American Journal of Industrial Medicine 3:259-311 (1982)

Occupational Exposure to Asbestos: Population at Risk and Projected Mortality—1980-2030

William J. Nicholson, PhD, George Perkel, MA, and Irving J. Selikoff,

Estimates have been made of the numbers of cancers that are projected t past exposures to asbestos in a number of occupations and industries through 1979, 27,500,000 individuals had potential asbestos exposure at work. Of these, 18,800,000 had exposure in excess of that equivalent to two months employment in primary manufacturing or as an insulator (> 2-3 f-yr/ml). 21,000,000 of the 27,500,000 and 14,100,000 of the 18,800,000 are estimated to have been alive on January 1, 1980.

It is further estimated that approximately 8,200 asbestos-related cancer deaths are now occurring annually. This will rise to about 9,700 annually by the year 2000. Thereafter, the mortality rate from past exposure will decrease, but still remain substantial for another three decades.

Key words: asbestos, occupational exposure, risk assessment, morality projections

INTRODUCTION

A large volume of research has been conducted on the adverse health effects of exposure to asbestos. However, relatively little is known about the magnitude of the population at risk to asbestos-related disease. A number of occupations and industries have been identified as involving substantial occupational exposure to asbestos, but no detailed evaluation has been made to quantify the number of persons whose employment experience has resulted in sufficient exposure to warrant characterizing them as at risk. This analysis is designed to provide an assessment of the extent and consequences of occupational asbestos exposure in the United States between 1940 and 1979.

The task of estimating the population at risk to asbestos-related disease is complicated by a number of factors:

Environmental Sciences Laboratory, Mount Sinai School of Medicine (CUNY), New York.
The analysis was prepared as part of a study for the US Department of Labor entitled "Disability Compensation for Asbestos-Associated Disease in the United States," June 1982.
Address reprint requests to Dr. William J. Nicholson, Environmental Sciences Laboratory, Mount Sinai School of Medicine (CUNY), One Gustave Levy Place, New York, NY 10029.
Accepted for publication July 23, 1982.

0271-3586/82/0303-0259$14.00

1. The precise number of persons occupationally exposed to asbestos at any given time is not known.

2. The level of exposure to asbestos necessary to increase the risk of incurring asbestos-related disease is only imperfectly known, estimates being complicated by the varying interactions of the two elements that go into "dose" (time and intensity).

3. The extent to which workers have changed occupations and/or industries from time to time so as to place them at risk to asbestos-related diseases (or to end such exposure) at any time in the past four decades is not known.

We have sought to overcome these obstacles by compiling the best available data concerning worker exposure to asbestos and the turnover of workers in the occupations and industries involved. The sources and methods used to estimate the population at risk are set forth below.

MATERIALS AND METHODS

Identification of Industries and Occupations at Risk

Workers are exposed to asbestos in a wide variety of industrial pursuits from mining and milling to primary manufacturing (producing manufactured goods from raw asbestos fibers) to secondary manufacturing (processing asbestos manufactured products to make other products) to consumer industries (utilizing a finished product containing asbestos without modification) [Daly et al, 1976].

Mining and milling. Fewer than 600 persons in the United States are employed in mining and milling asbestos [Meylan, 1978]. In view of the small number involved and the lack of information on employee turnover, we have excluded this industry from our estimates.

Primary manufacturing. The Asbestos Information Association has estimated that there are upwards of 3,000 discrete uses of asbestos. A selection of major asbestos products and their uses is presented in Table I. The primary manufacturing industries in which asbestos products are produced and which involve substantial asbestos exposure to production and maintenance employees are as follows:

Asbestos products industry (SIC 3292). The major products of this industry are friction products, asbestos-cement pipe and sheet, asbestos textiles, floor tiles, roofing felts, insulating materials, and other asbestos building materials.

Extensive data indicate that excessive fiber concentrations existed in the production of asbestos products during previous years. In a study of retirees from one of the largest asbestos products manufacturers, Henderson and Enterline [1979] categorized work exposures according to total dust concentration (as measured by a midget impinger) times period of employment. Using recently obtained data on the conversion between such particle counts and fiber concentrations, it is estimated that the average concentration to which the members of his cohort were exposed was 30 fibers/ml [Asbestos Information Association, 1979]. Similar concentrations were suggested for the work force exposure in a large United States asbestos products manufacturer studied by Nicholson et al [in press]. Here subjective data, consistent with company measurements of dust concentrations, suggested that the person-weighted average exposure was approximately 25 fibers/ml between 1945 and 1965. In two asbestos insulation manufacturing facilities in Port Allegany, Pennsylvania, and Tyler, Texas, aver-

TABLE I. Selected Asbestos Products and Their End Uses*

Floor tile	Gaskets and packings	Friction products	Paints, coatings and sealants	Asbestos-reinforced plastics	Asbestos cement pipe
Office floors	Valve components	Clutch/transmission components	Automotive/truck body coatings	Electric motor components	Chemical process piping
Commercial floors	Flange components	Brake components	Roof coatings and patching compounds	Molded product compounds for high-strength/weight uses	Water supply piping
Residence floors	Pump components	Industrial friction materials			Conduits for electric wires
	Tank sealing components				

Asbestos textiles	Asbestos paper	Asbestos cement sheet
Packing components	Gas vapor ducts for corrosive compounds	Hoods, vents for corrosive chemicals
Gasket components	Fireproof absorbent papers	Chemical tanks and vessel manufacturing
Roofing materials	Table pads and heat protective mats	Portable construction buildings
Commercial/industrial dryer felts	Heat/fire protection components	Electrical switchboards and components
Heat/fire protective clothing	Molten glass handling equipment	Residential building materials
Clutch/transmission components	Insulation products	Molten metal handling equipment
Electrical wire and pipe insulation	Gasket components	Industrial building materials
Theater curtains and fireproof draperies	Underlayment for sheet flooring	Fire protection
	Electric wire insulation	Insulation products
	Filters for beverages	Small appliance components
	Appliance insulation	Electric motor components
	Roofing materials	Laboratory furniture
		Cooling tower components

*Source: Daly et al, 1976.

age concentrations of 35 fibers/ml were measured by NIOSH between 1968 and 1971 [National Institute for Occupational Safety and Health, 1972].

These concentrations were characteristic of early exposure levels in manufacturing industries. In recent years, considerable efforts have been made to reduce fiber concentrations. During 1975, air levels of from 0.5 to 4.0 f/ml were found to characterize most primary manufacturing processes (see below). With appropriate engineering, even asbestos textile manufacturing can be controlled to levels below 1.5 f/ml [Lewinsohn et al, 1979].

Since substantial asbestos exposure is involved in all production and maintenance operations in this industry, we have included all production and maintenance workers in our estimates of the population at risk.

Gaskets, packing and sealing devices industry (SIC 3293). This industry encompasses products made of asbestos, leather, metal, and rubber. Prior to 1972, asbestos was the predominant raw material used. A change in the industry classification system in 1972 expanded the definition of this industry to include products made of leather, metal, and rubber [Office of Management and Budget, 1972]. Since approximately one half of the employees of the newly defined industry were employed in plants manufacturing asbestos products, we have included one half of the production and maintenance employees since 1972 in our estimates of the population at risk. For years prior to 1972, we counted all employees in the at-risk group.

Building paper and building board mills (SIC 2661). This industry covers the production of asbestos paper, asbestos board, and sheeting and various types of papers and insulating boards used in building construction. Since approximately one half of the employees in 1972 were employed in construction paper plants (where asbestos was the principal raw material), we have included one half of the production and maintenance employees in our estimates of the population at risk.

Recent (1975) fiber concentrations measured in the primary asbestos manufacturing industry have been reported in the Asbestos Information Association-Weston submission to OSHA as a response to the October 1975 proposed revision to the asbestos standard [Daly et al, 1976]. These data indicate the following asbestos concentrations were present in the respective industry segments:

	1975 asbestos fiber concentrations (f/ml)	
Primary industry	Range	"Typical"
Asbestos paper	0.10– 2.8	0.75–1.9
Asbestos cement pipe	0.25– 4.5	0.50–2.2
Floor tile	0.25– 4.3	0.50–1.75
Friction products	0.10–22.0	1.00–3.3
Paints, coatings, and sealants	0.25– 8.0	1.00–2.5
Asbestos cement sheet	0.25– 8.7	1.00–3.0
Gaskets and packing	0.10– 2.5	—
Reinforced plastics	0.20– 3.0	0.75–2.0
Asbestos textiles	0.25–15.0	1.00–4.0

Secondary manufacturing. Secondary industries are those that receive products containing asbestos and further process, modify, or fabricate them to produce other intermediate or final products. The following industries involve such processes:

Heating equipment except electric and warm air furnaces (SIC 3433). This industry is engaged in the production of heating boilers; domestic furnaces and gas burners; and oil burners, space, and wall heaters, all of which tended to incorporate asbestos insulation in their construction. We have included one half of the production and maintenance employees in our estimates of the population at risk.

Fabricated plate workers (Boiler Shops) (SIC 3443). Establishments in this industry are engaged in manufacturing power and marine boilers, pressure and nonpressure tanks, processing and storage tanks, and heat exchangers and similar products, many of which include asbestos insulation. The subdivisions of this industry that utilize extensive asbestos insulation (heat exchangers and steam condensers; steel power boilers, parts and attachments; and nuclear reactor steam supply systems) accounted for approximately one half of the industry's total production workers in 1977. We have included one half of the production and maintenance employees in our estimates of the population at risk.

Industrial process furnaces and ovens (SIC 3567). This industry produces industrial process furnaces, ovens, induction and dielectric heating equipment, and related devices. All of the subdivisions make extensive use of asbestos insulation and all of the production and maintenance employees are included in our population at risk estimates.

Electric housewares and fans (SIC 3634). Establishments in this industry are engaged in manufacturing electric housewares for heating, cooking, and other purposes and electric fans. We estimate that 10% of the production and maintenance employees are at risk of asbestos-related disease.

Asbestos is used in a variety of other secondary industries. These include friction products, reinforced plastics, products containing asbestos paper, various industries manufacturing laboratory equipment, electrical switchboards, cooling tower components, fire protection materials, etc. It is impossible to extract the number of individuals in all secondary manufacturing from BLS data. The only published information is that from the Weston analysis done in cooperation with the asbestos industry [Daly et al, 1976]. They report the following 1975 employment data for secondary manufacturing industries, categorized by the primary source of asbestos:

Primary source of asbestos materials	Number of exposed employees
Asbestos paper	158,400
Friction products	27,600
Asbestos cement sheets	19,200
Gaskets and packings	12,000
Reinforced plastics	8,400
Asbestos textiles	6,000
Miscellaneous	8,400
Total	240,000

By comparison, our estimate of the asbestos-exposed employment during 1975 for the four industries listed previously (SIC 3433, 3443, 3567, and 3634) totaled 38,000. Moreover, only employees of companies manufacturing electric housewares and fans would appear to have been included in the Weston tabulations. However, it is difficult to be certain that their classification of primary and secondary is similar to ours. In their classification, they estimate 23,000 to be exposed in primary manufacturing in 1975 versus our estimate of 31,000.

Thus, some of our primary industry may be their secondary. It is difficult to estimate the exposures the individuals identified by Weston would have had. Some data are presented on current asbestos concentrations (see below). It is unlikely, however, that 158,000 employees would have had significant exposures during the manufacture of products containing asbestos paper. The data in the other manufacturing segments appear reasonable, however. To account for all these exposures, we will consider that a number equal to twice the four groups specified by SIC numbers are additionally exposed in secondary manufacturing. (This additional number totals 76,000 in 1975.)

Data provided by Asbestos Information Association-Weston on fiber counts in secondary manufacturing are:

Secondary industry[a]	Asbestos fiber concentration range reported (f/ml)
Asbestos paper	1.0–3.5
Friction products[b]	2.5–6.5
Asbestos cement sheet	1.0–6.0
Gasket and packing	0.2–5.0
Asbestos-reinforced plastic	0.5–2.0
Asbestos textiles	0.5–5.0

[a]Categorized by primary source of asbestos material.
[b]Does not include brake and clutch maintenance.

No information is available on dust counts in these industries in earlier years.

Shipbuilding and repair (SIC 3731). The risk of asbestos-related disease among shipyard workers was emphasized in 1968 by Harries, who reported five cases of pleural mesothelioma among employees of the Royal Navy Dockyard in Devonport [Harries, 1968]. His findings were noteworthy in that none of the patients was an "asbestos worker." They were employed in other trades (boilermaker, shipwright, laborer, welder, fitter) and worked in shipyards with asbestos workers but did not themselves often use asbestos. In addition, cases of asbestosis were noted. Stumphius described similar findings in the Netherlands [Stumphius, 1968]. Again, the mesotheliomas were among workers other than those in the usual asbestos trades. Since these initial communications, experiences have been detailed in many parts of the world identifying characteristic asbestos-associated disease among former shipyard workers, including pleural mesothelioma, peritoneal mesothelioma, asbestosis, and lung cancer. Evidence of asbestos-associated disease has been reported among workers employed in United States shipyards during and after World War II [Department of Health, Education, and Welfare, 1981; Felton, 1979; Selikoff, 1965]. These findings indicate that the nature of shipyard work during this period provided significant opportunity for exposure to asbestos of the many trades employed, even though such exposure might have been only intermittent or indirect.

We have included all production and maintenance employees of private and naval shipyards in our estimates of the population at risk. The estimates for naval shipyards, however, are taken from the United States Department of the Navy [Nunneley, Department of the Navy (Personal Communication, 1980)].

Construction. The construction industry accounts for an estimated 70%–80% of total United States consumption of asbestos fiber [Levine, 1978]. Substantial direct exposure to asbestos occurs in the following subdivisions:

1. General contractors—residential buildings other than single family (SIC 1522).
2. General building contractors—nonresidential buildings (SIC 154).
3. Water, sewer, pipe line, communication, and power line construction (SIC 1623).
4. Construction—special trade contractors (SIC 17, except 1771 [concrete work], 1781 [water well drilling], 1791 [structural steel erection], 1794 [excavating and foundation work], 1796 [installation or erection of building equipment, not elsewhere classified]).

Among the asbestos products involved in direct exposures in construction work are asbestos-cement pipe installation; asbestos-cement sheet installation; architectural panel installation; built-up roofing installation; drywall removal, replacement, and installation; removing of roofing felts; asbestos insulation of pipe, tubing, heating units, and electric power generation equipment; paints, coatings, and sealants. In addition to the direct exposure resulting from the use of the above products, construction workers have been subject to considerable indirect exposure to asbestos as a result of the practice of spraying asbestos insulation in multistoried structures during the period 1958–1972. An investigation of the spraying of mineral fiber insulation material in New York City collected on-site samples taken at various distances from the spraying nozzle. It showed fiber counts ranging from 70 f/ml 10 feet from the nozzle to 3 f/ml 25 feet away [Reitze et al, 1972]. Workers in occupations not directly involved in spraying (carpenters, electricians, pipefitters, plumbers, welders, and others) who were on construction sites during or after such spraying are at risk to asbestos-associated disease.

We have included all construction workers in SIC 1522 and 154 in our estimates of the population at risk and the following proportions of the workers in other construction subdivisions:

SIC 1623. Thirty percent of the water distribution pipe sold in the United States in 1974 was asbestos cement [Meylan et al, 1978]. We assumed that this proportion of the workers in the water, sewer, etc, line construction industry is exposed to asbestos from asbestos-cement pipe. In addition, we included maintenance mechanics and helpers employed in SIC 16 (construction other than building construction) to reflect the fact that these workers are exposed to asbestos during the repair of brakes on heavy construction equipment [Hill, 1980]. These workers comprise approximately 5% of the total number of construction workers in SIC 16 [Bureau of Labor Statistics, unpublished].

SIC 17. We have included all construction workers in 171 (plumbing, heating [except electrical], and air conditioning) and SIC 172 (painting, paperhanging, and decorating) in our estimates of the population at risk. The former group has extensive exposure to asbestos in pipe covering and insulation for heating and ventilation equipment. A mortality study of the members of the union of plumbers and pipefitters in the United States noted their potential exposures to asbestos and found significant excesses in proportional mortality ratios for malignant neoplasms of the esophagus, respiratory system, lung, bronchus, and trachea, and "other sites." [Kaminski et al, 1980]. Seven deaths were due to mesothelioma, a clear indicator of asbestos-associated disease.

The latter group (painting, paperhanging, and decorating) has been exposed to many asbestos-containing materials, including spackle compounds used by general painters, taping and joint compounds used in drywall construction, and additions of asbestos to sealant compounds or surfacing materials. Moreover, these workers have indirect exposure to asbestos materials used by other trades in the construction industry. A study of drywall taping workers employed in the New York metropolitan area found mean asbestos fiber concentrations ranging from 5.3 f/ml in hand-sanding to 47.2 f/ml in dry mixing operations [Fischbein et al, 1979]. Other researchers report mean fiber concentrations of from 0.9 to 19.6 f/ml during various activities of drywall taping [Verma and Middleton, 1980]. In addition to the tapers and painters directly engaged in these operations, members of all the construction trades working in the vicinity of ongoing drywall construction were significantly exposed. Mean fiber concentrations varying from 2.3 to 8.6 f/ml were observed at distances from 3 to 20 feet from the taping operation in the same room. In adjacent rooms, background mean fiber levels varied from 2.6 to 4.8 f/ml at distances from 15 to 25 feet from the taping operations.

For the remaining groups covered by SIC 17 (except the five groups identified under 4 above as not being substantially exposed), we have estimated that the proportion of the construction workers at risk during 1958–1972 was 50% (when multi-storied buildings were sprayed with asbestos fireproofing material) and 20% during 1940–1957 and 1973–1979. The following proportions of these groups were found to be exposed to asbestos in the National Occupational Hazard Survey [National Institute for Occupational Safety and Health, unpublished]:

SIC code	SIC description	% Employees exposed to asbestos
173	Electrical work	15
174	Masonry, stonework, tilesetting, and plastering	27
175	Carpentering and flooring	15
176	Roofing and sheetmetal work	41
1793	Glass and glazing work	40
1795	Wrecking and demolition work	NR
1799	Special trade contractors, not elsewhere classified	23

NR, Not reported.

It should be noted that the above percentages understate the proportions of "construction workers" exposed to asbestos in these industries since they are based on the total employment reported rather than total construction workers; the latter concept excludes executive and managerial personnel, professional and technical employees, and routine office workers [Bureau of Labor Statistics, 1976].

Electric, gas, and combination utility services (SIC 491, 492, 493). Power generating facilities have many work areas with elevated temperatures, which have been insulated with asbestos-containing materials, including preformed blocks of hydrous calcium silicate insulation reinforced with asbestos fibers. Other insulation used in this industry consists of asbestos boards, blankets, felts, cloths, tapes, sleeves, and cements that contained various quantities of asbestos [Fontaine and Trayer, 1975]. Studies conducted in England [Bonnell et al, 1975] and France [Fontaine and Trayer, 1975] have found substantial evidence of asbestos-associated disease among persons engaged in maintenance work at power stations, including persons not directly involved in applying or removing insulation materials. We have included one quarter of the "physical workers" employed in electric and gas utilities in our estimate of the population at risk: 10% representing maintenance workers and 15% other persons in the area who are indirectly exposed [H. Jones, 1980].

Occupational groups. The industrial activities for which employment statistics are gathered do not correlate closely with those in which there is occupational contact with asbestos. It has been necessary, therefore, to supplement the estimates derived from the above analysis of industrial employment statistics with estimates of the number of persons employed in particular occupations (crossing industry lines) where significant asbestos exposure has occurred. We have reduced the industry estimates of persons at risk by the numbers employed in the selected occupations to avoid double-counting. The following occupational groups were defined as at risk:

Asbestos and insulation workers. A strikingly increased death rate of lung and other cancers has been observed among a group of asbestos and insulation workers [Selikoff et al, 1979]. All such individuals have significant risk.

Data are available from three research groups on average fiber concentrations in insulation work prior to 1970, when the techniques of application and control measures used were typical of the industry during previous years [Balzer and Cooper, 1968; Ferris et al, 1971; Murphy et al, 1971; Nicholson, 1975]. The data are presented in terms of time (and job-weighted) average concentrations. During certain operations (cement mixing, hand- or band-saw cutting, removal), extremely high concentrations were observed (up to 100 f/ml). However, these operations constituted only a small fraction of the insulators' work activity. Data were also estimated for earlier years when the asbestos content of insulation was twice that of 1965–1970.

Summary of Average Asbestos Air Concentrations During Insulation Work

	Average fiber concentration (f/ml)	
Research group	Light and heavy construction	Marine work
Average concentrations of fibers longer than five micrometers evaluated by membrane filter techniques and phase-contrast microscopy		
Reitze-Nicholson, Mount Sinai [Nicholson, 1975]	6.3	
Balzer-Cooper, U. of Calif. [Balzer and Cooper, 1968]	2.7	6.6
Burgess-Lynch, Harvard [Ferris et al, 1971]		2.9

Average concentrations of all visible fibers counted with a konimeter and bright-field microscopy		
Murphy, Harvard [Murphy et al, 1971]		8.0
Fleischer, US Navy [Fleisher et al, 1946]		30–40
Estimates of past exposure based on current membrane filter data		
Nicholson, Mount Sinai [Nicholson, 1975]	10–15	

Automobile body repairers and mechanics. A study of brake-lining maintenance and repair work has found short-term concentrations of asbestos of 16.0, 3.3, and 2.6 f/ml at distances of 3–5 feet, 5–10 feet, and 10–20 feet, respectively, from a worker blowing dust out of automotive brake drums [Rohl et al, 1976]. Grinding truck brake-shoes gave an average concentration of four f/ml and bevelling produced an average count of 37 f/ml. Measurable concentrations (0.1 f/ml) were found at distances up to 75 feet from the blowing-out operation (14 minutes after), 60 feet from grinding and 30 feet from bevelling, indicating that other garage employees besides those directly involved in brake and clutch repair are at risk.

Average fiber concentrations during brake and clutch work, however, are much lower and average about 0.1–0.3 f/ml during the course of an entire brake repair job. These data and the sources are:

Summary of Asbestos Concentrations During Automobile and Truck Brake Maintenance Activities: Long-Term Samples During Lining Removal and Replacement

Source	Range of all concentrations measured (f/ml)	Range of garage mean concentrations (f/ml)
	Personal	
NIOSH [R. Zumwalde, personal communication] Sampling may have been done during non-brake work. No information on work practices.	0.01–3.24	0.03–0.59
Hickish and Knight [1970] Appears typical of past work practices with air blowing of drums. Sampling throughout complete brake repair job.	0.08–7.09	0.68–3.1
Raybestos-Manhattan [J. Marsh, personal communication] Well-controlled exhaust ventilation utilized.	0.02–0.4	0.05–0.1

	Area	
NIOSH [R. Zumwalde, personal communication]	0.01-1.72	0.1 -0.57
Hickish and Knight [1970]	0.07-0.28	0.15

Initial clinical surveys of garage mechanics indicate that they have a small excess prevalence of X-ray abnormalities (~5%) compared with blue-collar control groups, in agreement with the dust count information above [Nicholson, 1982].

Engine room personnel, seagoing vessels, United States Merchant Marine. The potential for exposure to asbestos insulation material on merchant ships is not confined to the shipyards where the ships are built or repaired. After the vessels have been put to sea, flaking and cracking of the asbestos insulating materials covering machinery casings, steam and hot water piping, and tanks are common. In the course of a voyage, crewmen make repairs on pipes, pipe flanges, or valve leaks. This generally requires tearing down the insulation materials and replacing them [Polland, unpublished]. A study of 6,671 X-ray films of marine engineers in the United States showed an unusually high proportion (16%-20%) of pleural abnormalities, indicating the adverse effects of inhaled asbestos. [R.N. Jones, 1980]. We have included all engine room personnel on seagoing vessels of the Merchant Marine in our estimates of the population at risk.

Maintenance employees: Chemicals and petroleum manufacturing. The manufacturing processes of chemical production and petroleum refining involve the use of extensive networks of pipes, boilers, and other high temperature equipment. Asbestos materials provide thermal insulation for these networks and a large force of maintenance workers is employed to maintain and repair the production equipment. A study of maintenance workers in a large chemical plant and an oil refinery showed relatively frequent chest X-ray abnormalities [Lilis et al, 1980]. These findings strongly suggest that asbestos exposure characteristic of maintenance work in chemical plants and in oil refineries, including indirect ("bystander") exposure, results in risks comparable to those documented for other types of asbestos exposure in other industries and occupations. We have included all maintenance workers in the chemicals and allied products (SIC 28) and petroleum refining and coal products (SIC 29) in our estimates of the population at risk.

Steam locomotive repair. Employees engaged in the overhaul of railroad engines during the period when steam locomotives were in service were heavily exposed to asbestos. The practices used in the "back shops" where overhauls were conducted, resulted in the generation of clouds of asbestos dust that contaminated the environment of all who worked in the area [Mancuso, 1976]. Five mesotheliomas have recently been identified by NIOSH among former employees of one shop in Reading, Pennsylvania We included all employees of railroad repair back shops in our at-risk estimates for the decade of the 1940s (when steam locomotives were the predominant type). For the 1950s (when the proportion of all locomotives in service which were steam declined from 63.4% to 1.7%), we reduced the annual number of employees at-risk by the annual proportion of nonsteam locomotives to all locomotives.

Stationary engineers, stationary firemen, and power station operators. Operation and maintenance of stationary engines and mechanical equipment to provide utilities for buildings and industrial processes involve the same types of exposure to asbestos-containing materials as are described above under electric, gas, and combination utility services. A preliminary field survey of 34 stationary engineers by this laboratory in the New York metropolitan area has found X-ray abnormalities consistent with asbestos-induced changes in 60% of the employees with more than 20 years of experience in this trade. We have included all employees in this occupational group in our estimates of the population at risk.

Population Estimates

In estimating the mortality (or morbidity) from past exposure to asbestos, we would wish information on the number of individuals exposed; the distribution of their employment periods; the time, duration, and intensity of the asbestos concentrations to which they were exposed; and mortality data, by industry, correlated with the above variables. Unfortunately, we have little of the above data. There are limited data on the number of individuals exposed to asbestos in different calendar periods of time. For some industries data are good (primary asbestos manufacturing, shipbuilding, auto repair and, to a lesser extent, insulation work). Much less certain are data on exposed populations in construction, secondary manufacturing, and the maintenance industries. Least certain is information on the turnover in a given industrial segment. Exposure data are available in recent years, but generally only from a limited number of measurements in an industry. Extrapolations to earlier years are possible but necessarily uncertain. Of most use are current data on the mortality of entire population groups exposed in previous years. Such information, if related to exposure periods, eliminates our need for information on exposure distributions as the mortality data for an entire group includes all exposure circumstances.

Further, as will be demonstrated subsequently, several studies show that the risk of lung cancer is linearly related to the total fiber exposure. This information allows one to properly account for different durations of employment in a given industry. Moreover, for the purposes of estimating excess mortality, it also reduces our need for accurate information on work force turnover within an industrial segment. The excess mortality for 1,000 men exposed for ten years is the same as for 2,000 men exposed for five. The important parameter is the person-years-at-risk. Thus, information on the total work force exposed at various points in time is much more important than information on turnover. However, for consideration of surveillance activities, one would wish knowledge of the total population at risk. This can be estimated, but greater uncertainties exist in the values obtained than in the number of asbestos-related cancers that might develop.

Methodological Considerations

Considerable information is available from data published by the Bureau of Labor Statistics and from industry or union sources on the number of individuals employed in an industry at periods of time. Data from publications of the Department of Labor also provide some information on the number of individuals entering or leaving a given industry on a yearly and monthly basis. For some industries subsequent to 1958, this includes information on the fractional number of accessions and separations that occurred for given employees within a calendar period. Often data are provided on the total fractional number of new hires, recalls, layoffs, and quits. While the information on the fractional number of new hires is of use to us in estimating the population entering a given industry, it does not represent true new hires for our purposes. This is because the industry data are based on individual establishment experiences. A new hire for an establishment may be an individual who previously worked in another establishment in the same industry. For some manufacturing industries, this may not be too great a duplication, but for construction trades particularly, it represents significant duplication.

To estimate the population at risk for a period of years, it would be most desirable to have information on the number of new employees entering a given occupation or industry at different points in time and information on the number of individuals currently leaving that occupation or industry permanently. If N = the number in an industry, α = the fractional number of new entrants in an occupation or industry in a given year (N_{new}/N_{tot}), and β = fractional number leaving an occupation or industry permanently, the change in an industry work force can be represented by $dN = N \times (\alpha - \beta)dt$.

For small changes in N, $N = N_0e^{(\alpha - \beta)t}$. In this model, in the absence of new entrants into an industry, the work force will decrease with a half-life, $T_{0.5} = 0.693/\beta$. In the absence of any separations, it will increase with the doubling time, $T_2 = 0.693/\alpha$. In any steady-state or near-steady-state situation, where $\alpha = \beta$, the average duration of employment is equal to $1/\alpha$. When one considers finite changes over a year period of time, $\Delta N = (\alpha - \beta)N$, where ΔN is the net increase or decrease. Thus, $\alpha = \beta + (\Delta N/N)$. If we consider the time necessary to achieve complete replacement of a work force in a steady-state situation, $\Delta N = N = \alpha NT$. Thus T, the time necessary for work force replacement is equal to $1/\alpha$ as expected from the earlier consideration of continuous changes. As indicated previously, we will be using information on the number of new entrants into a trade or industry, coupled with their average period of employment, to generate estimates on the expected excess mortality from past exposure to asbestos. The excess mortality among a group of individuals entering an industry during a decade will be proportional to $\alpha N \times T$ (new hires $\times$ employment period) $= k\alpha N \times 1/\alpha = kN$, where k, the proportionality constant, includes the appropriate risk and exposure variables for the industry. *Thus, the crucial item in estimating mortality in a steady-state work situation is information on the number employed in an industry rather than the number of new hires entering it.* More detailed information is only necessary if there are significant changes in the workforce over the period of time being considered.

Asbestos-Exposed Work Force

The data on the population exposed to asbestos in different industries has been estimated using the Bureau of Labor Statistics information on employment and earnings in the United States, 1909–1978. Here direct data are available on the yearly employment in the following industries under consideration: primary asbestos manufacturing; selected secondary asbestos manufacturing industries; construction; electric, gas and utility services; and chemical and oil refining employees. The segments of these industries that will be considered at risk have been described previously.

We used employment series published by the Bureau of Labor Statistics [1979] as the basis for estimating the number of persons employed. Where the data do not extend as far back as 1940, we extrapolated the BLS series to that year on the basis of regression equations with related variables (Table II) or on the assumption of a straight-line trend between Census Bureau data for 1939 (Census of Manufacturers) or 1940 (Census of Population) and the earliest year of the relevant BLS series.

In the construction industry, the employment data relate to "construction workers." This group covers "workers up through the level of working supervisors, who are engaged directly on the construction project either at the site or working in shops or yards at jobs ordinarily performed by members of construction trades. Exclusions from this category include executive and managerial personnel, professional and technical employees, and routine office workers" [Bureau of Labor Statistics, 1976].

In electric, gas, and combination utility services, the employment data relate to "physical workers." This group includes working foremen and other nonsupervisory workers engaged in nonoffice functions [Department of Labor, 1979].

In manufacturing industries (including private shipbuilding and repair), the employment data relate to "production workers." This group covers those employees, up through the level of working supervisors, who are engaged directly in the manufacture of the product. Among the exclusions from this category are persons in executive and managerial positions, those engaged in office work, and professional and technical functions [Bureau of Labor Statistics, 1976].

In the chemicals and allied products industry, it was estimated that 27% of the BLS employment figure represented maintenance workers. This proportion was calculated from the BLS Reports on 1971 occupational employment in this industry [Bureau of Labor Statistics, 1974]. The following classifications were excluded from the maintenance occupations to avoid duplication: insulation workers, stationary engineers, stationary boiler tenders.

In petroleum refining and coal products, it was estimated that 40% of the petroleum refining production employees and 20% of the production employees in the remaining divisions of the industry represented maintenance employees [Bureau of Labor Statistics, 1965]. The 1940 employment in the industry was estimated on the basis of a straight-line interpolation between the 1939 figure reported by the Bureau of the Census [1939], and the 1944 BLS figure. The same maintenance occupations were excluded as is noted under chemicals (above) to avoid duplication.

Data are not available that allow direct use of BLS employment data to estimate the number of individuals employed in insulation work, shipbuilding, automotive maintenance, merchant marine engine room work, and steam locomotive repair. Sepa-

TABLE II. BLS Employment Series Extrapolated to 1940 by Means of Regression Equations

Series to which extrapolation was applied	Related variable used for estimation	Measure of validity (r^2)
Construction—general building contractors: construction workers (SIC 15)	Construction—all employees 1964–1973 (SIC 15, 16, 17)	0.97
Construction—other than building general contractors: construction workers (SIC 16)	Construction—all employees 1960–1971 (SIC 15, 16, 17)	0.68
Construction—special trade contractors: construction workers (SIC 17)	Construction—all employees 1947–1956 (SIC 15, 16, 17)	0.99
Electric, gas, combined utilities employed	Production of utilities 1950–1959	0.84
Manufacturing: heating equipment excluding electrical: production workers	Manufacturing—fabricated structural metal products: production workers, 1972–1979	0.61

rate data are available in these industries from union sources, trade associations, the US Navy, and other government sources.

Insulation workers. For this important group of asbestos-exposed individuals, we will utilize information from the International Association of Heat and Frost Insulators and Asbestos Workers (IAHFIAW) to estimate the work force at any time and the new entrants into the trade [International Association of Heat and Frost Insulators and Asbestos Workers, unpublished; R. Steinfurth, personal communication]. The data available from the union are presented in Table III, which provides information on the cumulative entrants into the union, reduced by the number of Canadian members. Also available are data on the actual union membership in recent years and the number of new entrants and separations on an annual basis. For the years prior to 1960 where such data are uncertain, the estimates of Union membership were extrapolated from the trend available in the years 1960–1980. A small correction to the union membership is made for the estimated number of retired members over age 65. This correction is a small one because the high mortality in this trade limits the number who attain age 65.

The number of union construction insulation workers in Table III is increased by 40% for the years subsequent to World War II to account for workers employed on union jobs on a temporary (permit) basis and by an amount equal to the union membership to account for construction insulation workers not so represented. For the year 1940, few individuals would have been employed on permit because of the scarcity of jobs at that time. However, during World War II, a large number of insulators were so employed, particularly in shipyards. Data suggest that 0.2% of the wartime shipyard work force of 4,500,000 men and women were insulators. Thus 9,000 individuals would have been employed for approximately one year in this industry.

Unpublished data from the Bureau of Labor Statistics estimates that 31,900 men were at work during the spring of 1978 as insulation workers in construction and an additional 19,100 employed in industry elsewhere.[1] The 31,900 estimate from Bureau of Labor data is a reasonable agreement with the 38,900 estimate using union information as described above. Short-term layoffs during 1978 could well account for at least 10% of the work force. We will use the mean of the Bureau of Labor Statistics estimate and the estimate from union data as the value for construction insulation workers. This will decrease the values in Table III by 8.3%. The adjusted total number of construction insulators will then be increased by 54.4% (19,100/35,900) to account for insulators employed in maintenance elsewhere.

Shipbuilding and repair. BLS data awre available on civilian production shipyard workers. The number of employees in Naval shipyards was obtained from data of the US Navy [J.K. Nunneley, Department of the Navy, personal communication, April 22, 1980]. This information is listed in Table IV. While the Navy estimates that only 50% of the yard work force is exposed to asbestos, the data on mortality and morbidity that we will use estimates risk for all shipyard workers as a group. We will utilize, therefore, the percentage of civilian yard workers that are production employees for the Naval shipyard considered to be exposed to asbestos. (This ranges from 92% in 1950 to 80% in 1975). In estimating the shipyard employment for 1945, we have used a value of 175,000, which is intermediate between 1940 employment and that of the years subse-

[1]Based on the ratio of 1978 total employment reported by BLS (51,000) to the number employed in construction (31,948), an unpublished BLS estimate.

TABLE III. Insulator Work Force and New Hires Using Data From the International Association of Heat and Frost Insulators and Asbestos Workers*

Year	Cumulative new members (January)	Estimated union membership	Membership as a percentage of cumulative membership[a]	Estimated percentage of retired (> age 65)	Estimated percentage of Canadian membership	Estimated IAHFIAW active US membership	Estimated number of construction insulators
1940	9,100	6,280	69.0	2.5	0.0	6,120	12,250
1945	12,580	8,300	66.0	2.7	3.0	7,830	18,800
1950	16,360	10,310	63.0	3.0	3.1	9,690	23,260
1955	22,150	13,290	60.0	3.5	7.0	11,930	28,630
1960	26,800	15,750	58.7	4.0	8.0	13,910	33,380
1965	31,000	17,720	57.2	4.5	8.6	15,470	37,120
1967	32,700	17,800	54.4	4.9	9.9	15,250	36,610
1970	35,400	18,500	52.3	5.0	12.0	15,470	37,120
1975	41,000	19,800	48.3	5.5	14.0	16,090	38,620
1978	44,400	20,200	45.5	6.0	16.0	15,950	38,280
1980	46,600	20,000	42.9	6.0	16.6	15,680	37,630

*Source: Roy Steinfurth, Director, IAHFIAW Health Hazard Program (personal communication).
[a]Extrapolation from 1955 to 1940 was based on the trend of this parameter.

quent to World War II. We will consider this to be the "permanent" work force that would have been employed in the absence of World War II. During that conflict, it is estimated that an additional 4,325,000 men worked in shipyards for short periods of time [Selikoff and Hammond, 1978]. Their mortality and that of 9,000 wartime shipyard insulators will be estimated separately.

Automobile maintenance and repair. Mechanics exposed to asbestos during brake and clutch maintenance are included in SIC 75, auto repair, services and garages and SIC 515-2, new and used car dealers, and some in SIC 554, gasoline service stations. As it is not possible to separate mechanics from other employees in these categories, we have used census data of the number of individuals employed as mechanics in auto maintenance and auto body repair. Intercensus data were developed using a linear interpolation. See Table V for the basic data utilized.

Railroad steam locomotive repair. We have utilized employment data reported by the Association of American Railroads for occupations exposed to asbestos during the maintenance of steam railroad locomotives. This was done by reducing the number of men classified in equipment and stores [Association of American Railroads, annual] by 45% to reflect the proportion of the total craftsmen accounted for by the carmen classification. (Carmen were generally engaged in maintenance of railway cars rather

TABLE IV. Estimated Population at Work in United States Naval Shipyards, 1940–1979 (in thousands)*

Years	Employed at start of quinquenium	Estimated accessions during quinquenium
1940–1944	72	480
1945–1949	335	267
1950–1954	71	132
1955–1959	112	68
1960–1964	96	73
1965–1969	81	93
1970–1974	82	47
1975–1979	60	55

*Source: JK Nunneley, United States Department of the Navy (personal communication, April 22, 1980).

TABLE V. The Population Exposed to Asbestos in Automobile Maintenance and Repair

Year	Census[a] data (thousands)	Motor[b] vehicle registrations (millions)	Interpolated population at risk
1940	372	33	372
1945		32	370
1950	647	50	647
1955		63	655
1960	661	74	661
1965		92	800
1970	912	108	912
1975[c]		133	1,100

[a]Includes auto body repairmen.
[b]From Highway Statistics (annual) US Federal Highway Administration.
[c]Weston estimated that 900,000 workers were continuously exposed to asbestos in automobile brake repair and 1,070,000 were exposed occasionally or infrequently.

than locomotives.) The remaining number was reduced by 50% to exclude employees who were located at maintenance facilities other than "back shops" [DeHague, 1980]. The balance was reduced by 11% to exclude salaried supervisors, coach cleaners, and stores laborers. As described previously, the resulting number for the years 1950–1960 was reduced by the percentage of steam locomotives in service. These data are listed in Table VI.

A summary of the employment data for all of the previously mentioned occupations is given in Table VII for five-year intervals. The data are quite stable for the years 1950–1980 and well reflect both employment and its trend with time. One exception is the 1950 value for shipbuilding which is unrepresentative; for the five years, 1948–1952, employment averaged 189,000.

TABLE VI. Employment, Maintenance of Equipment and Stores, Class I Railroads

Year	Numbers of[a] employees (in thousands)	Locomotives[b] in service steam (in thousands)	diesel	Percentage steam	Exposed employees
1940	281	41.1	0.5	98.8	69
1945	387	39.7	3.0	93.0	95
1950	348	26.7	15.4	63.4	54
1955	273	6.3	26.6	19.1	13
1960	184	0.5	29.1	1.7	1

[a]Association of American Railroads, 1940–1960.
[b]Association of American Railroads, Annual, and Interstate Commerce Commission, 1961, 1958,

TABLE VII. Employed Populations Potentially Exposed to Asbestos in Selected Occupations and Industries, 1940–1975

Industry of occupation	Number employed in calendar year (in thousands) 40	45	50	55	60	65	70	75
Primary asbestos manufacturing	23	32	35	37	35	35	32	31
Secondary asbestos manufacturing	30	60	75	75	84	93	108	114
Insulation work[a]	17	27[b]	33	41	47	53	53	55
Shipbuilding and repair	157	175[c]	128[d]	194	184	185	181	177
Construction trades	426	379	741	893	1,102	1,215	1,341	1,029
Railroad engine repair	69	95	54	13	1	0	0	0
Utility services	44	62	62	65	65	64	69	74
Stationary engineers and firemen	295	303	311	348	385	289	291	293
Chemical plant and refinery maintenance	113	194	186	200	188	187	205	200
Automobile maintenance	372	370	647	655	661	800	912	1,100
Marine engineer room personnel (except US Navy)	34	76	37	37	34	35	31	22
Totals	1,880	1,773	2,309	2,558	2,766	2,956	3,223	3,095

[a]Insulators are included here and not in other trades in which they were employed, such as shipbuilding, construction, plant maintenance, or power generation.
[b]Does not include any of the 9,000 temporary wartime insulators in the shipbuilding industry.
[c]Estimate of "permanent" shipyard work force. Does not include any of the 4,325,000 temporary wartime shipyard workers.
[d]Unrepresentatively low value; average for 1948–1952 was 189.

New Entrants Into the Work Force 1940–1980

Data on the number of additions to the employment rolls in various manufacturing industries are reported monthly by the Bureau of Labor Statistics [1979]. However, BLS does not report cumulative annual rates for "new hires." Moreover, the BLS data refer to persons hired by individual establishments in each industry, not the number hired by the industry as a whole. There may be considerable duplication of persons involved in the new hires reported on a monthly basis over a year's time. There is additional duplication involved in counting new hires in a particular establishment who were previously employed in another establishment of the same industry. It was, therefore, necessary for us to develop a measure for estimating the unduplicated new hires in each industry for each year.

This was done by comparing the number of new hires obtained for major industry groups with data available from the continuous work history sample of the Social Security Administration (SSA) for the years 1957–1960 [Galloway, 1967]. Unfortunately, data are only available for major industry groups such as durable and nondurable goods manufacturing, construction, transportation, and services. Detailed information for individual industries is not provided. Information on the number of individuals who were employed in 1960 and were also employed in the same industry in 1957 is given in Table VIII. This allows one to calculate an annual transfer rate from one industry group to another but not from one industry to another within an industry group (eg, from the manufacture of asbestos products to the manufacture of bolts, nuts, and rivets). Bureau of Labor Statistics data on the permanent retirement or death in each of these industries are also available from Bureau of Labor Statistics publications. In a steady state, the SSA separation rate plus the annual rate of retirement and deaths would equal the new hire rate. As three years is a relatively short follow-up, there would be some transfers back to an industry group after the observation period. The correction for this, however, would be relatively small and somewhat compensates for the greater adjustment required to account for transfers between industries within an industry group.

The SSA data are shown in Table IX and compared with the annual rate of new hires from the Bureau of Labor Statistics data for the years 1958–1960, corrected by the increase or decrease in the total work force over the three-year period of time (January 1958–January 1961). The correction consisted of attributing the annualized change in work force between 1958 and 1961 to a change in the number of new hires. Terminations are much less affected by work force changes and then only with severe conditions. The corrections were virtually all less than 10%.

In comparing the data obtained in this manner from the Social Security Administration with that estimated using BLS new hires, fractional employment additions in the chemical industry and oil refinery operation closely matched the fractional number of transfers from the nondurable goods industry (0.166 and 0.132 vs 0.111). For these industries, we will utilize the Bureau of Labor Statistics data on new hires in SIC 28 or SIC 29 reduced by 30% to reflect possible transfers within these respective industries. Transfers are expected to occur inasmuch as the industries are concentrated within geographic areas and movement from one company to another is expected. This reduces the new hire rate for oil refineries to a value less than that for the nondurable goods industry as a whole. However, both oil refinery and chemical manufacturing have much less labor turnover than other industries in the nondurable goods manufacturing segment.

TABLE VIII. Industry of Major Job: Male Wage and Salary Workers Employed in Both 1957 and 1960 (Based on 1% Sample of Social Security Administration Data)*

Wage and salary workers employed in both 1957 and 1960	Manufacturing			Construction	Transportation, communications, public utilities	Services
	All	Durable goods	Nondurable goods			
All workers whose major job was in this industry in 1957	123,713	78,458	45,255	27,603	22,507	30,019
Industry of major job in 1960 the same as in 1957	102,854	63,676	34,653	19,280	17,906	20,778
Annualized "permanent" separations from work sector	0.063	0.072	0.093	0.127	0.079	0.130

*Source: Interindustry Labor Mobility in the United States 1957 to 1960 [Galloway, 1967].

TABLE IX. The Average Fractional Number of New Hires Entering a Specific Industry Group Each Year During the years 1958–1960

Industry	Change of industry from SSA continuous work history	Retirements and deaths	Annual permanent transfers from industry	BLS data on new hires	SIC group used for BLS estimate
All manufacturing	0.063	0.018	0.081	0.280	20–39
Durable goods manufacturing	0.072	0.018	0.090	0.265	24–25, 32–39
Primary asbestos products				0.343	329[a]
Secondary asbestos products					
Heating equipment				0.240	343[b]
Boiler shops				0.290	3443
Furnaces and ovens				0.159	356
Electrical housewares				0.199	363
Shipbuilding and repair				0.432	3731
Construction	0.127	0.020	0.147		15–17
Insulation work (IAHFIAW)				(0.030)	
Other construction workers				NA	
Nondurable goods manufacturing	0.093	0.018	0.111	0.303	20–23, 26–31
Chemical plant maintenance				0.166	28
Oil refinery maintenance				0.132	29
Transportation and public utilities	0.079	0.020	0.099	NA	491–493
Marine engine room personnel				NA	
Services (stationary engineers)	0.130	0.025	0.155	NA	
Auto mechanics	0.130	0.013	0.142	NA	

[a]New hires were estimated using durable goods new hires adjusted for the relationship between 329 and durable goods for the years 1972–1979.
[b]Production work force for the years 1958–1960 was based on durable goals and the relationship between 343 and durable goods for the years 1972–1979.
NA, not available.

For primary and secondary asbestos manufacturing, it would be expected that there would be less transfer between similar companies. This occurs because of the widespread geographical distribution of the respective plants. Individuals terminated by one company would unlikely be hired by another manufacturer in the same industry. Thus, we will adopt a value for the new hires in primary and secondary manufacturing that would be equal to 80% that of the Bureau of Labor Statistics data. It would be expected that a greater percentage of terminated shipyard employees would be rehired by other yards or by the same yard at some later date. This occurs because of the highly fluctuating nature of shipyard business, depending as it does upon large contracts of uncertain frequency. Thus, for shipyard employees we will adopt a value of 50% of the Bureau of Labor Statistics' new hires rate for SIC 3831. The rate of new hires for 1958–1960 is, thus, 0.216. This compares with 0.138 estimated by the US Navy for naval shipyards in these years. The agreement is reasonable as turnover in government shipyards is considerably less than in civilian yards.

Individuals employed in construction trades (except insulation work), stationary engineers and firemen, and automobile mechanics are a highly mobile segment of the work force. However, they would tend to maintain employment in their respective trade, simply moving from one employer to another. Therefore, we feel that the Social Security Administration data on labor turnover well represent the members of these industries. It is felt that termination from employment in utility services, however, is less likely to lead to employment in a corresponding industry and data on new hires using Social Security Administration information would underestimate the actual percentage. Thus, we have increased the SSA new hires estimate by 50%. The sources of all new hire data are listed in Table X. For those industrial segments where the numbers of new hires are not provided, the new hires for all manufacturing are utilized adjusted by the ratio of new hires as determined by Social Security Administration data, 1958–1960, to new hires in the corresponding years for all manufacturing.

The number of new hires for insulation workers will utilize the data on new entrants into the insulation workers' union from their membership (column 1 of Table III). We will use the same acquisition data proportionately for the nonconstruction insulators, as data from the chemical and refining industry indicate average employment periods nearly equal to those of insulators. However, the turnover for those on permit and employed as nonunion workers is likely to be considerably higher. We have no information on what their turnover may be relative to union insulators but a value twice as great would appear to be reasonable. To account for this, we will increase the IAHFIAW new hires by 0.8 to account for permit workers, by 2.0 to account for nonunion new hires and by 1.2 for nonconstruction insulators. Thus the total insulator new hires will be five times the IAHFIAW US new members. The 9,000 wartime shipyard insulation workers employed for one year are also included in the new hires for the 1940–1949 decade. Their mortality, however, will be calculated separately as will that of other wartime shipyard workers.

It should be emphasized that these estimates are approximate and subjective. They are felt to be the best basis for estimating the number of new individuals that enter a given industrial segment and are important in estimating the total number of individuals potentially exposed to asbestos. As discussed previously, however, their influence on the total mortality experience from past exposure will be small. A misestimate on the new hires rate will lead to a balancing increase or decrease in the average employment time. These annual new hire rates were applied to annual employment data for each occupation and industry to arrive at estimates of the number of new persons exposed to asbestos on the job in each year. The data were then cumulated for each decade since 1940. In those industries in which a significant portion of the employees were already included in our tally under an occupational group (asbestos and insulation workers; stationary engineers, stationary firemen and power station operators; or automobile body repairers and mechanics), an adjustment was made to the 1940 industry employment data and new-hires data to remove duplication. These adjustment factors were derived from the BLS National Industry-Occupational Matrix in the case of Asbestos and insulation workers [Bureau of Labor Statistics, 1969b] and the 1970 Census of Population in the case of stationary engineers, stationary firemen and power station operators. No adjustment was necessary for the automobile body repairers and mechanics since the duplication between this occupation and the industries included in this study is insignificant.

An additional adjustment in the new-hires data was made to eliminate the double-counting of persons who were hired in an occupation or industry during the period since 1940 and who had previously been exposed to asbestos in another occupation or industry. We developed an adjustment factor for this purpose by analyzing the occupational histories of 2,544 workers employed in operations exposed to asbestos in cohorts being studied by this laboratory. Table XI lists the percentage of individuals in several study groups with previous substantial exposure to asbestos (equivalent to greater than six months employment in a shipyard). This correction reduces the num-

TABLE X. Source of Annual New Hire Rates by Industry or Occupation

Industry or occupation	Source of annual new hire rates[a]	Average 1958–1961 new hire rates[d]
Primary asbestos manufacturing	0.8 × (SIC 329)[b]	0.294
Secondary asbestos manufacturing	0.8 × (SIC 343, 3443, 356, 363)[b]	0.127–0.232
Insulation	Data from union new entrants used	—
Shipbuilding and repair	0.5 × (SIC 3731)[b] and US Navy data	0.216
Construction trades	1 × (SIC 20–39) × (0.147/0.268)[c]	0.147
Railroad engine repair	1 × (SIC 20–39) × (0.099/0.268)	0.099
Utility services	1.5 × (SIC 20–39) × (0.149/0.268)	0.149
Stationary engineers and firemen	1 × (SIC 20–39) × (0.155/0.268)	0.155
Chemical plant and refinery	0.7 × (SIC 28)[b]	0.116
maintenance	0.7 × (SIC 29)[b]	0.092
Automobile maintenance	1 × (SIC 20–39) × (0.142/0.268)	0.142
Marine engine room personnel	1 × (SIC 20–39) × (0.099/0.268)	0.099

[a]The percentage of various workers within each SIC category, as described in the text, will be used as the basis population for calculating new hires.

[b]Data are utilized for the years available. For years for which new hire data were not published, the new hire data for all manufacturing were used, adjusted by the relationship to the specific SIC code for the years published.

[c]The rate 0.268 is the average annual fraction of new hires in manufacturing for the years 1958–1960, corrected for changes in the work force.

[d]Values for other years are proportional to the new hire rates in the indicated SIC classification.

ber of people ever exposed by 10% (the correction factor used). It will not reduce the mortality, however, as we must account for all person-years of exposure in asbestos-related industries. This will be done by using the adjusted population of new entrants to calculate an average time of exposure (see below) which will overestimate the exposure time by 10% to account for the 10% reduction in exposed populations. It should be emphasized that the uncertainties in either the populations exposed or the average durations of employment greatly exceed 10%

POPULATION AT RISK

The results of the estimation of employment and new-hires at risk are shown in Table XII, indicating that approximately 27,500,000 individuals were potentially exposed to asbestos from 1940 through 1979 in the occupations analyzed. The uncertainties in estimating this number have been described previously, but they cannot be overstressed. The number is an approximation. Further, it includes a large number of individuals whose potential exposure to asbestos would have been of low intensity or of short duration because of high labor turnover (see section on lower risk population). Finally, the term potential should be emphasized. In categorizing a segment of a work force (such as all production shipyard workers) as being potentially exposed to asbestos, some individuals will be included with no actual exposure. On the other hand, individuals in other jobs (such as management) who did have exposure were not counted. The numbers may or may not balance. These uncertainties will be compensated for in the estimates of mortality by using data on the mortality or morbidity of representative work-force segments, which will also include the full spectrum of exposure circumstances.

It should also be noted that a large number of asbestos-exposed individuals are not included in the estimates of Table XII. Important groups with identified risks include family contacts of asbestos-exposed workers, engine room personnel aboard US Navy ships in World War II, and individuals exposed environmentally to asbestos by virtue of residence or work near the use of asbestos. Additional exposures occur to many from the use of asbestos in surfacing materials in schools, night clubs, and auditoriums, or as fireproofing material in office buildings.

Average Duration of Employment

The average duration of employment can be calculated from the fractional new-hire rate adjusted by changes in total work force at different periods in time (see section on methological considerations). Alternatively, the average employment over a decade can be divided by the average yearly number of new hires entering an industry to obtain the average employment time. In essence, this is the period of time that is required for the number of new entrants into an industry to completely replace the work force. These data for the years 1940–1979 are presented in Table XIII and were used for the average durations of exposure in each decade for each industry or occupational group.

Supplemental Labor Turnover Data

The Environmental Sciences Laboratory has access to several seniority lists of work forces employed in asbestos-using industries. These include a large integrated asbestos products manufacturer, a major East Coast shipyard and a plastics polymer plant. Additionally, information on the employment times of all employees in an as-

TABLE XI. Workers Exposed to Asbestos in Five Cohorts Under Study by the Environmental Sciences Laboratory, Mount Sinai School of Medicine

Location	Industry/occupation	Period	No. of workers currently exposed: Total	No. of workers currently exposed: Also exposed in previous employment
Metropolitan New York	Brake repair and maintenance	1979–1980	699	104
Groton, Connecticut	Shipyard	1976	1,024	98
Baltimore, Maryland	Shipyard	1979	286	10
Port Allegany, Pennsylvania	Asbestos products manufacturing	1979	254	21
Quincy, Massachusetts	Shipyard	1979	281	16

TABLE XII. Population at Risk to Asbestos-Associated Disease: Workers Exposed to Asbestos in Selected Occupations and Industries, 1940–1979 (in thousands)

Industries or occupations	1940	New entrants 1940–1949	New entrants 1950–1959	New entrants 1960–1969	New entrants 1970–1979	Totals
Primary asbestos manufacturing	23	200	103	86	76	488
Secondary asbestos manufacturing	30	324	227	259	308	1,148
Insulation work[a]	17	35	47	38	47	184
Temporary, World War II		9				9
Shipbuilding and repair	157	433	354	434	383	1,761
Temporary, World War II		4,325				4,325
Construction trades	426	1,786	1,452	1,866	1,975	7,505
Railroad engine repair	69	194	26	0	0	289
Utility services	44	223	116	116	129	628
Stationary engineers and firemen	295	1,136	623	549	510	3,113
Chemical plant and refinery maintenance	104	542	260	239	248	1,393
Automobile maintenance	372	1,884	1,099	1,282	1,779	6,416
Marine engineer room personnel (except US Navy)	34	121	46	40	27	268
Totals	1,571	11,202	4,353	4,909	5,482	27,527

[a]Insulators are included here and not in other trades in which they were employed, such as shipbuilding, construction, plant maintenance, or power generation.

bestos insulation production plant is available. These sources can be utilized for comparison with the data obtained from the Social Security Administration and Bureau of Labor Statistics on labor turnover. They can further be utilized to obtain estimates of the distribution of employment times in a given industry by comparing the number of individuals actually employed to those that were known to have been hired in different time periods. The latter quantity is available from the seniority lists as individuals were assigned sequential clock numbers upon employment. These data are presented in Table XIV and supplement the turnover data obtained otherwise.

One notable feature is that the asbestos products manufacturer has an extremely high turnover during the first month after hire. This occurs because of terminations of individuals during a one-month probationary period. After that time, the man enters the union bargaining unit, and any individual terminations are subject to grievance procedures. While such practices are not universal, they are certainly not unique, and it is expected that in primary and secondary manufacturing an extremely high turnover will result during the first month or two of employment as individuals are screened for their performance and suitability for a job. In contrast, in construction, shipbuilding, automobile maintenance, and other industries that require a skill, the turnover in early periods of time is expected to be less as an individual would have demonstrated professional competence prior to being hired. Further, he would likely be represented by a union before employment with a given employer. Thus, nonarbitratable dismissals are less common.

TABLE XIII. The Average Employment Time of All Individuals Potentially Exposed to Asbestos, 1940–1979

Industry or occupation	Average duration of employment (years) calendar periods 1940–1949	1950–1959	1960–1969	1970–1979
Primary asbestos manufacturing 1.6	1.6	3.5	3.8	4.0
Secondary asbestos manufacturing	2.0	3.5	4.0	3.8
Insulation work	13.7[a]	12.4	15.9	12.5
Shipbuilding and repair	4.3[a]	5.3	4.2	4.6
Construction trades	3.3	8.3	7.5	4.5
Railroad engine repair	4.4	7.7	—	—
Utility services	2.8	5.7	5.7	6.0
Stationary engineers and firemen	2.7	6.3	5.8	5.7
Chemical plant and refinery maintenance	3.7	7.4	8.7	8.1
Automobile maintenance	2.7	6.0	7.7	7.0
Marine engineer room personnel (except US Navy)	4.7	7.4	7.8	6.1

[a]Does not include short-term wartime shipyard workers.

TABLE XIV. Labor Turnover in Selected Industrial Establishments

Establishment	Time period	Number of individuals considered	Number employed by time after hire: 1 year	6 months	2 months	1 month
Shipyard products	1977	1,449	–	73%	80%	–
Asbestos products manufacture	1965–1966	759	37%	–	51%	53%
Asbestos products manufacture	1961–1962	306	42%	–	45%	48%
Asbestos products manufacture	1957–1958	108	27%	–	52%	75%
Plastics production	1961–1962	17	–	100%	100%	100%
Insulation products manufacture	1941–1945	820	38%	53%	82%	93%

A study of workers exposed to brominated chemicals in three plants provides data on the distribution of employment times of all 3,579 individuals employed in the facilities [Wong, 1981]. It substantiates the presence of a large number of individuals with very short employment times. Of all employees, 16.4% worked for less than one month and an additional 28.5% for 1–5.9 months. The full distribution of employment times can be characterized by a two-component decreasing exponential. Thus, the work force can be considered as made up of two groups. The average employment time of one, consisting of approximately 2,200 individuals, was 0.5 years and of the other, with 1,400 individuals, was 11.7 years in good agreement with the data of Table XIII.

Relative Risk by Industry

To calculate the asbestos-related cancer mortality in a given industry or operation, it is necessary to have an absolute or relative measure of exposure for the employee group. While detailed information is not available on the asbestos air concentrations that have been prevalent in previous years in each of the above industries, estimates can be made of the relative risk of death from asbestos exposure on the basis of a variety of other studies. In the calculation of asbestos-related cancer mortality for a given industry or occupation, we will utilize the available data for insulation workers for the dose and time dependence of asbestos cancer. To translate available data for insulation workers to other industries, it is necessary to establish measures of exposure for the different groups considered at risk relative to that of insulation workers. These *relative risks for equal times of employment* will be determined by three indices. The primary one is the directly measured mortality data, especially that of mesothelioma or lung cancer, in an industry or trade. A second is the directly measured average concentrations of asbestos that can be attributed to the work activity. The third is the prevalence of X-ray abnormalities after long-term employment in an industry. Here, we will assume that the percentage of X-ray abnormalities attributable to an exposure circumstance after 20 years of employment will be proportional to the total dose of asbestos inhaled by the workers in that industry. Where the percentage of abnormal X-rays approaches 100%, the relative risks will be determined using the percentages of X-rays having a category 2 or greater abnormality on the ILO U/C scale. Information on these direct and indirect measures is shown in Table XV along with the sources of the various data.

For industries in which none of the above indices are available (construction, railroad steam engine repair) or for which the data are very uncertain, relative risk estimates were made from the numbers of mesotheliomas identified among individuals in different asbestos exposure circumstances compared with the total work force exposed. These data utilized the nationwide survey of mesothelioma in 1972 and 1973 by McDonald and McDonald [1980]. The numbers from this series are shown in Table XVI.

The relative risks, by industry, estimated from all of the above data, are listed in Table XVII. Also Indicated in Table XVII are the principal data sources considered in the relative risk estimates. The data available for the estimates are limited and the estimates are necessarily approximate. For the years 1972–1979, the relative risks for manufacturing, insulation work, shipbuilding, and utility employment will be reduced to 0.1, and those of the other industries (except automobile maintenance) to 0.05 to re-reflect the adoption of control measures. Further, exposures subsequent to 1979 will not be considered.

TABLE XV. Indices of Relative Asbestos Exposure in Selected Occupations and Industries

Industry of occupation	Estimated average fiber concentrations	Relative risk of lung cancer	Percentage of deaths from mesothelioma	Applicable employment period (years)	Percentage of: parenchymal abnormalities 1+	2+	pleural abnormalities	Applicable employment period (years)
Primary manufacturing	20–40	2.8[a]–6.1[b]	2.6[b]–9.1[a]	1–20+				
Insulation work	15[a]	4.8[c]	8.7	20+	85[d]	42[d]	56[e]	20+
Shipbuilding and repair	2[f]	1.6[g]		2–3	86[h]	17[h]	54[h]	20+
Chemical plant and refinery maintenance		1.5[i]		15 est	33[j]	3[j]	44[j]	20+
Automotive maintenance	0.1–0.3[k]				5[k]			10+
Marine engine room personnel							16–20[l]	15

[a][Nicholson, 1981a.]
[b][Seidman et al, 1979.]
[c][Selikoff et al, 1979.]
[d][Selikoff et al, 1965.]
[e][Selikoff, 1965.]
[f][J. Thorton, quoted in Enterline, 1981.]
[g][Blot et al, 1981.]
[h][Selikoff et al, 1981.]
[i][Hanis et al, 1979.]
[j][Lilis et al, 1980.]
[k][Nicholson, 1982.]
[l][R.N. Jones, 1980.]

TABLE XVI. The Numbers of Mesotheliomas by Work Activity in North America (1960–1972, Canada; 1972, USA)*

Occupation or industry	Number of cases
Primary and secondary manufacturing	21
Insulation work	27
Shipbuilding and repair	21–49[a]
Construction trades	45–76[b]
Railroad engine repair	5
Utility services	
Stationary engineers and firemen	13+
Chemical plant and refinery maintenance	3
Automobile maintenance	11
"Heating trades"	59[c]

*[McDonald and McDonald, 1980].
[a]Highest number only includes some insulators and heating trades workers.
[b]Highest number may include some insulators, shipyard workers or individuals with employment in heating trades.
[c]Includes many individuals that would be assigned to other categories, as stationary engineers and firemen (furnace repair), shipyard employment (welders, steamfitters), utilities (plumbing, heating, boiler work), manufacturing (boilermakers).

TABLE XVII. The Risk of Asbestos Cancer Relative to Insulation Work After 25 Years Employment

Occupation or industry	Risk	Source of data for estimate
Primary manufacturing	1	Group mortality data, exposure measurements
Secondary manufacturing	0.5	Exposure measurements
Insulation work	1	Reference population
Shipbuilding and repair (except insulators)	0.5	Group mortality data, prevalence of X-ray abnormalities
Construction trades[a] (except insulators)	0.15–0.25[b]	No. of mesothelioma cases in general population
Railroad engine repair	0.2	No. of mesothelioma cases in general population
Utility services	0.3	No. of mesothelioma cases in general population
Stationary engineers and firemen	0.15	Prevalence of X-ray abnormalities
Chemical plant and refinery maintenance	0.15	Prevalence of X-ray abnormalities, group mortality data
Automobile maintenance	0.04	Prevalence of X-ray abnormalities, exposure measurements
Marine engine room personnel (except US Navy personnel)	0.1	Prevalence of X-ray abnormalities

[a]See test for percentage of construction population considered at risk.
[b]Risk for years 1958–1972 when the use of sprayed asbestos fireproofing was common.

The relative risks in Table XVII for insulation work, manufacturing, utility services ("heating trades") shipyard employment, and construction yield "population" risks virtually identical to those found by McDonald and McDonald [1980] in their case-control analysis. They found values of 46.0, 6.1, 4.4, 2.8, and 2.6, respectively, for the relative risks of the above populations. Multiplying our equal exposure risks by the average durations of employment of all workers from 1940 through 1969 (13.2, 2.0, 4.7, 1.9, and 6.4 years, respectively) and further dividing the risk for construction workers by two to account for the 50% of workers to whom we attributed no risk, we obtain for the relative "population" risks the values, 13.2, 1.3, 1.4, 0.95, and 0.5. Adjusting to the McDonald and McDonald [1980] risk of 46 for insulators, we obtain for "population" risks, 46.0, 4.6, 4.9, 3.3, and 1.8.

Lower Risk Population

While we are unable to obtain full data on the distribution of employment times in all industries, the information depicted above allows us to identify a segment of the work force with considerably less exposure to asbestos. Taking a period of employment of two months in primary manufacturing or insulation work as a measure of a low exposure, we have estimated the number of individuals with such an exposure among the 27,500,000 individuals identified previously. This would correspond to a total exposure of 2–3 f-yr/ml (12–18 f/ml × 1/6 yr). The estimates were made assuming 40% of the new hires in primary and secondary manufacturing and 20% of the new hires in other industries left within two months. For longer periods, we utilized an exponential function, $e^{-\beta t}$, for the distribution of employment times where β is the average steady-state permanent separation rate. The period of employment characterizing "lower exposure" for a given industry will be inversely related to the relative risk of the industry (Table XVII). These data are presented in Table XVIII and suggest that 8,700,000 of those potentially exposed to asbestos will have a significantly lower risk by virtue of their short employment period. The extremely large number in automobile maintenance arises because of the low relative risk of asbestos disease in that industry. Thus, individuals with as much as four years of employment in automobile maintenance were included in the estimates that gave rise to Table XVIII.

The data in Table XVIII indicate that an enormous number of individuals are likely to have had *some* exposure to asbestos: 27,500,000 since 1940. Of this number, it is estimated that 21,000,000 were alive on January 1, 1980. (This figure was calculated

TABLE XVIII. The Percentage of Asbestos-Exposed Individuals With Lower Exposure*

	Total exposed		Number with lower exposure	Percentage with lower exposure
	1940	1940–1979		
Primary asbestos manufacturing	23	465	186	38
Secondary manufacturing	30	1,118	493	43
Insulation work	17	167	33	18
World War II		9	2	20
Shipbuilding and repair	157	1,604	362	20
World War II		4,325	1,303	30
Construction trades	426	7,079	1,842	24
Railroad engine repair	69	220	72	25
Utility services	44	584	141	22
Stationary engineers and firemen	295	2,818	834	27
Chemical plant and refinery maintenance	104	1,289	350	25
Automobile maintenance	372	6,044	3,032	47
Marine engine room personnel	34	234	75	28
Totals	1,571	25,956	8,715	32

Lower exposure is characterized as being less than that equivalent to two months employment in an asbestos factory or as an insulator (approximately 2-3 f-yr/ml). It is *not* to be construed as being without risk.

using procedures detailed in the mortality estimates to follow.) Of those exposed, 18,800,000 of the total and 14,100,000 of those alive on January 1, 1980 were estimated to have had an exposure greater than 2–3 f-yr/ml. Such exposures carry significant risk of asbestos disease (as will be detailed subsequently). Further, some risk of asbestos disease exists for the 6,900,000 alive on January 1, 1980, estimated to have experienced lesser exposures.

CANCER FROM OCCUPATIONAL ASBESTOS EXPOSURE: PROJECTIONS 1965–2030

In recent years, considerable data have accumulated that allow projections to be made of the cancer mortality associated with past exposure to asbestos. These include new information on the dose and time dependence of asbestos-related cancers in various occupational circumstances, an increased awareness of the various trades in which possible asbestos exposure occurred in past years, as well as information on the absolute and relative exposures of these different occupational groups. While the relevant data are less complete than desired, they are sufficient to allow estimates of future asbestos-related mortality to be made. These may be useful in directing priorities for appropriate surveillance and interventive activities that might be undertaken.

The Spectrum of Asbestos-Related Cancer

The spectrum of malignant disease that occurs from asbestos exposure is best seen in data from the mortality study of Selikoff et al [1979] on 17,800 insulation workers. This information is shown in Table XIX in which the numbers of deaths, by

TABLE XIX. Deaths Among 17,800 Asbestos Insulation Workers in the United States and Canada, January 1, 1967–December 31, 1976*

		Observed		Ratio o/e	
Underlying cause of death	Expected[a]	(BE)	(DC)	(BE)	(DC)
Total deaths, all causes	1658.9	2271	2271	1.37	1.37
Total cancer, all sites	319.7	995	922	3.11	2.88
Cancer of lung	105.6	486	429	4.60	4.06
Pleural mesothelioma	b	63	25	—	—
Peritoneal mesothelioma	b	112	24	—	—
Mesothelioma, n.o.s.	b	0	55	—	—
Cancer of esophagus	7.1	18	18	2.53	2.53
Cancer of stomach	14.2	22	18	1.54	1.26
Cancer of colon-rectum	38.1	59	58	1.55	1.52
Cancer of larynx	4.7	11	9	2.34	1.91
Cancer of pharynx, buccal	10.1	21	16	2.08	1.59
Cancer of kidney	8.1	19	18	2.36	2.23
All other cancer	131.8	184	252	1.40	1.91
Noninfectious pulmonary diseases, total	59.0	212	188	3.59	3.19
Asbestosis	b	168	78	—	—
All other causes	1280.2	1064	1161	0.83	0.91

*Number of men: 17,800, man-years of observation: 166,853. From Selikoff et al [1979].

[a]Expected deaths are based upon white male age-specific US death rates of the US National Center for Health Studies, 1967–1976.

[b]Rates are not available, but these have been rare causes of death in the general population.

(BE) Best evidence; number of deaths categorized after review of best available information (autopsy, surgical, clinical). (DC) Number of deaths as recorded from death certificate information only.

cause, over a ten-year period, are tabulated along with those expected from national rates. Causes of death are characterized both according to those listed on the certificates of death (DC) and according to the best evidence (BE) available from a review of autopsy protocols, medical records, and pathological specimens. For most causes of death, the agreement is relatively good, but for mesothelioma and asbestosis, considerable differences exist. Because deaths from these causes are rare in the absence of asbestos exposure, their misdiagnosis has little effect upon general population rates. However, as they are common causes of death among asbestos-exposed workers, their misdiagnosis can seriously affect determination of asbestos mortality. Thus, the "best evidence" mortality will be used for the estimate of asbestos-related cancers. However, as we will attribute all excess cancer among insulators to their asbestos exposure (see below), the overall results will not differ greatly from that using certificate of death diagnosis. Higher rates of death at one site (as mesothelioma) will be balanced by lower rates at another (as pancreas).

In addition to mesothelioma and cancer of the lung, cancer of the stomach, colon, rectum, esophagus, larynx, pharyx, buccal cavity, and kidney are each elevated significantly compared with rates expected for these sites in the general population. (This group will be referred to subsequently as "asbestos-related" malignancies.) Opportunity for fiber contact with the epithelial surfaces of the lung and gastrointestinal tract is clearly evident. Exposure to the mesothelial tissue and kidney can occur as fibers readily penetrate into lung lymphatics and reach the pleural mesothelium ("pleural drift") or can be transported to the kidney or peritoneal mesothelium. Similarly, fiber dissemination occurs to other extrapulmonary organs, such as brain, liver, spleen, etc [Langer, 1974]. While excesses at these other sites are not of statistical significance for individual malignancies, the category "all other cancers" is elevated at a high level of significance ($p < 0.0001$), and we will attribute these excess malignancies to asbestos exposure as well. Their contribution accounts for less than 8% of the total excess cancer compared with the contribution of lung cancer, 56%; mesothelioma, 26%; and the other above specified "asbestos-related tumors," 10%.

The Time Course of Asbestos-Related Cancer

The time course of asbestos-related mortality from bronchogenic carcinoma is shown in Figure 1 according to ages for individuals exposed initially between ages 15 and 24, and 25 through 34. As can be seen, the two curves of relative risk, according to age, rise with the *same* slope and are separated by approximately ten years. This suggests that the *relative risk* of developing lung cancer is independent of age and of the pre-existing risk at the time of exposure. In contrast, had one plotted the *added risk* of cancer, the slope and the amount for the group first exposed at older ages would have been two to four times greater than for those exposed at younger ages. If one combines these data and plots them according to time from onset of exposure, the curve of Figure 2 is obtained. A linear increase with time from onset of exposure is seen for 35 to 40 years (to about the time when many insulators terminate employment). After 40 years the relative risk falls significantly, rather than remaining constant after cessation of exposure as might be expected from the linear increase with continued exposure. The decrease is not solely the result of the elimination of smokers from the population under observation as a similar fall occurs for those individuals who were smokers in 1967. (In calculating the relative risk of lung cancer in smokers, smoking-specific data from the American Cancer Society study of one million people were utilized [Hammond, 1966].) Selection processes, such as differing exposure patterns or differing individual

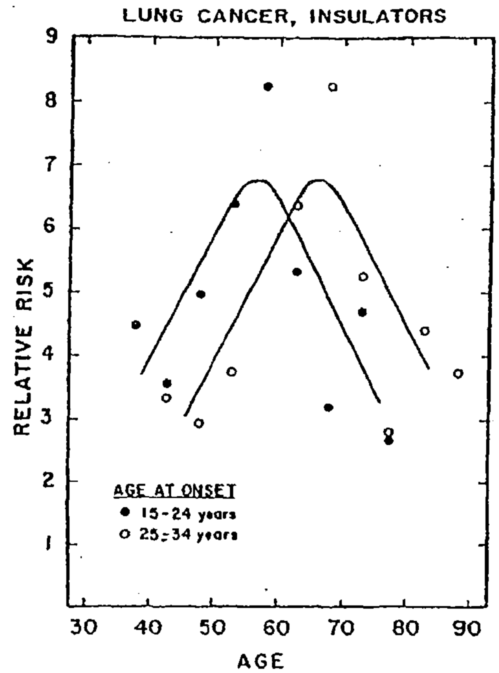

Fig. 1. The ratio of observed to expected deaths from lung cancer among insulation workmen according to age and age at onset of employment.

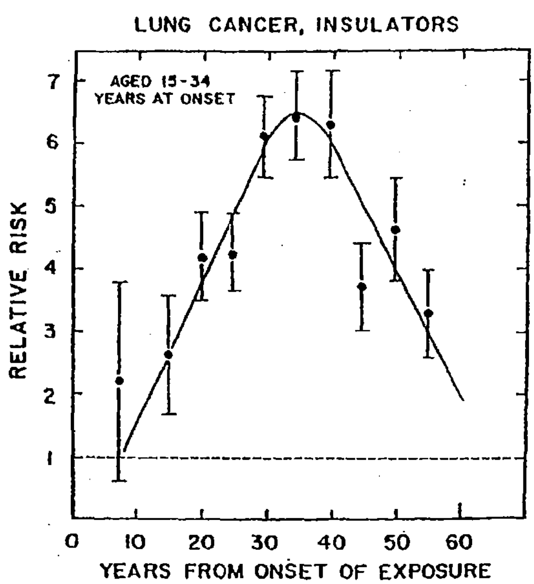

Fig. 2. The ratio of observed to expected deaths from lung cancer among insulation workmen according to time from onset of employment.

biological susceptibilities may play a role, but the exact explanation for the effect is not understood. It is, however, a general phenomenon seen in many mortality studies.

The early portion of the curve of Figure 2 is remarkable in two aspects. Firstly, it shows a linear increase in the relative risk of lung cancer according to time from onset of exposure. This suggests that the dose of asbestos received in a given period of time increases the risk of cancer by an amount that is proportional to that which existed in the absence of exposure. This increased *relative risk* is proportional to the dose of inhaled asbestos, which in turn is proportional to the time worked. Thus, the linear rise in Figure 2. However, the linear rise can occur only if the increased relative risk that is created by a given dose of asbestos continues to multiply the "background" risk for several decades (at least until age 60), even though the background risk will increase tenfold or twentyfold in 30 years. Secondly, the extrapolated line through the observed data points crosses the line of relative risk equal to one (that expected in an unexposed population) very close to the onset of exposure. At most, the line might be adjusted so that it passes through the relative risk of one line at a time from onset of exposure of about ten years. (Note that we are plotting the relative risk of death. Irreversible malignancy would have been initiated several years earlier, since usually one or two years elapse between identification of lung cancer and death, and it is likely that a malignant growth was present, unseen, for at least one or two years before becoming clinically evident.) This means that an increased relative risk appropriate to a given exposure is achieved very shortly after the exposure takes place. However, if there is a low risk in the absence of asbestos exposure, as in young workers, cancers that will arise from that increased relative risk may not be seen for many years or even decades until the background risk becomes significantly greater.

The same two points, 1) that the effect of an exposure to asbestos is to multiply the pre-existing risk of cancer in the exposed population and 2) that the multiplied risk

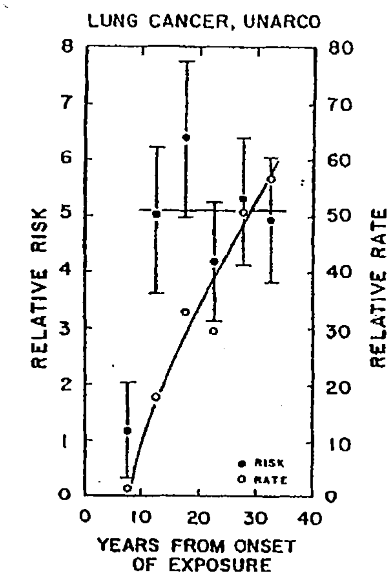

Fig. 3. The ratio of observed to expected deaths from lung cancer and the relative lung cancer mortality rates among asbestos insulation production employees according to time from onset of employment.

becomes manifest in a relatively short time, can also be seen in the mortality from lung cancer in a study of Seidman et al [1979]. Figure 3 depicts the time course of the mortality from lung cancer of a group (UNARCO) exposed for short periods of time, beginning five years after onset of exposure. As 77% were employed for less than two years, exposure largely ceased prior to the follow-up period. As can be seen, a rise to a significantly elevated relative risk occurs within ten years, and then that increased relative risk remains constant throughout the observation period of the study. Furthermore, the relative risk from a specific exposure is independent of the age at which the exposure began. This is seen in Table XX, where the relative risk of death for lung cancer for individuals exposed for less than and greater than nine months is listed according to the age at entrance into a ten-year observation period. Within a given age category, the relative risk is similar in different decades of observation, as we saw before in Figure 3 with the overall data. However, the relative risk also is independent of the age decade at entry into a ten-year observation period. (See lines labelled "All" in each exposure category.) There is some reduction in the oldest groups. This can be attributed to the same effects manifest at older ages in insulators or to relatively fewer cigarette smokers that might be present in the 50-59 year observation groups because of selective mortality.

In the calculation of asbestos-related cancer, the time course of nonmesothelial cancer will be treated as follows. The increase in the relative risk of lung cancer will begin 7.5 years after onset of exposure and increase linearly, following the line of Figure 2 for the number of years a specified group is employed. After a period equal to the average duration of employment, the relative risk will remain constant until 40 years from onset of exposure, after which it will linearly decrease to one over the subsequent three decades. The magnitude of the increase will be equal to that of Figure 2 for insulators and factory employees. The rate of increase for other groups will be proportional to their estimated exposure relative to that of insulators. The same time course

TABLE XX. Relative Risk of Lung Cancer During Ten-Year Intervals at Different Times From Onset of Exposure*

Years from onset of exposure	Age at start of period		
	30-39	40-49	50-59
		Lower exposure (< 9 months)	
5	0.00 [0.35]	3.75 (2)	0.00 [3.04]
15	6.85 (1)	4.27 (3)	2.91 (4)
25	—	2.73 (2)	4.03 (6)
All	3.71 (1)	3.52 (7)	2.58 (10)
		Higher exposure (> 9 months)	
5	0.00 [0.66]	11.94 (4)	9.93 (8)
15	19.07 (2)	11.45 (5)	5.62 (5)
25	—	13.13 (6)	7.41 (8)
All	11.12 (2)	12.32 (16)	7.48 (21)

*From Seidman et al [1979].
( ) = Number of cases.
[ ] = No cases seen. Number of cases "expected" on the basis of the average relative risk in the overall exposure category.

will be used for all other nonmesothelial tumors with the magnitude of the increase in insulators being adjusted by the observed frequency of these tumors compared with that expected and that of other groups by their estimated exposure relative to insulators as well.

The treatment of the time course of mesothelioma differs from that of lung cancer and other malignancies in that there is no background rate in the absence of asbestos exposure with which to compare the asbestos-related risk. Thus, it is necessary to utilize absolute risks of death. Figure 4 shows the risk of death of mesothelioma according to age for individuals exposed first between ages 15 and 24 and between ages 25 and 34 as in Figure 1. As can be seen, these data, while somewhat uncertain because of small numbers, roughly parallel one another by ten years as did the increased relative risk curves for lung cancer. Thus, the absolute risk of death from mesothelioma appears to be directly related to onset of exposure and is independent of the age at which the exposure occurs. The risk of death from mesothelioma among the insulation workers is plotted according to time from onset of exposure on the right side of Figure 4. It increases as the fourth or fifth power of time from onset of exposure for about 40 or 50 years. Thereafter, data are scanty and information on the time course is not reliable. For the purposes of analyzing the mortality experience among various groups of workers, the relationship depicted in Figure 4 will be used. After 45 years from onset of exposure, we will consider the risk of death from mesothelioma to remain constant at 1.2 per 100 person-years for insulation workers employed for 25 or more years. For insulators employed for shorter periods, the risk will be reduced by the fraction of 25 years worked. For other exposed groups the risks depicted in Figure 4 will be reduced by the relative exposure of the group compared with insulators and by the fraction of 25 years that a population is exposed.

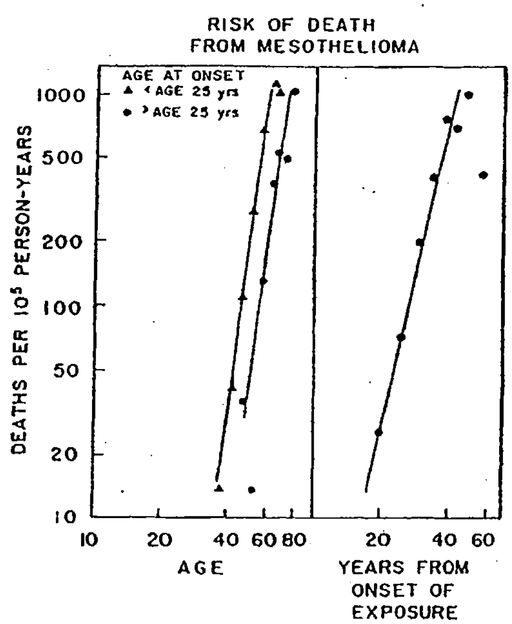

Fig. 4. The death rates for mesothelioma among insulation workmen according to age and age at onset of employment and according to time since onset of employment.

Dose-Response Relationships for Asbestos-Related Cancer

Four recent studies have demonstrated that the risk of lung cancer increases linearly with dose over a fairly wide range of exposures [Dement et al, in press; Henderson and Enterline, 1979; Liddell et al, 1977; Seidman et al, 1979]. Unfortunately, the studies are not directly comparable. For three, the measure of dose was the exposure to asbestos and other dusts in terms of millions of particles per cubic foot (mppcf) times the duration of exposure. This exposure categorization is highly dependent upon the proportion of nonfibrous material in the aerosol being considered. Some relationships between particle counts and fiber concentrations in fibers longer than 5 micrometers per milliliter (f/ml) have been provided in the literature, but these are tenuous at best, based as they are upon a limited number of observations. Further, the study of Henderson and Enterline [1979] was limited to retirees over age 64 of a major asbestos product's manufacturer in the United States. As was seen in Figure 2, observations of exposed groups begun late in life can differ considerably from those in which follow-up starts at younger years (as, for example, at age 40–45, 20 years after onset of employment). In the fourth study, that of Seidman et al [1979], exposure characterization involved the use of data from plants other than that in which the mortality experience occurred. A discussion of some of the differences of the slopes of the dose-response functions obtained in these studies has been made elsewhere [Nicholson, 1981a]. The important aspect is the linearity of effect with increasing amounts of asbestos inhaled.

In the analysis which follows, it is not necessary that one fully understand the reasons for the differences in the slopes of dose-response relationships in mining and various manufacturing operations as the relative risks in different industries will be based largely upon the observed mortality experience in those industries or upon a comparison of the number of cases of mesothelioma or excess lung cancers in different work activities. In this subsequent comparison, however, we will utilize a linear dose-response relationship to adjust for different periods of employment. While the evidence of linearity is strong for lung cancer, we will assume that it also obtains for mesothelioma and other malignancies. The evidence for this is more limited, but an analysis of the risks of mesothelioma according to time of employment in the study of Seidman et al would suggest that it is true for that tumor as well. For example, 0 of 215 deaths from mesothelioma occurred from less than 6 months exposure, 3 of 82 from 6 to 11 months exposure, 4 of 74 from 1 to 2 years exposure, and 7 of 63 from more than 2 years exposure.

Calculation of Asbestos-Related Mortality

As discussed previously, for those trades in which workers have possible asbestos exposure, estimates were made of the number of employees potentially at risk, the relative exposure of those workers compared with insulators, the average employment time of individuals entering a particular trade or industry, and the age distribution of new hires in the various trades or industries. The asbestos-related cancer mortality was calculated as follows. For those employees entering a trade subsequent to 1940, the above data from Table XII were utilized to obtain the number of new entrants into an industry during different periods of time. The age distribution of new manufacturing employees of 1960 (Table XXI) was used to calculate age-related mortality of new entrants into a trade or industry. This distribution also was found in new hires during 1974 at a major northeast US shipyard (E. Christian, personal communication). For each quinquennium at entry, the appropriate age, calendar year, and asbestos risk specific rates were applied to calculate the excess lung and other cancer mortality, the risk of death from mesothelioma, the total mortality (based on US national rates for the entry quinquennium and all subsequent quenquennia until the year 2030 (assuming 1975–1979 rates to apply to the year 2030). This was done for each five-year period of entry, 1940–1980, and the calculated numbers summed for each calendar quinquennium, 1940–2030. For those employed in 1940, the appropriate age distribution for an industry or trade in 1940, as given by the US census, was used. For those employed in 1940, it was assumed that onset of asbestos exposure occurred at age 22.5 or 1930 for those 32.5 years or older in 1940.

The excess, nonmesothelial cancer mortality was calculated using the time dependence displayed in Figure 2 with the assumption that the manifestation of risk from a given exposure will first take place 7.5 years after its occurrence and increases linearly until 7.5 years after cessation of exposure. The risks of death from mesothelioma were calculated using the data of Figure 4, adjusted for each industrial group, with risk assumed to be constant after 45 years from first exposure. Account was taken of the different periods of exposure for each group in each decade, as indicated in Table XIII. Calculations were made using US white male rates. Some blacks and some women would have been employed in the industries under consideration, although their numbers would have been small. Were data available on the number of blacks and women, the use of black male rates would have increased the number of nonmesothelioma cancers and the female rates would have decreased the number, resulting in only a small change from these data.

The results of such calculations are shown in Table XXII through XXV, which list the average annual excess number of lung cancers, mesotheliomas, gastrointestinal, and other asbestos-related cancers, and total excess cancer attributable to asbestos exposure in each quinquennium from 1965 to 2030 for the populations in Table XII. In these tables the average annual mortality in each quinquennium is listed by the midyear of the period. As can be seen, the dominant contributors to the asbestos-related disease are the shipbuilding and construction industries. Industries directly involved in the manufacturing of asbestos products or with the application of insulation material contribute a significantly smaller proportion to current asbestos disease and that to be expected for the next two decades.[2]

It is instructive to look at a display of the number of mesotheliomas and asbestos-related cancers in the shipbuilding industry from the year 1940 to the year 2000. While the total number of malignancies are necessarily uncertain, the data on the time course of the cancers that will occur are relatively good. These data are shown in Figures 5 and 6 for the populations first employed prior to 1940, during World War II, and subsequent to 1945. As can be seen, the relative importance of the wartime and postwar exposures are roughly equal, even though a considerably greater number of individuals were employed in World War II. This, of course, occurs because of the relatively short periods of work for the wartime group. Further, while the exposures in the construction industry are more uncertain, the important disease experience is also ahead of us in

[2]A preliminary report on this research has been presented elsewhere (W.J. Nicholson, G. Perkel, I.J. Selikoff, and H. Seidman. Cancer from occupational asbestos exposure: Projections 1980–2000. Banbury Report 9, Cold Spring Harbor Laboratory, 1981, pp 87–111). In that publication, an estimate was presented of the population at risk from asbestos exposure since 1940 (13,200,000) and projections of asbestos-related mortality (8,770 deaths in 1982 to 9,750 in 1990). The estimates of the population exposed to asbestos presented there, however, did not fully account for the extremely high turnover in workplace employment that we have discussed here. However, as the mortality estimates did not depend on the total population exposed, they are virtually identical to those presented here.

that industry, largely because of the extensive use of asbestos in spray fireproofing materials between 1958 and 1972. A measure of the overall future disease experience can be seen in Figure 7, which depicts the projected annual mesothelioma deaths from 1940 to the year 2000. Of all mesotheliomas that are estimated to occur between the years 1940 and 2000, about one third have occurred to date.

The number of mesotheliomas estimated by this procedure is approximately 40% greater than those that would be estimated to occur nationwide using data of the SEER program for white males during 1978 [R. Connelly, National Cancer Institute, personal communication, 1981]. Here, initial data (with one center not analyzed) report 98 mesothelioma deaths in nine of the ten SEER areas. As they represent approximately a

TABLE XXI. Age Distribution of Employees Hired During 1965 Who Were Not Working January 1, 1965*

Age	Number (in thousands)	Percent in age interval	Percent of shipyard workers in age interval[a]
18-19	892	15.1	17.8
20-24	1,614	27.3	31.6
25-34	1,431	24.3	27.6
35-44	861	14.6	12.0
45-54	588	10.0	6.1
55-64	361	6.1	2.9
65+	146	2.5	0.0

*Data from Bureau of Labor Statistics [1965].
[a]Based on 478 new hires during 1974. Data from Christian, Sec. Local 5, Industrial Union of Marine and Shipbuilding Workers of America (personal communication, 1981).

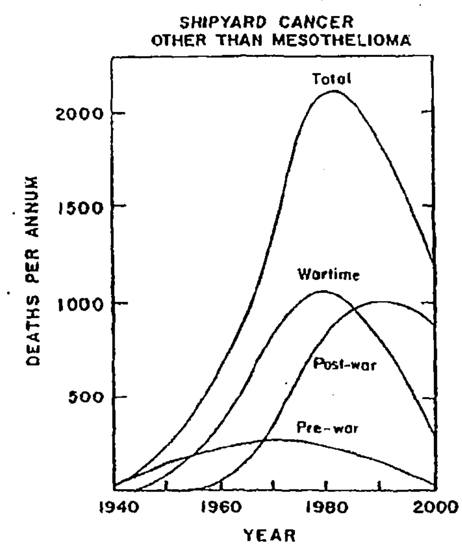

Fig. 5. The estimated and projected numbers of mesothelioma deaths per annum from past asbestos exposure from 1940 through 1999 among three groups of shipyard employees (those employed in 1940 or earlier, those employed during World War II, and those employed subsequent to World War II).

10% sample of the US population, the national estimate of cases for 1978 would exceed 1,000. This is to be compared with our estimate of 1,400 for the quinquennium 1976–1980 (and for the year 1978). In this comparison, however, it should be noted that the information used for the estimate of asbestos-related cancers in this work relied upon data that identified asbestos malignancy following analysis of all medical evidence and after a review of all pathological material available. The SEER program, on the other hand, used records-based reports with no review of pathological material. Experience has shown that pathological review will identify as mesothelioma many neoplasms initially categorized otherwise [Levine, 1978]. Further, while well representing the shipbuilding industry, the ten SEER areas underrepresent industrial areas and

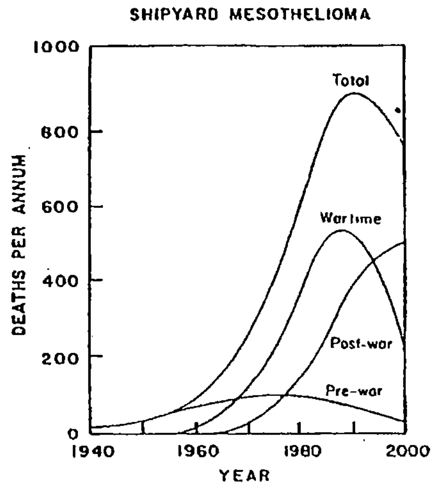

Fig. 6. The estimated and projected numbers of excess asbestos-related cancers per annum from 1940 through 1999 among three groups of shipyard employees (those employed in 1940 or earlier, those employed during World War II, and those employed subsequent to World War II).

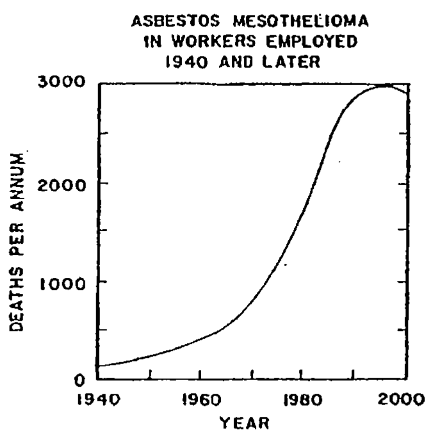

Fig. 7. The estimated and projected numbers of mesotheliomas per annum from 1940 through 1999 from occupational asbestos exposure.

TABLE XXII. The Projected Annual Excess Deaths From All Asbestos-Related Lung Cancer in Selected Occupations and Industries, 1967-2027

Industry or occupation	Number deceased in calendar year												
	1967	1972	1977	1982	1987	1992	1997	2002	2007	2012	2017	2022	2027
Primary asbestos manufacturing	129	189	240	270	288	284	260	224	173	122	77	43	20
Secondary manufacturing	146	192	261	321	374	387	377	343	291	228	160	102	56
Insulation work	158	235	319	379	418	421	390	333	299	185	119	68	35
Shipbuilding and repair	847	1,125	1,411	1,479	1,436	1,247	1,027	786	562	401	268	157	78
Construction trades	445	717	1,093	1,405	1,649	1,815	1,893	1,828	1,584	1,235	884	487	228
Railroad engine repair	66	79	88	84	62	55	36	19	8	2	0	0	0
Utility services	82	111	142	161	175	177	168	150	124	95	66	41	22
Stationary engineers and firemen	234	306	380	435	478	493	486	438	378	305	223	147	85
Chemical plant and refinery maintenance	116	163	209	246	267	270	254	224	181	136	93	56	30
Automobile maintenance	100	142	192	240	290	316	340	326	304	266	210	148	90
Marine engine room personnel	21	27	33	35	35	32	28	22	17	12	8	5	2
Totals	2,344	3,286	4,368	5,055	5,472	5,497	5,259	4,693	3,921	2,987	2,108	1,254	646

metropolitan regions that would have had significant construction activities 30 or more years ago. Thus, it is not unexpected that actual US rates may exceed those estimated from the SEER program.

There is observational evidence to support the analytical approach used in these calculations. The data for insulation workers suggest that 650 mesotheliomas and 2,300 excess lung cancers would occur between 1967 and 1976 among members of this craft. This is to be compared with 175 mesotheliomas and 380 excess lung cancers seen among insulators in the single union (The International Association of Heat and Frost Insulators and Asbestos Workers, AFL-CIO) studied by Selikoff et al [1979]. The ratios of 0.27 and 0.17 for the number of deaths among Asbestos Workers Union members to those calculated here is in reasonable agreement with the fraction of all insulators that the union has organized (0.29). The difference in lung cancer and mesothelioma ratios can be attributed to the fact that the insulators organized by this union are older than the entire group estimated to be at risk from 1967 through 1976 and, thus, have a proportionally greater risk of death from mesothelioma than from lung cancer compared to other insulators. Forty-two percent of the Asbestos Workers Union members were 45 years of age or older at the midpoint of the Selikoff et al study. A comparison of the ratios of the calculated 1977 mesothelioma deaths from industries (Table XXIII) with those observed in the study of McDonald and McDonald [1980] (Table XVI) also shows reasonable agreement.

As discussed previously, one third of those estimated to have had a potential exposure to asbestos were exposed for only a short period of time and were believed to have a risk less than that equivalent to that from employment in an asbestos products plant or as an insulator for two months. By calculating the person-years of exposure of the "lower risk population" and comparing the result to the total person-years of employment in each industry the contribution of the lower-risk group to the estimated excess mortality can be obtained. These results are shown in Table XXVI and indicate that 32% of the exposed group will contribute less than 2% of the excess asbestos-related deaths. The numbers are approximate because of uncertainties in the assumed short-term separating rate. They do, however, dramatize the consequences of inclusion of lower exposed individuals in the population at risk.

Asbestosis Deaths

The above estimates are of deaths from malignancy. There will be additional deaths from asbestosis that will occur in individuals exposed to high concentrations over long periods of time. In contrast to the asbestos cancers, deaths from asbestosis generally require considerable fiber exposure. They will largely occur in insulators, manufacturing workers and long-term shipyard employees. They will be fewer than the number of mesothelioma deaths among insulators (perhaps one half to three fourths). Because of the high labor turnover in manufacturing we would estimate that about one third as many deaths will occur from asbestosis as from mesothelioma. A similar ratio is probably appropriate for pre- and post-World War II shipyard workers (short-term wartime work would carry only a limited risk of death from asbestosis). Thus, approximately 200 deaths annually are now occurring from asbestosis (the condition, however, will be contributory to many more deaths). This number will perhaps double during the next two decades and decline thereafter.

TABLE XXIII. The Projected Annual Deaths From Asbestos-Related Mesothelioma in Selected Occupations and Industries, 1967–2027

Industry or occupation	Number deceased in calendar year 1967	1972	1977	1982	1987	1992	1997	2002	2007	2012	2017	2022	2027
Primary asbestos manufacturing	56	64	80	102	128	149	160	161	147	123	89	59	34
Secondary manufacturing	42	52	70	99	134	167	195	213	214	199	163	123	78
Insulation work	51	65	91	130	173	207	227	229	209	157	128	86	50
Shipbuilding and repair	292	386	542	612	884	865	770	659	541	409	287	201	120
Construction trades	169	193	251	355	495	696	901	1,065	1,176	1,126	882	624	378
Railroad engine repair	38	42	50	60	65	60	45	30	18	7	2	0	0
Utility services	37	41	49	62	76	87	96	99	96	86	68	50	31
Stationary engineers and firemen	120	125	148	168	207	238	259	262	247	214	165	117	71
Chemical plant and refinery maintenance	46	55	70	91	117	138	149	152	145	128	99	71	44
Automobile maintenance	40	48	60	78	100	122	148	172	190	200	190	158	108
Marine engine room personnel	10	11	14	18	19	19	19	18	16	12	9	6	3
Totals	901	1,082	1,425	1,775	2,398	2,748	2,969	3,060	2,999	2,661	2,082	1,495	917

Comparison With Other Studies

Some previous estimates of asbestos-related mortality exceed those discussed here. In the Department of Health, Education, and Welfare estimate that 13%–18% of all cancers in the near future will be asbestos-related, recognition was taken that a large number of individuals were potentially exposed to asbestos, their estimate being 8–11 million compared with ours at 27.5 million, 18.8 million of whom had exposures greater than 2–3 f-yr/ml [Department of Health, Education, and Welfare, 1981]. However, their estimates of the number of heavily exposed individuals was subjective and no explicit adjustment was made for the different employment periods of exposed groups. The estimates by Hogan and Hoel [1981] that up to 12,000 deaths may occur annually from asbestos cancer placed great emphasis upon possible effects from the shipbuilding industry. They, too, subjectively estimated the number of heavily exposed individuals in this trade and did not explicitly account for variations in employment time and may have overestimated the asbestos-related mortality. However, their estimates of the effect of other industries neglected large numbers of individuals with potential exposure. Thus, their estimates for other than shipbuilding would appear to understate the asbestos disease potential [Nicholson, 1981b]. Finally, Blot and Fraumeni [1981] estimate that 120,000 lung cancer deaths will occur (over the population lifetime) from wartime shipyard employment. Our estimate is 25,000. The difference lies largely in our assigning a much lower risk to the very short term (< 1 year) employees.

A lower estimate of 4,000 asbestos cancers annually has been made by Higginson et al [1980] based upon mid-1970 SEER data for mesothelioma and a multiplier of three for other cancers. However, the multiplier depends on time from onset of exposure and population age and exceeded four during the 1970s. (Compare Tables XXII and XXIII.) Further, the previously mentioned limitations of the SEER data apply here. Enterline has also estimated that approximately 4,000 deaths will occur annually [Enterline, 1981]. He attributes 530 lung cancer deaths/yr to primary manufacturing and insulation work, 900 to secondary, 421 to shipyard employment, 212 to auto maintenance, and 438 for other occupations. In addition to lung cancer, he estimates 1,250 other cancers and 333 mesotheliomas will be asbestos-related. The values for primary manufacturing, insulation work, and auto maintenance are similar to our estimates and that for secondary manufacturing considerably more. However, much lower estimates are given for shipbuilding, construction, and other trades. This is in contrast with the finding that a much greater number of mesotheliomas occur in these trades compared with manufacturing and insulation work [McDonald and McDonald, 1980].

Expected Mortality in Asbestos-Exposed Workers

Tables XXII through XXV list the projections for the excess mortality associated with past asbestos exposures. For a given work category, these excess deaths will add to those expected in the absence of exposure but, with the exception of mesothelioma, an "excess" death cannot be distinguished from an "expected" one. As each of these deaths may lead to a claim for compensation or a third party suit, the potential of such cases can greatly exceed the number of excess deaths calculated above. For the heavily exposed (insulators, for example), where the excess deaths exceed those expected, the problem is not a great one. However, for groups with lesser exposure, the total number of lung cancer deaths that could be asbestos-related is very much greater than the numbers in Table XXII. Table XXVII lists the expected lung cancer deaths over the

TABLE XXIV. The Projected Annual Excess Deaths From All Asbestos-Related Gastrointestinal and Other Cancers in Selected Occupations and Industries, 1967–2027

Industry or occupation	Number deceased in calendar year												
	1967	1972	1977	1982	1987	1992	1997	2002	2007	2012	2017	2022	2027
Primary asbestos manufacturing	52	59	65	73	78	77	71	60	47	33	21	12	6
Secondary manufacturing	48	60	72	87	102	105	102	93	79	62	44	27	15
Insulation work	57	74	87	103	114	114	106	90	70	50	32	19	9
Shipbuilding and repair	313	354	384	402	390	339	279	214	153	109	73	43	21
Construction trades	164	225	297	383	449	493	514	497	431	336	230	132	63
Railroad engine repair	25	25	24	23	20	15	10	5	2	1	0	0	0
Utility services	30	35	39	44	48	48	46	41	34	26	18	11	6
Stationary engineers and firemen	80	96	103	118	131	134	130	119	103	83	61	40	23
Chemical plant and refinery maintenance	43	51	58	67	73	74	69	61	49	37	25	15	8
Automobile maintenance	36	46	52	66	80	86	90	88	82	72	58	40	24
Marine engine room personnel	8	9	9	10	10	9	8	6	5	3	2	1	1
Totals	856	1,034	1,190	1,376	1,495	1,494	1,425	1,274	1,055	812	564	340	176

TABLE XXV. The Projected Annual Excess Deaths From All Asbestos-Related Cancer in Selected Occupations and Industries, 1967-2027

Industry or occupation	Number deceased in calendar year												
	1967	1972	1977	1982	1987	1992	1997	2002	2007	2012	2017	2022	2027
Primary asbestos manufacturing	237	312	385	445	494	510	491	445	367	278	187	114	60
Secondary manufacturing	236	304	403	507	610	659	674	649	584	489	367	252	149
Insulation work	266	374	497	612	705	742	723	652	578	392	279	173	94
Shipbuilding and repair	1,452	1,865	2,337	2,493	2,710	2,451	1,076	1,659	1,256	919	628	401	219
Construction trades	778	1,135	1,641	2,143	2,593	3,004	3,308	3,390	3,191	2,697	1,996	1,243	669
Railroad engine repair	129	146	162	167	147	130	91	54	28	10	2	0	0
Utility services	149	187	230	267	299	312	310	290	254	207	152	102	59
Stationary engineers and firemen	434	527	631	721	816	865	875	819	728	602	449	304	179
Chemical plant and refinery maintenance	205	269	337	404	457	482	472	437	375	301	217	142	82
Automobile maintenance	176	236	304	384	470	524	578	586	576	538	458	346	222
Marine engine room personnel	39	47	56	63	64	60	55	46	38	27	19	12	6
Totals	4,101	5,402	6,983	8,206	9,365	9,739	9,653	9,027	7,975	6,460	4,754	3,089	1,739

years 1965–2030 (assuming 1978 rates for subsequent years). As can be seen, the expected numbers exceed the excess by nearly six times. Even if the 32% of individuals with lower exposure are excluded from consideration, the ratios of expected to excess range from 0.4 to 11.7.

Figure 8 shows the distribution of excess lung cancers expected between 1980 and 2030 according to equivalent insulator-years of exposure. (An insulator-year of exposure is that which would create the same risk as employment as an insulator for one year). The approximate exposure for a doubling of lung cancer risk is also indicated. Of the excess lung cancers, 50% occur in individuals with more than this doubling exposure. The total number of lung cancers is also shown for this group and is about 60% more than the excess due to asbestos exposure. For lesser exposures, the curve of the total cancer rises extremely steeply because of the large number of exposed individuals. At the peak of the asbestos related lung cancer curve, the total lung cancer curve would be four times higher. Parenthetically, the exposure distribution of mesothelioma cases will be similar to that of the excess lung cancers.

As mentioned previously at a given exposure level an "excess" death cannot be distinguished from an "expected" one. The problem, however, extends even across exposure levels. Many individuals with less than 5 insulator-years of exposure will have abnormal X-rays, and a significant percentage with greater exposure will have normal X-rays. This follows from the finding that more than 30% family contacts of

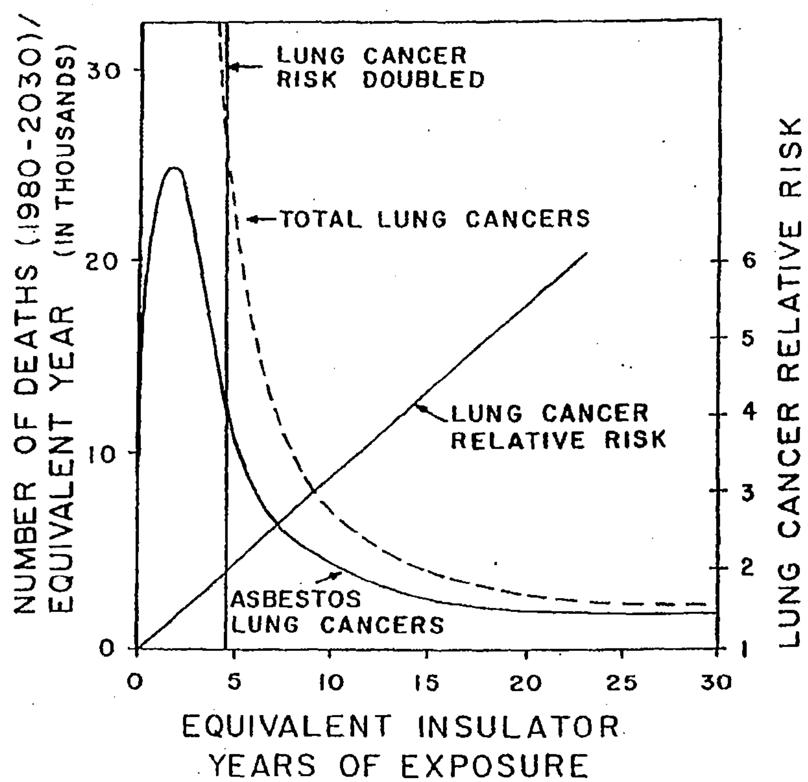

Fig. 8. The distribution of excess lung cancers expected between 1980 and 2030 according to equivalent insulator-years of exposure. (An insulator-year of exposure is that which would create the same risk as employment as an insulator for one year.)

TABLE XXVI. Percentage of Asbestos-Related Cancers That Occur Among Those With Lower Exposure Who Were Exposed After January 1940*

Industry or occupation	Percentage of deaths
Primary asbestos manufacturing	1.2
Secondary manufacturing	1.3
Insulation work	0.1
Shipbuilding and repair	1.9
Construction trades	1.0
Railroad engine repair	1.8
Utility services	0.8
Stationary engineers and firemen	1.8
Chemical plant and refinery maintenance	1.0
Automobile maintenance	12.4
Marine engine room personnel	2.3

*Lower exposure is considered to be less than 2–3 f-yr/ml. The overall contribution to mortality of all individuals with lower exposure is 1.9%.

asbestos factory workers (Anderson et al, 1979) and insulators (Nicholson et al, to be published) have asbestos related X-ray abnormalities (20-30 years after onset of less than 5 equivalent years of exposure) and that a fair number of insulators with 20 or more years in the trade have normal X-rays. Pulmonary function tests are even less revealing. While procedures based on exposure or on clinical evidence of exposure are possible, the allocation of compensation resources to the deserving individuals is clearly an enormously difficult scientific problem. It is an even more difficult social problem.

CONCLUSIONS

Estimates have been made of the numbers of cancers that are projected to result from past exposures to asbestos in a number of occupations and industries. Only those potentially exposed by virtue of their employment have been considered. Additional deaths will result from exposure among family contacts (household contamination), from environmental exposures, from exposure during consumer use of asbestos products, and from exposure while in the Armed Forces, particularly in engine rooms of naval ships. No estimates have been made of deaths resulting from asbestosis. These estimates indicate that:

1. From 1940 through 1979, 27,500,000 individuals had potential asbestos exposure at work. Of these, 18,800,000 had exposure in excess of that equivalent to two months employment in primary manufacturing or as an insulator (>2–3 f-yr/ml). 21,000,000 of the 27,500,000 and 14,100,000 of the 18,800,000 are estimated to have been alive on January 1, 1980.
2. Approximately 8,200 asbestos-related cancer deaths are currently occurring annually. This will rise to about 9,700 annually by the year 2000.
3. Thereafter, the mortality rate from past exposure will decrease but still remain substantial for another three decades.

TABLE XXVII. Expected Lung Cancer Deaths in Selected Occupations and Industries, 1967–2027

Industry or occupation	Number deceased in calendar year												
	1967	1972	1977	1982	1987	1992	1997	2002	2007	2012	2017	2022	2027
Primary asbestos manufacturing	230	327	435	528	604	646	642	588	499	400	308	238	186
Secondary manufacturing	424	628	870	1,100	1,297	1,446	1,518	1,497	1,394	1,237	1,047	833	605
Insulation work	67	97	132	162	187	204	210	203	187	164	138	109	79
Shipbuilding and repair	4,420	5,956	7,550	8,694	9,202	8,553	7,541	5,522	3,595	2,188	1,478	1,144	800
Construction trades	2,501	3,793	5,325	6,761	8,033	9,061	9,648	9,677	9,173	8,246	7,005	5,536	3,942
Railroad engine repair	258	334	404	441	451	421	350	248	143	62	17	20	0
Utility services	316	438	572	684	770	819	827	764	672	566	461	358	256
Stationary engineers and firemen	1,703	2,316	2,969	3,491	3,895	4,114	4,080	3,769	3,253	2,660	2,082	1,557	1,075
Chemical plant and refinery maintenance	736	1,026	1,139	1,576	1,791	1,881	1,870	1,715	1,474	1,205	948	716	504
Automobile maintenance	2,761	3,969	5,358	6,592	7,572	8,231	8,450	8,172	7,543	6,894	5,731	4,646	3,436
Marine engine room personnel	177	236	295	337	361	363	338	288	231	176	133	97	64
Totals	13,593	19,120	25,049	30,366	34,136	35,739	35,374	32,443	28,164	23,798	19,398	15,236	10,947

These projections are from past exposures to asbestos. Over one million tons of *friable* asbestos material are in place in buildings, ships, factories, refineries, power plants, and other facilities. The maintenance, repair and eventual demolition of these facilities provide opportunities for continued significant exposures. If such work is not properly done, or if asbestos is otherwise used with inadequate controls, the burden of disease and death from past exposures will be increased by the environmental exposures of the future.

ACKNOWLEDGMENTS

This work has benefited from the critical review and suggestions of Thomas C. Brown, Fred Siskind, and Howard Vincent of the Department of Labor. Support for this research was provided by Contract J-9-M-8-0165 of the Department of Labor and Center Grant ES00928 of the National Institute of Environmental Health Sciences.

REFERENCES

Anderson HA, Lilis R, Daum SM, Selikoff IJ: Asbestosis among family contacts of asbestos factory workers. Ann NY Acad Sci 330:387-399, 1979.

Asbestos Information Association: Comments submitted to the Environmental Protection Agency on the Ambient Water Quality Criteria for Asbestos, 1979.

Association of American Railroads. Statistics of railroads of Class I in the United States, annual, 1940-1960.

Balzer JL, Cooper WL: The work environment of insulating workers. Am Ind Hyg Assoc J 29:222-227, 1968.

Blot WJ, Harrington JM, Toledo A, Hoover R, Heath Jr, CW, Fraumeni Jr, JF: Lung cancer after employment in shipyards during World War II. N Engl J Med 229:620, 1978.

Blot WJ, Fraumeni Jr, JF: Cancer among shipyard workers. Banbury Report #9. Cold Spring Harbor Laboratory, 1981, pp 37-49.

Bonnell JA, Bowker JR, Browne RC, Erskine JF, Fernandez RHP, Massey MO: A review of control of asbestos processes in the Central Electricity Generating Board. XVIII International Congress on Occupational Health, Brighton, England, 1975.

Bureau of the Census: Census of Manufacturers, Washington, DC, 1939.

Bureau of Labor Statistics: "Employment and Earnings, United States, 1909-1978." BLS Bulletin 1312-11, 1979.

Bureau of Labor Statistics: "Handbook of Methods for Surveys and Studies." US Department of Labor, 1976.

Bureau of Labor Statistics: "Occupational Employment." Report 430, Series, 1,9,10,16,29,55,56,61,81, 1974.

Bureau of Labor Statistics: Occupational mobility of employed workers. Special Labor Force Report 84, 1965.

Bureau of Labor Statistics: Occupational employment in the construction industry, June 1978 (unpublished).

Bureau of Labor Statistics: "Tomorrow's Manpower Needs." App. A., US Department of Labor, vol 1, 1969a.

Bureau of Labor Statistics: "Tomorrow's Manpower Needs." US Department of Labor, vol 4, 1969b.

Bureau of Labor Statistics: Wartime employment, production, and conditions of work in shipyards. BLS Bulletin 824. US Government Printing Office. Washington, DC, 1945.

Christian E: Sec. Local 5, Industrial Union of Marine and Shipbuilding Workers of America. Personal communication, 1981.

Connelly, R: National Cancer Institute. Personal Communication, 1981.

Daly AR, Zupko AJ, Hebb JL: Technological feasibility and economic impact of OSHA proposed revision to the asbestos standard. Roy F. Weston Environmental Consultants-Designers, prepared for Asbestos Information Association/North America, Washington, DC, 1976, vol 2.

DeHague GR: International Association of Machinists. Personal communication, November 14, 1980.

Dement JM, Harris Jr, RL, Symons MD, Shy C: Estimates of dose-response for respiratory cancer among chrysotile asbestos textile workers. Presented at Fifth Int Conf on Inhaled Particles, Cardiff, Wales, Sept. 1980 (in press).

Dept Health, Education, and Welfare: Estimates of the fraction of cancer in the United States related to occupational factors. Sept. 15, 1978 (unpublished). Reprinted in Banbury Report #9, Cold Spring Harbor Laboratory, 1981, pp 701-726.

Department of Labor: Industrial Work Survey: Electric and Gas Utilities, February 1978, p. 60, 1979.

Electric and Gas Utilities: Industry Wage Survey. February 1978, BLS, 1979.

Enterline PE: Proportion of cancer due to exposure to asbestos. Banbury Report #9, Cold Spring Harbor Laboratory, 1981, pp 19-36.

Felton JS: Radiographic search for asbestos-related disease in a naval shipyard. Ann NY Acad Sci 330: 341-352, 1979.

Ferris Jr, BG, Ranadine MV, Peters JM, Murphy RLH, Burgess WA, Pendergrass HP: Prevalence of chronic respiratory disease. Arch Environ Health 23:220-225, 1971.

Fischbein A, Rohl AN, Langer AM, Selikoff IJ: Drywall construction and asbestos exposure. Am Ind Hyg Assoc J 40:402-407, 1979.

Fleisher WE, Viles FJ, Glade RJ, Drinker P: A health survey of pipe covering operations in construction naval vessels. J Ind Hyg Tox 28:9, 1946.

Fontaine JH, Trayer DM: Asbestos control in steam-electric generating plants. Am Ind Hyg Assoc J 36: 126-130, 1975.

Galloway LE: Interindustry Labor Mobility in the United States 1957 to 1960. US Department of Health, Education and Welfare, 1967.

Hammond EC: Smoking in relation to death rates of one million men and women. In: "Epidemiological Study of Cancer and Other Chronic Diseases." Natl Cancer Inst Monogr 19:172, 1966.

Hanis NM, Stavraky KM, Fowler JL: Cancer mortality in oil refining workers. J Occup Med 21:261, 1979.

Harries PG: Asbestos hazards in naval dockyards. Ann Occup Hyg 11:136, 1968.

Henderson VI, Enterline PE: Asbestos exposure: Factors associated with excess cancer and respiratory disease mortality. Ann NY Acad Sci 330:117, 1979.

Higginson J, Bahar JC, Clemmesen H, Demapoulos H, Garfinkel L, Hirayama T, Schottenfeld D: Proportion of cancers due to occupations. Prev Med 9:180, 1980.

Hickish DE, Knight KL: Exposure to asbestos during brake maintenance. Ann Occup Hyg 13:17-21, 1970.

Hill Jr, AB: International Union of Operating Engineers. Personal communication, April 29, 1980.

Hirsch A, DiMenza L, Carre A, Harf A, Pedriget S, Cooreman J, Bignon J: Asbestos risk among full-time workers in an electricity-generating power station. Ann NY Acad Sci 330:137-145, 1979.

Hogan MD, Hoel DG: Estimated risk associated with occupational asbestos exposure. Risk Analysis 1:67-76, 1981.

International Association of Heat and Frost Insulators and Asbestos Workers. Unpublished data (R. Steinfurth, personal communication).

Interstate Commerce Commission: Interstate Commerce Transportation Statistics in the U.S. Part I. Statistical Abstract. Annual.

Jones H: International Union of Operating Engineers. Personal communication, March 3, 1980.

Jones RN: Shipboard asbestos exposure: Hearings before the Subcommittee on Coast Guard and Navigation. US House Committee on Merchant Marine and Fisheries, Serial No. 96-41. Washington, DC, 1980, pp 229-232.

Kaminski R, Geissert KS, Dacey E: Mortality analysis of plumbers and pipefitters. J Occup Med 22:183-189, 1980.

Langer AM: Inorganic particles in human tissues and their association with neoplastic disease. Environ Health Perspect 9:229, 1974.

Lawton GM: Paper on the US Navy asbestos programs and problems. Armed Forces Epidemiological Board, Ad Hoc Subcommittee on Asbestos-related Health Problems. September 29, 1977.

Levine RJ (ed): "Asbestos: An Information Resource." DHEW Publication (NIH) 79-1681, 1978.

Lewinsohn HC, Kennedy CA, Day JE, Cooper PH: Dust control in a conventional asbestos textile factory. Ann NY Acad Sci 330:225-241, 1979.

Liddell FDK, McDonald JC, Thomas DC: Methods of cohort analysis appraised by application to asbestos mining. J R Statist Soc A 140-649, 1977.

Lieben J, Pistawka H: Mesothelioma and asbestos exposure. Arch Environ Health 14:559, 1967.

Lilis R, Daum S, Anderson H, Andrews G, Selikoff IJ: Asbestosis among maintenance workers in the chemical industry and oil refinery workers. In: Biological Effects of Mineral Fibers. International Agency for Research on Cancer, 1980.
Lorimer WV, Rohl AN, Nicholson WJ, Selikoff IJ: Asbestos exposure of brake repair workers in the United States. Mt Sinai J Med 43:207–218, 1976.
Love E: Maritime Administration, US Department of Commerce. Personal communication, Feburary 27, 1976.
Mancuso TF: "Help for the Working Wounded." International Association of Machinists, Washington, DC, 1976.
Maritime Administration, US Department of Commerce: Seafaring employment, ocean-going commercial ships, 1,000 gross tons and over (unpublished).
Marsh J: Director of Environmental Affairs, Raybestos Manhattan, Trumbull, CT. Personal communication.
McDonald AD, McDonald JC: Malignant mesothelioma in North America. Cancer 46:1650, 1980.
Meylan WM, Howard PH, Lande SS, Hantchett A: Chemical market input/output, analysis of selected chemical substances to assess sources of environmental contamination: Task III: Asbestos. Syracuse Resource Corp., prepared for USEPA, Washington, DC, August 1978.
Murphy RLH, Ferris BG, Jr, Burgess WA, Worcester J, Gaensler EA: Effects of low concentrations of asbestos: Observations in shipyard pipe coverers. N Engl J Med 285:1271–1278, 1971.
National Institute for Occupational Safety and Health: Criteria for a Recommended Standard: Occupational Exposure to Asbestos. HMS 72-10267. US Government Printing Office, Washington, DC, 1972.
National Institute for Occupational Safety and Health. Unpublished data. (R. Zumwalde, personal communication).
National Institute for Occupational Safety and Health, National Occupational Hazard Survey, 1972–1974. (Unpublished data on SIC code sequence within alphabetized hazard description).
Newhouse ML, Thompson H: Mesothelioma of the pleura and peritoneum following exposure to asbestos in the London area. Br J Ind Med 22:261–269, 1965.
Nicholson WJ: Insulation Hygiene Progress Reports 3:1. Mount Sinai School of Medicine, NY, 1975.
Nicholson WJ: Dose-response relationships for asbestos and inorganic fibers. Arb och Hÿlsa 17, 1981a.
Nicholson WJ: Comment: The role of occupation in the production of cancer. Risk Analysis 1:77, 1981b.
Nicholson WJ, Perkel G, Selikoff IJ: Cancer for occupational asbestos exposure: Projections 1980–2000. Banbury Report #9. Cold Spring Harbor Laboratory, pp 87–111, 1981.
Nicholson WJ, Selikoff IJ, Seidman H, Hammond EC: Mortality experience of asbestos factory workers: Effect of differing intensities of exposure. Environ Res (in press).
Nicholson WJ: Health hazards of brake repair and maintenance. Report of the National Institute for Occupational Safety and Health, Contract 210-770-119, 1982.
Nunneley JK: Department of the Navy. Personal communication, April 22, 1980.
NYT (Nov. 15, 1981): The New York Times, Workers tested in cancer study, p. 30.
Office of Management and Budget, Executive Office of the President: Standard Industrial Classification Manual 1972. Washington, DC, 1972.
Polland LD: "The American Merchant Marine and the Asbestos Environment." US Maritime Administration, May 1979 (unpublished).
Raybestos Manhattan Co. unpublished data (J. Marsh, personal communication).
Reitze WB, Nicholson WJ, Holaday DA, Selikoff IJ: Application of sprayed inorganic fiber containing asbestos: Occupational health hazards. Am Ind Hyg Assc J 33:179–191, 1972.
Rohl AN, Langer AM, Wolff MS, Weisman I: Asbestos exposure during brakelining maintenance and repair. Environ Res 12:110–128, 1976.
Seidman H, Selikoff IJ, Hammond EC: Short-term asbestos work exposure and long-term observation. Ann NY Acad Sci 330:61, 1979.
Selikoff IJ, Churg J, Hammond EC: Asbestos exposure and neoplasia. JAMA 188:22, 1964.
Selikoff IJ: The occurrence of pleural calcification among asbestos insulation workers. Ann NY Acad Sci 132:351, 1965.
Selikoff IJ, Churg J, Hammond EC: The occurrence of asbestosis among insulation workers in the United States. Ann NY Acad Sci 132:139, 1965.
Selikoff IJ, Hammond EC: Asbestos-associated disease in United States shipyards. CA-A Cancer J for Clinicians 28(2):87–99, 1978.

Selikoff IJ, Hammond EC, Seidman H: Mortality experience of insulation workers in the United States and Canada. Ann NY Acad Sci 330:91–116, 1979.

Selikoff IJ, Nicholson WJ, Lilis R: Radiological evidence of asbestos disease among ship repair workers. Am J Industrial Medicine 1:9–22, 1981.

Selikoff IJ: Disability Compensation for Asbestos-Associated Disease in the United States. US Department of Labor J-9-M-8-0165. June 1982.

Steinfurth R: Director of Health Hazard Program, International Assoc. of Heat, Frost Insulators and Asbestos Workers. Washington, DC (personal communication, 1980).

Stumphius J: Epidemiology of mesothelioma in Walchern Island. Br J Ind Med 28:59–66, 1968.

Wong O: An epidemiologic study of workers exposed to brominated chemicals: With a discussion of multifactor adjustment. Banbury Report #9, Cold Spring Harbor Laboratory, pp 359–378, 1981.

Verma DK, Middleton CG: Occupational exposure to asbestos in the drywall taping process. Am Ind Hyg Assoc J 41:264–269, 1980.

Zumwalde R: National Institute for Occupational Safety and Health, Cincinnati, OH (personal communication, 1980).