.

Paxton, M. B., Chinchilli, V. M., Brett, S. M., and Rodricks, J. V. 1992. Reanalysis and update of the leukemogenic risk associated with occupational benzene exposure in the Pliofilm cohort. *Risk* Analysis, submitted.

Rinsky, R. A , Smith, A. B., Hornug, R., Filloon, R. G., Young. R. J., Okun. H. A., and Landrigan, P. H. 1986. *Benzene and* leukemia. *An Epidemiologic Risk Assessment* Cincinnati, Ohio: National Institute for Occupational Safety and Health.

Rinsky, R. A., Smith, A. B., Hornug, R., Filloon, R. G., Young. R. J., Okun. A. H., and Landrigan, P. J. 1967. Benzene and leukemia: An epidemiologic risk assessment. *N. Engl. J. Med* 316.1044-1050.

Rinsky, R. A., Young. R. J., and Smith, A. B. 1981. Leukemia in benzene workers. *Am. J. Ind. Med* 2:217-245.

Rothstein, D. E. 1942. Memorandum from L. Levine to D. E. Rothstein. War Production Board. Re Development in the synthetic rubber industry. July 2. National Archives, Washington, D.C.

Ruch, W. E., Nelson, C. O., Lindekan, C. L., Johnson, R. E., and Hodgkins, D. J. 1972. Respirator cartridge efficiency studies I. Experimental design. *Am. Ind. Hyg J.* 33:105.

Sappington, C. O. 1950. Occupational morbidity and mortality. In *Essentials* of Industrial *Health* Philadelphia: J. B. Lippincott.

Schoch, D. 1991. Survey of Various Reported Concentrations of Benzene Measured near Different Manufacturing Steps. Rochester, N.Y.: Eastman Kodak.

Sefarian, S. 1956 Report on Investigation of Benzol Exposures within Coodyear Tire and Rubber Company St. Marys, Ohio. January 17.

Silverman, L. 1956. Sampling and analyzing air for contaminants in work placer. In *Encyclopedia of Instrumentation for Industrial Hygiene*. Ann Arbor, Mich.: University of Michigan.

Tabershaw, I. R., and Lamm, S. H. 1977. Benzene and leukemia (letter to the editor) *Iancer 2* 867-868

United Rubber Workers 1977. United Rubber Worker Testimony. OSHA Hearing Docket H-059. OSHA Hearing Transcript, August 10. Washington, D.C.

University of North Carolina 1974. Preliminary Environmental Survey Report. St. Marys, Ohio, dated November 11, 1974. Exhibit 187.C.6, Docket H-059, Submitted to OSHA docket on benzene. Occupational Safety and Health Administration, Washington, D.C.

U.S. Environmental Protection Agency. 1985. Interim Quantitative Center-Unit Risk Estimates due to Inhalation of Benzene Office of Air Quality Planning and Standards, Carcinogen Assessment Group. EPA-600/X-85-022. February 15.

Vigliani, E C 1976. Leukemia associated with benzene. *Ann. N Y. Acad. Sci.* 271:143-151.

von Oettingen, W. F. 1940. *Public Health Bull.* 225. Washington, D.C.: U.S. Public Health Service

Voytek, P. E . and Thorslund, T W 1991. Benzene risk assessment Status of quantifying the leukemogenic risk associated with the low dose inhalation of benzene. *Risk Anal.* 11(3):355-357.

Weeks, R. W. , and McLeod, M. J. 1982. Permeation of protective garment material by benzene and titrated water. *Am. Ind. Hyg.* Assoc. *J.* 43:201-211.

White, M. C., Infante, P. F., and Chu, K. C. 1982. A quantitative estimate of leukemia mortality associated with occupational exposure to benzene. Risk Anal. 4:9-13.

Wilson, R, 1942. Benzene poisoning in industry. *J. Lab Clin. Med.* 27:1517-1521.

Wingfoot Clan. 1983. Operations at St. Marys plant span 43 year period. Goodyear *Tire and Rubber Company Newlett St. Marys Ed* 42(4):1-5.

Wong, O. 1983. An Industry-Wide Study of Chemical Workers Occupationally Exposed to Benzene. Report to the Chemical Manufacturers Association (CMA), Environmental Health Associates, Berkeley, Calif.

Yin, S.-N., Li, G.-L., Iain, F.-L., Fu, Z.-I., Jin, C., Chen, Y.-J., Luo, S.-J., Ye, P.-Z., Zhang. J.-Z., Wand, C.-

C., Zhang, X.-C., Wu, H.-N., and Zhong, Q.-C. 1987. Leukemia in benzene workers. A retrospective cohorr study I. General results *Br J. Ind. Med* 44:124-128.

Young. R., Rinskey, R.. and Johnson, P. 1977. Walk-Through Survey of Coodyear Tire and Rubber Co. Cast Film Division. St Marys, Ohio. Survey date February 9-10, 1976. Survey conducted by P. Johnson, R. Rinsky, P. Infante, M. Jones, and R. Young from the Division of Field Studies. Hazard Evaluations. and Field Studies, National Institute lor Occupational Safely and Health. Cincinnati. Ohio.

Zimmer, V. A. 1941. letter to B. McGurn from V. A. Zimmer, Director, Division of Labor Standards. Department of labor, December 20. Re. Labor shortage during World War II. National Archives, Washington, D.C.

Received *July* 75, 1991
Accepted January 75, 1992