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ENVIRONMENTAL AND OCCUPATIONAL HEALTH HAZARDS ASSOCIATED WITH THE PRESENCE OF ASBESTOS IN BRAKE LININGS AND PADS (1900 TO PRESENT): A "STATE-OF-THE-ART" REVIEW

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Throughout the history of automobile development, chrysotile asbestos has been an essential component of vehicle brake linings and pads. Acceptable alternatives were not fully developed until the 1980s, and these were installed in vehicles produced over the past decade. This article presents a "state-of-the-art" analysis of what was known over time about the potential environmental and occupational health hazards associated with the presence of chrysotile asbestos in brake linings and pads. As part of this analysis, the evolution of automobile brakes and brake friction materials, beginning with the early 1900s, is described. Initial concerns regarding exposures to asbestos among workers involved in the manufacture of friction products were raised as early as 1930. Between 1930 and 1959, eight studies were conducted for which friction product manufacturing workers were part of the population assessed. These studies provided evidence of asbestosis among highly exposed workers, but provided little information on the magnitude of exposure. The U.S. Public Health Service proposed the first occupational guideline for asbestos exposure in 1938. The causal relationship between asbestos exposure and lung cancer was confirmed in 1955 in asbestos textile workers in the United Kingdom, and later, in 1960, in South Africa, mesothelioma was attributed to asbestos exposure to even relatively low airborne concentrations of crocidolite. Between 1960 and 1974, five epidemiology studies of friction product manufacturing workers were conducted. During this same time period, the initial studies of brake lining wear (dust or debris) emissions were conducted showing that automobile braking was not a substantial contributor of asbestos fibers greater than 5 μm in length to ambient air. The first exposure surveys, as well as preliminary health effects studies, for brake mechanics were also conducted during this period. In 1971, the Occupational Safety and Health Administration promulgated the first national standards for workplace exposure to asbestos. During the post-1974 time period, most of the information on exposure of brake mechanics to airborne asbestos during brake repair was gathered, primarily from a series of sampling surveys conducted by the National Institute of Occupational Safety and Health in the United States. These surveys indicated that the time-weighted average asbestos concentrations (about 1–6 h in duration) during brake servicing were between 0.004 and 0.28 fibers per cubic centimeter, and the mean time-weighted average concentration was about 0.05 fibers per cubic centimeter. The data also showed that brake mechanics were not exposed to time-weighted average concentrations above workplace exposure limits in effect at the time of the study. From 1975 to 2002, more than 25 epidemiology studies were conducted examining the risks of asbestos-related diseases in brake mechanics. These studies clearly indicated that brake mechanics were not at increased risk of adverse health effects due to exposure to asbestos. Specifically, the studies found no increased risk of mesothelioma or asbestosis in brake mechanics, and no evidence that lung cancer in this occupational group can be attributed to exposure to asbestos during brake repair. This could be due to one or a number of factors: the airborne concentration of chrysotile asbestos and the duration of exposure are too small to be significant, the chrysotile fibers are too short to be biologically important, that chrysotile fibers are substantially less potent than amphibole fibers in inducing lung cancer and mesothelioma, or other yet-to-be-understood factors. Finally, there were 20 studies published during this time period evaluating asbestos exposure or asbestos-related health effects in friction product manufacturing workers. These studies indicated that these workers were historically exposed to concentrations of chrysotile fibers perhaps 10 to 50 times greater than those of brake mechanics, but the risk of asbestosis, mesothelioma, and lung cancer, if any, was not apparent, except for those workers who had some degree of exposure to amphibole asbestos during their careers.

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Braking involves the use of a controlled force to reduce speed, stop, or hold an object in a stationary position, and is accomplished by rubbing two surfaces together that produce friction. Friction is the resistance to the relative motion between two surfaces in contact. Brake linings and brake pads* are the sacrificial frictional materials that are placed in contact with the brake drum or rotor to stop the vehicle (Figure 1). Improvements in brake performance have been a necessary part of the history of the automobile. As automobiles became larger and heavier, and were able to achieve higher speeds, it became increasingly necessary to redesign brakes and friction materials to improve automobile transportation and safety (Harper, 1997).

The evolution of brakes and brake linings and pads has been largely tied to the physical and chemical properties of the types of materials composing the brake linings and pads. The friction materials used in the earliest automobiles (approximately 1890 to 1910) consisted of camel hair, cotton belting, or elm wood, and later, cotton-based textile materials that were impregnated with various ingredients (Harper, 1997). However, as automobiles became more widely used, it was determined that these materials did not offer adequate driver protection, given their inability to withstand heat or control speed under a variety of conditions (Harper, 1997). Heat is an unwanted product of friction and must be dissipated to the surrounding environment as efficiently as possible (Baker, 1986). Early automobile manufacturers were therefore confronted with the need to design a brake that could stop vehicles relatively quickly, but not so quickly that passengers would be thrown from their seats. Brakes were also required to function under different vehicle speeds and environmental conditions (e.g., hot, cold, dry, and wet).

At the start of the 20th century, it was shown that some chrysotile* fibers were sufficiently long and flexible to be woven into fabric for brake linings (Harper, 1997). Unlike cotton fibers or hair, the

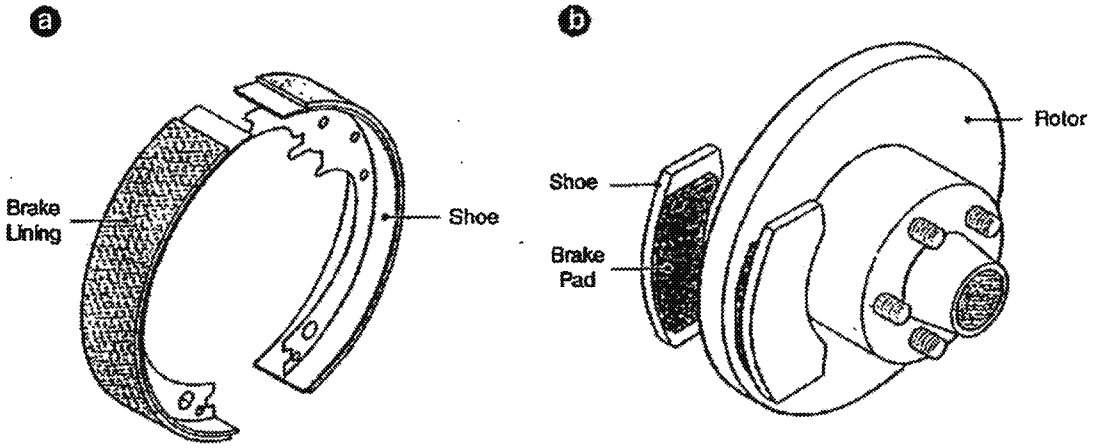

FIGURE 1. Diagrams of a brake lining and brake pad. (a) A brake lining designed to be used with an internal drum brake. (b) A brake pad designed for use with a disc brake.

* The term brake "linings" is used when referring to the friction material used with external band or internal drum brakes. The term brake "pads" is used when referring to the friction material used in disc brakes.

* The word "asbestos" was originally intended by mineralogists to refer to a specific mineral series. However, "asbestos" has been defined in U.S. courts as "a generic term for a number of hydrated silicates that, when crushed or processed, separate into flexible fibers made up of fibrils" (Zoltai, 1977). The U.S. Environmental Protection Agency (EPA) and the Occupational Safety and Health Administration (OSHA) have used the term to refer to six, once commercially viable, silicate minerals: chrysotile, which is part of the serpentine mineral family, and amosite, crocidolite, tremolite, actinolite, and anthophyllite, which are part of the amphibole mineral family (OSHA, 1986; U.S. EPA, 1994). However, the nonfibrous forms of actinolite, anthophyllite, and tremolite are not included in the regulatory definition of asbestos (OSHA, 1992). Unfortunately, many of the studies mentioned in this paper did not indicate the specific type of asbestos applicable to the study. Where possible, the specific form of asbestos applicable to a study is identified. Otherwise, the term "asbestos" will refer to one or more of the six forms of asbestos recognized by OSHA and the U.S. EPA.

chrysotile fibers better maintained their integrity under higher temperatures (such as those generated during braking) and during increased vehicle speeds (Harper, 1997). Chrysotile ore was readily available during this time and, when willowed during refining, was easily separated into silky fibers of various lengths. The longer fibers tended to be curly, flexible, and easily spun into cloth. Chrysotile fibers also had good tensile strength and were heat resistant, durable, and pliable (Skinner et al., 1988). Because of its unique characteristics, chrysotile became a key component of vehicle brake linings starting in the early 1900s. The superiority in performance of the chrysotile fibers to that of other fibers resulted in the continued use of chrysotile through the end of the 20th century, even as vehicular modifications were made to address increasing public demands for improved vehicle performance and faster speeds (Rosato, 1959; Harper, 1997).

It was not long after the initial use of chrysotile fibers in brake linings, however, that exposure to the fibrous forms of asbestos was recognized as a possible occupational health hazard. For example, at least 10 case reports had been published between 1900 and 1930 that suggested exposure to high concentrations of airborne asbestos dust might produce lung disease (Auribault, 1906; Marchand & Riesal, 1906 [as cited in Merewether, 1933]; Murray, 1907; Fahr, 1914; Cooke, 1924, 1927; Pancoast & Pendergrass, 1925; Oliver, 1927; Simson, 1928; Seiler, 1928; Wood, 1929; Wood & Page, 1929; Stewart & Haddow, 1929). By 1930, it was clearly shown that occupational exposures to asbestos fibers in manufacturing settings could cause asbestosis, a potentially debilitating lung disease, at high airborne concentrations (Merewether & Price, 1930). A causal association between occupational exposure to asbestos and two types of cancer (lung cancer and mesothelioma) was later established in the second half of the 20th century based on studies by Doll (1955); Wagner et al. (1960); Mancuso and Coultier (1963); and Selikoff et al. (1964, 1965) (IARC, 1976; Levine, 1981 [in a review for the U.S. Department of Health, Education and Welfare]; Enterline, 1991).

Due to concerns about disease incidence in asbestos-exposed workers, as well as the hazards posed by other chemicals and substances, occupational guidelines for airborne asbestos and a host of other chemicals were offered in the United States as early as the 1940s (Beaetjer, 1984). Federal regulations for asbestos, however, were not established until the early 1970s, when the Occupational Safety and Health Administration (OSHA), U.S. Environmental Protection Agency (EPA), and Consumer Product Safety Commission (CPSC) were formed. Over time, occupational health and environmental regulations regarding asbestos exposure became increasingly stringent, and in the late 1980s, the federal government banned asbestos in products, including brake linings and pads. This ban was later overturned in court; however, the national effort to remove asbestos from commercial products has continued. Today, virtually all new automobiles produced in the United States contain nonasbestos organic (i.e., nonchrysotile) brake linings and pads.

This article presents a state-of-the-art analysis of the development of chrysotile-containing brake linings and pads,* the potential health hazards associated with these materials, and the governing regulations over the last 100 yr. This review also considers automobile clutch plates, the other asbestos-containing friction material product widely used in automobiles; however, the focus is on brake linings and pads because dry clutch plates operate in a closed housing and have a long wear life. Emphasis is placed on what was known over time about the potential health hazards to friction product manufacturers† and brake mechanics posed by exposure to chrysotile in brake linings and pads. This article represents the most comprehensive review of the asbestos exposure and health effects literature to date on these occupational groups. The review of the history of the automobile braking system and brake linings is based on previously published summaries.

* This chronology applies only to U.S. passenger cars and light trucks. The development of automobile braking systems in other countries differs from that which occurred in the United States, and as a result, the history associated with friction material use and development in other countries will also vary from that of the United States.

† The term "friction product manufacturers" is used to refer to those involved in the manufacturing of brake linings and pads. This more generic term is used over "brake lining manufacturers," because some of the studies cited refer to workers who manufactured friction products other than brake linings or pads.

This analysis is divided into three time periods: 1900 to 1959, 1960 to 1974, and 1975 to 2002. These were selected based on what were perceived to be seminal events. The first period covers the use of chrysotile fibers in brake linings and the growing awareness and eventual recognition of asbestos-related diseases in manufacturing workers. The second period is defined by the expanding use of the disc brake by automobile manufacturers; the initial studies of asbestos emissions from automobile braking and occupational exposure of brake mechanics; and establishment of the first federal regulations governing asbestos exposure. The third and final period is marked by the 1975 meeting between researchers from Mount Sinai School of Medicine (Mount Sinai), the National Institute of Occupational Safety and Health (NIOSH), and labor and industry representatives, where the concern regarding brake mechanics and their potential exposure to chrysotile fibers in brake linings and pads was raised and during which most of the exposure surveys and epidemiological studies of brake mechanics were conducted. This section also discusses the search by friction product, brake, and automobile manufacturers for alternatives to chrysotile fibers in brake linings and pads. For each time period, the following topics are addressed in the following order: (1) major developments in brakes and brake linings and pads associated with passenger vehicles and light trucks used in the United States, (2) relevant brake safety and performance issues, (3) exposure and health effects studies on brake mechanics and friction product manufacturing workers, (4) toxicology studies on asbestos-related diseases, and (5) guidelines and regulations governing occupational exposure to asbestos that were in effect. This approach is intended to illustrate at which time specific scientific knowledge about brakes and brake linings and pads, exposure to asbestos during brake repair, as well as asbestos toxicity, was gained over the past century.

THE EARLY YEARS (1900–1959)

During this time period, the use of asbestos in commercial products expanded dramatically. Vehicle brake linings made of chrysotile were initially used in the United States and Europe about 1910. From 1900 to 1959, significant advances were made in the manufacture and design of brakes and brake linings. These developments, as well as related events described in later sections, are summarized in Table 1. In 1930, the first epidemiology study was published showing that exposures to high concentrations of asbestos in dusty manufacturing settings resulted in asbestosis (Merewether & Price, 1930). In 1938, the first guidance level for asbestos in the workplace was proposed (Dreessen et al., 1938). It was two decades later that a causal relationship between asbestos exposures at levels that produced asbestosis and lung cancer was documented for manufacturing settings (Doll, 1955). It was the next decade before the first epidemiological studies of asbestos workers in the United States showing an association between asbestos exposure and lung cancer (Mancuso & Coultier, 1963; Selikoff et al., 1964) and mesothelioma (Selikoff et al., 1964, 1965) were published.

During the 1900 to 1959 period, the focus of health effects studies was primarily on asbestosis and other forms of non-malignant lung disease in dusty industries. Little consideration was given to the types of asbestos to which workers were exposed or differences in exposure among occupations. There were three studies during this early time period that specifically looked at asbestosis in friction material manufacturing workers (George & Leonard, 1939; Brachmann, 1940; Stone, 1940). The data provided during this time period were, however, inadequate to describe the dose-response relationship between airborne concentrations of asbestos and the prevalence of asbestosis among friction product manufacturing workers, and no data were provided on the potential exposures of or possible health hazards to brake mechanics who worked in less dusty settings.

Developments in Brakes and Brake Linings and Pads

In an analysis of the early years of transportation safety, Yanik (1997a) concluded that automobiles were not considered a significant hazard to drivers or bystanders, even with their rudimentary braking and steering apparatus at the turn of the twentieth century. This finding is not surprising given that there were only about 8000 motor vehicles in the United States in 1900 (Sundstrom, 1985). While the stopping distances afforded by the brake systems during this time were excessive (i.e., a distance of 59 ft was necessary to stop a car at 20 mph), automobiles were so few and driving speeds were so

TABLE 1. Timeline of Key Events Relating to the Development of Brakes, Brake Linings, and Brake Performance Standards for Passenger Cars and Light Trucks

Woven Cotton to Woven Asbestos Brake Linings	
1901	Herbert Frood develops and patents cotton-based textile material brake lining
1902	Disc brake is patented (but is not commonly used)
1903	Introduction of the internal-expanding brake mechanism
1906	Raybestos develops woven asbestos and brass wire brake lining
1908	Herbert Frood develops composition brake linings
1920s	Molded brake linings with internal drum brakes become popular
1922	U.S. Bureau of Standards develops standardized test for severe service conditions and long wear/durability of brake linings
Innovation in the Friction Material and Brake Lining Industry	
1930s	Internal-expanding drum brake dominates the market
1946	First asbestos exposure limit is established (5 mppcf)
1948	Introduction of bonded brakes
1950s	Introduction of sintered metal linings
Mid-1950s	Tapered, bonded, riveted linings available directly from automobile factory
1960s	Introduction of semimetallic brake lining formulations
1965	Introduction of the disc brake in U.S. passenger cars
1966	National Motor Vehicle Safety Act is passed establishing the National Highway Safety Bureau (later renamed the National Highway Safety Administration)
1968	Disc brakes become the norm for front brakes of automobiles
Asbestos Substitutes in Brake Linings	
1970s	Initiation of research for non-asbestos organic brake linings
1975	First federal standard (FMVSS 105) developed—defines stopping distance
1986	U.S. EPA proposes banning manufacture of asbestos-containing goods, including friction materials
1989	U.S. EPA passes the Ban and Phase Down Rule
1991	U.S. Court of Appeals annuls the U.S. EPA ban, but companies continue to phase out asbestos-containing brake linings
1993	Per the original U.S. EPA ban, phase-out begins for original equipment manufacturers of passenger cars and light trucks
2000	Virtually all U.S. passenger cars and light trucks use asbestos-free brake linings and pads

low (i.e., no more than 9–16 mph) that collisions were infrequent and often not very serious. Further, because of the openness of the roads, drivers were frequently able to steer out of the way of accidents (Yanik, 1997a). As automobiles became more popular, however, public awareness of brake performance and automotive safety issues increased significantly.

Shift from Woven Cotton and Hair to Chrysotile-Based Brake Linings Automobiles in the late 19th century had either a small brake block applied directly on the tire tread or external band brakes. These latter brakes consisted of a flexible steel band lined with woven frictional material that was drawn tight against the outside of a steel or cast iron drum on the rear wheels, thereby causing friction and braking action (Ferodo, 1968; Newcomb & Spurr, 1971). Elm wood, camel hair, and cotton belting were initially used as friction materials, but after 1901, these materials were replaced with Herbert Frood's more temperature-resistant cotton-based brake block (Harper, 1997). These cotton-based friction materials maintained their integrity as long as the bulk temperature generated during vehicle braking did not exceed approximately 250 °C (Newcomb & Spurr, 1971). However, when the brake linings underwent severe use with continuous application, such as downhill descents, the heat generated during braking charred the cotton-based materials and rendered them ineffective (Harper, 1997). This failure in performance resulted in increased risks to drivers and passengers, as well as other drivers or nearby pedestrians. Safety precautions became even more pronounced with the introduction in 1903 of an internal expanding braking mechanism that effectively sealed off the linings from the cooling air (Harper, 1997), and by 1910, there was an increased number of vehicles on the roadway (approximately 500,000 vehicles; McGeveran, 2001). At this time, a substitute friction material was necessary to meet the evolving needs of brake systems.

Although the use of chrysotile in brake linings* was first conceived in the late 1800s (Hutchings 1896), about 10yr had passed before this idea materialized into a product. In 1906, the Raybestos Company introduced a brake lining made from a combination of woven chrysotile and brass wire in the United States (Automobiles, 1922; Stenberg, 1935), while in 1908, Herbert Frood (who is credited with inventing composition brake linings) introduced chrysotile brake linings in the United Kingdom (UK) (Nicholson, 1995). The first test of the adequacy of an asbestos-based lining reportedly occurred in July 1907, where an asbestos brake lining showed no wear, while a leather lining charred, after equal brake usage on a 4000-lb test car (History, 1935). From that time until the early 1920s, woven asbestos brake linings were predominantly used in the automotive industry (History, 1935).

The asbestos textile fabric used in these linings was woven from long chrysotile fibers spun into a continuous length and these yarns sometimes included wire reinforcement, such as brass, copper, or zinc (Nicholson, 1995). The process used to make brake linings involved carding, spinning, and weaving of the chrysotile fiber into various textile fabrics and was similar to that used in the wool and cotton industries (Automobiles, 1922). The fabric was then impregnated with various oils and resins to provide the desired frictional properties (Soulis, 1929), and once impregnated, the fabric was drained, dried, calendered (i.e., subjected to a rolling operation to straighten out the linings and generate constant thickness), and then cut to width. The lining material was then baked for several hours. After this curing, the hardened material was cut to size using abrasive saws or band saws (Nicholson, 1995). It was normal to handle woven materials as far as possible in the process as coils and to control the thickness and width by rolling rather than grinding (Nicholson, 1995).

Although different weaving techniques and manufacturing processes were developed over time to improve the performance of the woven chrysotile textile linings, the lack of homogeneity of the woven textile material became a limiting factor as vehicle loads and speeds continued to increase (Sneed, 1929; Soulis, 1929; Harper, 1997). The development of improved versions of the woven fabric material was further limited by the relative scarcity of the long chrysotile fiber, which was needed for the making of yarn used for a variety of other asbestos products (Harper, 1997).

Rising Popularity of Internal Drum Brake and Molded Brake Linings Around 1920, a completely new process evolved where shorter chrysotile fibers were mixed with certain resins, oils, and other additives and subjected to pressure in heated dies (i.e., molds) to form the required shape for a lining (Soulis, 1929; Stenberg, 1935; Harper, 1997). The term "molded linings" was, thereafter, used to identify all types of brake linings that were cured in molds under pressure (Rosato, 1959). This new generation of linings included both dry and wet mixed molded formulations, as well as impregnated or nonimpregnated millboard (Rosato, 1959). The molding process completely revolutionized the industry, enabling the manufacturer to use chrysotile fiber grades that were plentiful and less costly, in combination with whatever resins and additives were required, to produce a material with more homogeneous friction characteristics and better wear properties (Harper, 1997). In addition, the process allowed researchers to vary the composition of the blend to create molded friction materials with different characteristics needed to stop the various types of vehicles on the market (Motorist's, 1968; Ferodo, 1968).

Molded linings together with the internal drum brake became popular in the late 1920s due to more severe service requirements for automotive brakes. Because the shoes in internal drum brakes were rigid, the requirements for flexibility in the linings, as was necessary for external band brakes, no longer applied, and molded linings could be used (Motorist's, 1968). Molded linings, unlike woven ones, could incorporate powdered resins that enabled the linings to maintain more consistent friction behavior at higher temperature ranges (Motorist's, 1968; Harper, 1997). Simply changing the amounts of the different raw materials added to the mixture could readily alter the composition of molded linings. This ability to tailor the composition of molded linings for the various types of

*Chrysotile asbestos fibers were the only type of asbestos fibers incorporated into the brake linings and pads for the passenger cars and light trucks sold in the United States (Rosato, 1959; A. E. Anderson, personal communication, 2002). The majority of articles reviewed used the generic term "asbestos" to describe chrysotile fibers in brake linings and pads. The authors of this article have tried to identify the specific asbestos types where possible without compromising the intent of the source article.

vehicles on the market resulted in an increased market demand for molded linings in lieu of woven ones. By the mid-1930s and over the next 30 yr, the internal-expanding drum brake dominated the market (Newcomb & Spurr, 1989). External brakes continued to be used as the parking brake for select car models until at least the mid-1960s (Bendix, 1966; Anderson, personal communication, 2002).

Continued Innovation in the Friction Product and Brake Lining Industries During this time period, there were several additional important developments in the friction product industry. For example, rivets were used to attach brake linings to shoes prior to the 1940s and replacement brake linings were available as prefinished segments, or could be cut and machined from large rolls. It was during these cutting, drilling, and grinding operations that exposures to chrysotile fibers could occur (Sheehy et al., 1989). By the late 1940s, however, bonded brakes were introduced and mechanics merely exchanged old brake shoes for ones with linings already attached to them (Bonding, 1948). The concept of preattached lining and shoe sets became popular for both bonded and riveted linings (Anderson, personal communication, 2002). Because entire shoes were replaced, the need to cut, drill, or rivet replacement brake linings was eliminated, and the potential for exposure to chrysotile by brake mechanics was reduced. For a limited period of time in the mid-1950s, when brake shoes were first installed with a fixed anchor, brake mechanics sometimes needed to taper the new brake linings to achieve a proper fit. Shortly thereafter, however, tapered, bonded, or riveted linings were available from the factory. After 1960, considerably fewer beveling or grinding operations were performed by automobile mechanics replacing brake linings (Sheehy et al., 1989).

In the 1950s, sintered metallic linings were introduced. These linings operated effectively under severe usage conditions and at high temperatures, such as those experienced in some police cars or taxicabs (McCuen, 1959; Reinsch, 1970). Sintered metallic linings were made using powder metallurgy techniques and contained combinations of metallic powders, ceramic powders, and "green" binders (i.e., materials that hold the compact together prior to firing). This type of friction material, which could be iron or copper based, was predominantly used in heavy-duty applications. Some sintered ferrous drum brake linings were later released for a few original equipment manufacturer car applications. However, these linings tended to be sensitive to environmental conditions (e.g., temperature and moisture) and required higher pedal pressures (Anderson, personal communication, 2002). These factors limited their commercial applications such that they were not considered a plausible substitute for asbestos-based linings on autos at that time (ASME, 1988).

Brake Safety and Performance Standards

In the early years of brake lining development, it was up to the individual manufacturers of friction products, in conjunction with auto manufacturers, to determine the appropriate balance between efficiency in stopping a vehicle versus the wearing and durability qualities of a friction material (Automobiles, 1922). Eventually, the friction product, brake, and automobile manufacturers developed laboratory and field tests to ensure that the braking system of a vehicle would perform up to a minimal standard set by the individual automobile manufacturers. These early internal tests eventually evolved into the laboratory and field performance tests similar to those used today by friction product, brake, and automobile manufacturers to test vehicles prior to their commercial release (e.g., Pikes Peak, Detroit City Traffic) (Anderson, personal communication, 2002). The laboratory and field programs were designed to test how well the car and its associated braking system, not just the brake lining, behaved in a variety of operating conditions intended to simulate real-life and nonideal conditions (i.e., hot, cold, dry, and humid environments, steep descents). Over time, as problems or deficiencies in performance arose during actual long-term use of various car models, new field tests were developed and specified by the automotive industry. While the individual auto manufacturers had variations of each test type (i.e., high-altitude environment, hot-temperature environment) tailored to their own specifications, generally all of the U.S. auto manufacturers ran the same types of tests with the philosophy that car models would not be released for use by the public until these were passed (Anderson, personal communication, 2002). For many decades, these internal standards set by the automobile manufacturers were the only requirements of vehicle braking systems; there were no federally mandated safety standards in effect during this era.

TABLE 2. Timeline of Case Reports Published Prior to the First Epidemiology Study of an Asbestos-Exposed Worker Population (1900–1929)

Decade	Year	Topic	Reference
1900s	1906	High mortality in an asbestos textile factory is reported and considered probably due to a pneumoconiosis from asbestos dust	Auribault (1906)
	1906	"Unusual bodies" noted in asbestos worker's lungs	Marchand and Riesal (1906) (as cited in Merewether 1933)
	1907	"Asbestos spicules" observed in lungs of asbestos worker who died of pulmonary fibrosis without tuberculosis (initially observed in 1899)	Murray (1907)
1910s	1914	Asbestos workers with pneumoconiosis, including large "crystals" in lungs	Fahr (1914)
1920s	1924	Lung fibrosis in asbestos worker attributed to inhalation of asbestos dust	Cooke (1924)
	1925	Actual danger in asbestos factories considered comparatively slight. Authors dispute Cooke's 1924 conclusions.	Pancoast and Pendergrass (1925)
	1927	First reviews of asbestosis. "Curious bodies" identified in pulmonary tissues from an asbestos worker.	Cooke (1927)
	1927	Several asbestos-related deaths in British asbestos factories likely misreported as being related to tuberculosis	Oliver (1927)
	1928	"Curious golden yellow segmented structures" reported in lung tissue of four asbestos miners in Rhodesia	Simson (1928)
	1928	A case of pneumoconiosis attributed to inhalation of asbestos dust rather than tuberculosis	Seiler (1928)
	1929	Several cases of pulmonary fibrosis (likely asbestosis) in subjects who had been exposed to asbestos dust	Wood (1929)
	1929	Asbestosis observed in subject who worked as a weaver in an asbestos factory	Wood and Page (1929)
	1929	"Asbestosis bodies" recommended to replace the term "curious bodies." Authors identify the presence of asbestosis bodies in sputum samples as well as pulmonary tissues.	Stewart and Haddow (1929)

Health Effects Studies

During the first 30 yr of the 20th century, there were only a few case reports suggesting that exposure to asbestos might be associated with adverse health effects, either similar to those associated with other dusts or, later, adverse effects unique to asbestos. However, as the use of asbestos became pervasive in society, there was a corresponding increase in the number of case reports. Not surprisingly, additional studies were initiated to understand asbestos-related health hazards. With few exceptions, the workers evaluated in those studies performed activities in manufacturing settings (e.g., among the dustiest environments) and were not end users of asbestos-containing products. Brake mechanics were therefore not included in the earliest study populations. Some of the early studies included friction product manufacturing workers, although they were not the focus of these investigations nor were the data for friction product manufacturing workers sufficient to quantitatively characterize their exposures to asbestos or risks of contracting asbestosis.

In general, the focus of many occupational health studies conducted prior to 1930 was on the dusty trades, such as coal mining and stone masonry. It was recognized that long-term exposure to highly dusty environments could lead to lung diseases—generally called pneumoconioses or "dusty lung disease" (Hoffman, 1918; Pancoast & Pendergrass, 1925). During this time period, asbestos was initially considered to be similar to certain other workplace dusts, such as silica and coal dust, to which persons were exposed in other occupations.

As shown in Table 2, the first documented case of lung disease associated with asbestos exposure was observed in 1899 and reported in 1907 (Murray, 1907). Specifically, necropsy revealed extensive and diffuse pulmonary fibrosis and the presence of asbestos spicules in the subject's lungs (Murray, 1907). Testifying before an inquiry at the British Government Commission on Occupational Disability, Murray (1907) connected the workplace exposure to airborne asbestos to the scarring he observed in the worker's lungs (Kilburn, 1992). Around the same time, case reports were published in France and Germany (Auribault, 1906; Marchand & Riesal [1906], as cited in Merewether, 1933; Fahr, 1914), and factory inspectors in the UK and the United States were reporting about the possible

dangers associated with asbestos dust observed during their surveys of manufacturing environments (Anonymons, 1898; Collis, 1911; Hoffman, 1918).

More than 10 years later, Cooke (1924) published a description of pulmonary fibrosis in a woman who had worked for 20 years in an asbestos textile factory. Shortly thereafter, the term "asbestosis" was used to describe the asbestos spicules observed in the lungs of case report subjects, and the term "pulmonary asbestosis" was used to describe the pneumoconiosis condition observed (Cooke, 1927, 1929; McDonald, 1927; Oliver, 1927). By the late 1920s, additional case reports were published in the literature, all of which contributed to a growing awareness that inhalation of asbestos dust might be a potential cause of disease (Pancoast & Pendergrass, 1925; Seiler, 1928; Simson, 1928; Stewart & Haddow, 1929; Wood, 1929; Wood & Page, 1929). However, these early case reports provided little, if any, information regarding the specific activities of the workers, the concentration of airborne particles, or details about the disease in these workers. Often, these reports were also complicated by the presence of tuberculosis (TB), making it unclear whether the lung dysfunction or pathology was primarily caused by asbestos or TB, or whether one disease had to precede the other (Pancoast & Pendergrass, 1925). Furthermore, these workers had also often been exposed to other dusts during their careers, were smokers, and may have had lung infections—all factors that made it more difficult to clearly associate asbestos exposure with respiratory disease. For example, it was recognized that "the proneness of workers with dust fibrosis to be affected by pulmonary tuberculosis has been shown to be the main cause of the increased mortality rate from the latter disease in certain dusty occupations" (Merewether & Price, 1930, p. 5). Thus, although there were a number of case reports about asbestos, their usefulness was limited. The purpose of case reports is to describe interesting and unusual observations, but they cannot be used to determine disease causation (Last, 2001). Rather, an epidemiology study that considers exposure to the agent (and confounders), the background rate of the disease, and the rate of the disease in the exposed population is needed to confirm a causal association.

Confirmation of the health hazards specific to asbestos exposure occurred around 1930 after Merewether and Price (1930) conducted the first epidemiology study* of asbestos manufacturing workers, which was brought about by an earlier case report of a worker with asbestosis who did not appear to have TB. In this cross-sectional study conducted in the United Kingdom, the population was divided into groups representing the following manufacturing processes: (1) crushing, opening, disintegrating, and mixing; (2) carding; (3) spinning, twisting, doubling, and plaiting; (4) insulating mattress making; (5) weaving and associated processes; and (6) miscellaneous processes and unclassified workers (Merewether & Price, 1930). Merewether and Price (1930) concluded that there was a clear risk of developing asbestosis from inhalation of asbestos dust, and that duration of exposure and amount of dust inhaled were key factors for predicting disease. This study did not provide data on the dose-response relationship between asbestos exposure and disease, but appears to have resulted in the British Asbestos Regulations of 1931 (His Majesty's Stationery Office, 1931), which required monitoring and dust control in industries where workers were exposed to asbestos (Bartrip, 2001). Following their study, the number of asbestos-related health effects studies of worker population published in various journals increased dramatically. These studies considered asbestos-related exposures and nonmalignant disease incidence in a number of occupations, including textile manufacturers, mattress makers, miners, and other manufacturing operations† (Osborn, 1934; Wood & Gloyne, 1934; Fulton et al., 1935; Home Office, 1935; Lanza

* There are two types of commonly used observational epidemiological studies: cohort and case-control. In cohort studies, the investigator selects a study population of exposed and nonexposed individuals and follows both groups to compare disease incidence rates or disease-specific mortality rates in the two groups. The case-control study divides the study participants into two groups: the first group (cases) includes people who have the disease to be studied and the second group (controls) consists of people who do not have the disease. Epidemiologists then obtain and compare data regarding past exposures by both groups. A separate category of observation studies is surveillance studies, which use preexisting data sources such as death certificates to determine cause of death and recorded occupation. Record-linkage studies link disease and occupational registries to determine occupation-disease associations. An additional study design is the cross-sectional study that examines the relationship between disease and other factors, such as exposure, at a point in time.

et al., 1935; Page, 1935; Donnelly, 1936; McPheeters, 1936; Windel, 1937 [as cited in Teleky, 1937]; Dreessen et al., 1938; George & Leonard, 1939; Brachmann, 1940; Stone, 1940; Vigliani, 1940 [as cited in Teleky, 1941]; Fleischer et al., 1946, Wegelius, 1947; Castrop, 1948; Lynch & Cannon, 1948; Canepa, 1949; Barnett, 1949; Cartier, 1952; Lynch, 1953; Breslow et al., 1954; Knox & Beattie, 1954; Bonser et al., 1955; Cartier, 1955; Doll, 1955; Frost et al., 1956; Williams, 1956; Thomas, 1957; Braun & Truan, 1958; Horai et al., 1958). With few exceptions, the workers identified in these studies performed activities in manufacturing settings, and were not end users of asbestos-based products. Most studies during this period did not identify the type of asbestos or quantify the concentration of fibers to which workers were exposed. Fulton et al. (1935) did indicate that chrysotile composed about 95% of the asbestos in commerce in the United States during the 1930s. Brake linings for automobiles in North America and Europe are believed to have contained only chrysotile fibers, although amphibole fibers are reported to have been used in some railroad engine brake linings in the UK during this time period (Newhouse et al., 1982), and amphibole fibers, sometimes in combination with chrysotile fibers, were also used during this period in insulation and other products such as asbestos cement pipe (Fleischer et al., 1946; Finkelstein, 1983). The absence of specific information on chrysotile and amphibole fiber concentrations experienced by populations with potential mixed fiber exposures complicates the understanding of the contribution of fiber type to reported health effects for workers during this era.

Exposure and Health Effect Studies of Workers in the Manufacture of Asbestos Brake Linings Of the more than 30 studies of workers in asbestos-related industries that were published between 1930 and 1959 referenced earlier, eight discussed in varying levels of detail the potential exposures to and/or possible diseases observed in friction product manufacturing workers but none provided a quantitative evaluation of asbestos exposure nor incidence of asbestosis (Merewether & Price, 1930; Osborn, 1934; Fulton et al., 1935; Lanza et al., 1935; George & Leonard, 1939; Brachmann, 1940; Stone, 1940; Thomas, 1957) (Figure 2).

As indicated earlier, Merewether and Price (1930) conducted the first epidemiology study of asbestos workers in primarily the textile branch of the industry, which likely included some workers employed in the manufacture of woven brake linings, although no specific information on this component of the study population was provided. They concluded that there was an increased incidence of asbestosis in asbestos manufacturing workers in the dusty factory environments evaluated in the UK. No quantitative exposure information was provided in this study, which is not surprising given that the field of industrial hygiene was just emerging. Despite this lack of quantitative information, Merewether and Price (1930) reported that they believed asbestos could be safely handled in the manufacturing setting with the implementation of proper industrial hygiene engineering controls: "From the consideration of the nature of the processes in the asbestos industry, and other relevant matters, it is felt that the outlook for preventive measures is good. That is to say that in the space of a decade, or thereabouts, the effect of energetic application of preventive measures should be apparent in a great reduction in the incidence of fibrosis" (Merewether & Price, 1930, pp. 17–18).

Several years later, Osborn (1934) reported air sampling results from four asbestos plants that produced woven and molded brake linings, clutch facings, and wire insulation. Dust measurements collected during these operations ranged from less than 1 to 82 million particles per cubic foot (mppcf), depending on the operation and whether dust control measures were in place (Osborn, 1934).* No analysis of health effects was performed in this study. Around this same time period, Fulton et al. (1935) conducted a cross-sectional study of asbestos factory workers from various industries including woven brake lining manufacturing. Six air samples of dust from two plants in areas where the weaving of brake linings took place showed concentrations of 8.5 to 34.7 mppcf.

[1] Includes studies published in or translated into English that provide data on the incidence of an asbestos-related disease in a worker population, and is not intended to be a complete list of asbestos-related publications during this era.

* The impinger collection/light field illumination dust counting method was the common method for determining dust concentrations in air from the late 1930s to the early 1960s. Air concentrations reported by this method are in million particles per cubic foot of air (mppcf) and are total dust counts, which are nonspecific for fibers. A thorough evaluation of asbestos sampling techniques is provided in Walton (1982).

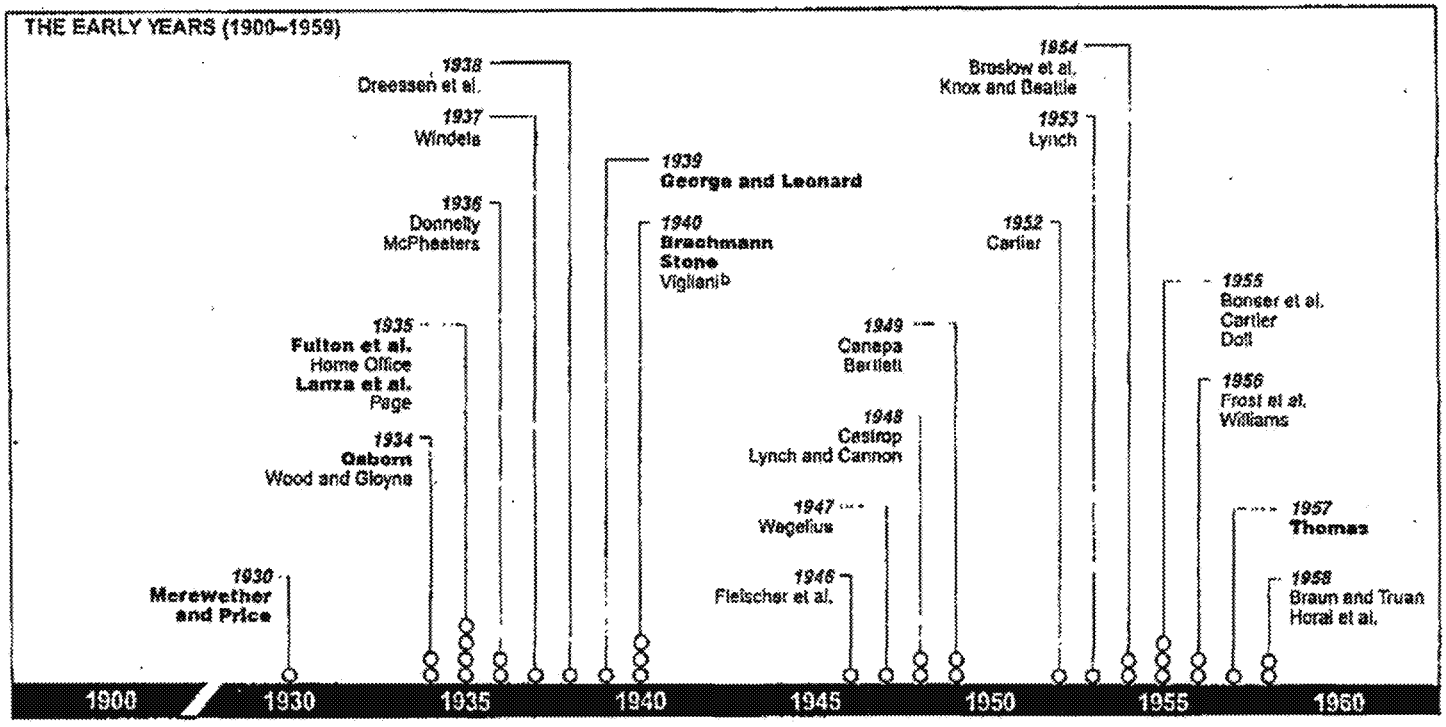

FIGURE 2. A Chronological depiction of various important exposure and health effects studies of worker populations exposed to asbestos (1900–1959). Note: Citations in bold lettering indicate that workers involved in friction product manufacturing (e.g., production of brake linings) were included in the study population. (a) As cited in Teleky (1937). (b) As cited in Teleky (1941).

Fulton et al. (1935) also reported that 14 of 56 workers (approximately 25%) evaluated from the textile departments of the four fabricating facilities studied had slight or moderate symptoms of asbestosis. Whether any of these workers were involved in the manufacturing of brake linings was not specified. Lanza et al. (1935) conducted a similar cross-sectional study of 126 workers in asbestos fabricating plants in the United States, including one facility that produced brake bands and clutch plates. Airborne dust samples collected in the molded brake band and clutch department showed concentrations of one-half and three-fifths mppcf with asbestos comprising about 25% of the dust. Lanza et al. (1935) reported that 67 of the 126 workers studied were diagnosed with asbestosis; however, it is again unclear how many, if any, of these were involved in the manufacture of brake linings and clutch plates or what specific exposures they had experienced. Lanza et al. (1935) concluded it was "not practicable as yet to establish standards for the asbestos dust content of air" (p. 11), and likewise Fulton et al. (1935) noted that it was not "possible from our findings to establish the maximum safe concentration of asbestos dust in the air" (p. 28).

Several years later, more specific evaluations of the health effects of asbestos in friction material manufacturing workers were conducted. George and Leonard (1939) and Stone (1940) examined cases of asbestosis in brake lining manufacturing workers as part of disability claims submitted to insurance companies. These researchers diagnosed asbestosis in 13% (George & Leonard, 1939) and 82% (Stone, 1940) of the workers examined, respectively, but neither study provided quantitative information on the concentration of airborne dust to which these workers may have been exposed nor the criteria used to diagnose asbestosis. Furthermore, it was not known whether the effects were caused by handling or processing raw asbestos or due to exposure to dusts associated with fabricating the molded lining. Similarly, Brachmann (1940) in a cross-sectional study reported asbestosis in a subset (number unspecified) of 151 textile brake lining manufacturing workers involved in grinding and drilling operations in Germany, but no quantitative information on airborne dust levels was provided.

In the mid-1950s, Thomas (1957) conducted a cross-sectional study of asbestos factory workers from various industries in Australia including brake lining manufacturing. Although this researcher observed asbestosis in 15% of the workers, the study (as in previous studies) did not specify whether any of the workers diagnosed with asbestosis were involved in the manufacture of brake linings (Thomas, 1957). In addition, no quantitative information on the concentration of airborne dust to which these workers may have been exposed was provided.

Although studies were conducted from the 1930s to the 1950s that investigated asbestosis in asbestos manufacturing workers, including friction product manufacturing workers, most of these studies were not specifically focused on friction product manufacturing workers. These studies did show asbestosis among highly exposed worker populations; however, they often contained inadequate information to determine the asbestos exposures of these workers, and therefore were insufficient to estimate the dose-response relationships for friction product manufacturing workers and other manufacturing workers exposed to asbestos. The tasks of the workers diagnosed with asbestosis were not specified; quantitative exposure information was not provided; and quantitative diagnostic criteria were not applied in identifying asbestosis. Finally, these studies did not address lung cancer.

There also were no studies of brake mechanics during this period. Because the studies of friction product manufacturing workers during this era were insufficient to characterize exposures and disease incidence for this occupation, they too provided no insight as to the potential asbestos exposures or risks to brake mechanics. The working conditions as well as the types and duration of activities potentially contributing to asbestos exposures of the two groups of workers were very different from one another, and end users of asbestos such as brake mechanics were generally considered to work in far less dusty environments than friction material manufacturing workers and therefore to be at lower risk of adverse health effects.

The Dreessen Study In the late 1930s, the assistant U.S. Surgeon General and several coworkers were the first researchers to quantify exposure to asbestos and relate it to specific health effects (Dreessen et al., 1938). This study was commissioned and conducted by the U.S. Public Health Service, the primary environmental and occupational health agency within the federal government during that time. The study consisted of 541 employees of asbestos textile factories in North Carolina

and, based on review of the air sampling data and the observed incidence of asbestosis in workers, it was concluded that exposure to airborne concentrations of less than 5 mppcf of dust containing asbestos would not produce an increased risk of developing asbestosis. These researchers further concluded that "if the dust concentration in asbestos factories could be kept below 5 million particles...new cases of asbestosis probably would not appear" (Dreessen et al., 1938, p. 177). Although considered a thorough study for the time (McDonald, 1984), one shortcoming, which Dreessen noted, was that the employees studied were much younger than the average industrial employee and that they had been employed in this industry for relatively short periods of time. Specifically, about 85% of the employees studied had been exposed for less than 10 yr (Dreessen et al., 1938).

Little Concern Expressed During This Era for End Users of Asbestos-Containing Products During this time period, thousands of products containing asbestos fibers were being developed with numerous end uses; however, only a few asbestos-related studies were published that identified asbestos-related exposures to end users of asbestos-containing products, as shown in Figure 2 (Fleischer et al., 1946; Canepa, 1949; Breslow et al., 1954; Frost et al., 1956). The largest epidemiology study involving end users of asbestos-containing products, conducted by Fleischer et al. (1946), indicated that few cases of asbestosis were observed in more than 1000 shipyard pipe fitters exposed to amosite asbestos fibers in pipe-covering material. Based on this observation, the researchers concluded that covering pipe with asbestos insulation, known to be a dusty task, was not a dangerous occupation. Similar to the Dreessen et al. (1938) study, a shortcoming of this study is that only 5% of those examined had worked in this occupation for more than 10 yr (Fleischer et al., 1946). Nevertheless, over the course of the next 15 yr, the focus of asbestos-related health effects studies continued to be on workers in manufacturing environments, and not on end users of asbestos products. Not surprisingly, no industrial hygiene or worker health studies were therefore published on brake mechanics (who used finished products) prior to 1970.

Confirmed Association Between Asbestos Exposure and Lung Cancer Although there were numerous case reports published in the 1930s and 1940s suggesting that exposure to asbestos might be linked to an increased risk of lung cancer, it was not until 1955 that a clear epidemiological association between asbestos exposure and lung cancer was confirmed (Doll, 1955). Prior to that time, it was difficult to know whether smoking; asbestos; exposure to other dusts; previous lung ailments, such as tuberculosis; or other factors (individually or combined) were the cause of an increased incidence of lung disease among exposed asbestos workers. Specifically, Doll conducted a cohort mortality study of 113 men and, on the basis of the results, concluded that asbestos workers with 20 or more years of experience had 10 times the risk of developing lung cancer compared to the general population. In this cohort, all 11 men whose deaths were attributed to lung cancer also had signs of asbestosis. Doll further observed that the incidence of both asbestosis and lung cancer associated with asbestos exposure greatly diminished as the number of years during which workers were exposed prior to 1930 decreased (i.e., prior to implementation of dust control measures in the UK). Thus, it was unclear to him whether the increased incidence of lung cancer was due only to very high exposure to asbestos or whether there might also be an increased risk at much lower airborne concentrations. Specifically, he noted that "Whether the specific industrial risk of lung cancer has yet been completely eliminated cannot be determined with certainty; the number of men at risk, who have been exposed to the new conditions only and who have been employed for a sufficient length of time, is at present too small for confidence to be placed in their experience. It is clear, however, that the risk has for some time been greatly reduced" (Doll, 1955, p. 86).

It was during the same time period that Breslow et al. (1954) published the first epidemiological study showing occupation and cigarette smoking as factors in lung cancer. With regard to occupations using asbestos, Breslow et al. (1954) concluded that "The group of steam fitters, boiler makers, and asbestos workers lies on the borderline of statistical significance when the effect of cigarette smoking is controlled" (p. 180). In short, during the 1950s, a number of researchers were uncertain whether exposure to asbestos alone, without exposure to cigarette smoke, could increase the incidence of lung cancer.

Toxicology of Asbestos

At least until the mid-1940s, the field of toxicology was in its infancy. Until this time, very few animal toxicity studies were being conducted, and of those conducted, most were designed to identify whether any health effects occurred within one or two days of exposure (acute toxicity testing). Long-term (chronic) toxicology studies that mimicked occupational exposures were generally not conducted until the 1950s. Additionally, the Society of Toxicology was not formed until 1960.

Despite several early case reports, which raised questions about the health hazards posed by asbestos exposures, few attempts were made during this time to address the severity or dose-response relationship for asbestos diseases using worker population data or animal toxicology studies. In the 1930s and 1940s, a small number of toxicology studies were initiated to better understand the development of asbestos-related health effects, including the relationship between asbestos exposure and TB, with the intent of helping to treat or alleviate symptoms of asbestos-induced fibrotic changes observed in worker populations. These studies evaluated acute, subchronic, or chronic exposures to asbestos via several routes of administration in various species to replicate asbestos-related fibrosis. These early studies suggested that the severity of asbestosis and the fibrotic response was dependent on the size of the fiber (i.e., length), as well as the animal species studied, with rats and guinea pigs generally identified as the more sensitive species to asbestos-induced fibrosis (Gardner, 1942; King et al., 1946; Vorwald et al., 1951). Vorwald et al. (1951) were the first to publish a comprehensive series of experiments comparing the fibrotic response of different asbestos fibers of varying lengths in several animal species. They also reported a difference between lung response and fiber size, indicating the significance of fiber size in the pathogenesis of asbestosis. In general, these early studies identified that longer fibers induce more severe fibrosis than short fibers (King et al., 1946; Vorwald et al., 1951).

Although asbestos-related lung fibrosis was successfully reproduced in animal models by the late 1950s, the laboratory studies at the time were unable to induce lung cancer in animals via inhalation (Vorwald et al., 1951; Lynch et al., 1957). Only one study reported lung tumors in mice following chronic inhalation exposure to chrysotile (Nordmann & Sorge, 1941); however, results of the study were later questioned because one of the tumors they identified was an adenomatous type not uncommon as a spontaneous tumor in mouse lungs and the other lesion was questionable as to whether it may have been an area of squamous metaplasia, rather than neoplasia (Smith et al., 1965). It has also been alleged that data supporting the association between asbestos and lung cancer in animals was omitted from the Vorwald et al. (1951) study (Hardy & Egilman, 1991; Lillenfeld, 1991). However, as noted earlier, the association between asbestos exposure and lung cancer was confirmed by an epidemiological study (Doll, 1955) during the same time frame as the animal studies discussed earlier. Asbestos is an agent for which epidemiological studies, rather than animal toxicological studies, provided the clearest evidence of the association of asbestos exposure with both asbestosis and lung cancer.

Asbestos Guidelines and Regulations

For the first four decades of the 20th century, there were no national guidelines or regulations to limit exposure to airborne contaminants in the workplace or outdoors (i.e., ambient air). Various states had offered some guidance values for certain chemicals and substances, but these were largely ignored or were intended for selected industries (Frederick, 1984). This is not surprising given that people interested in industrial hygiene were first coming together in the early 1930s through organizations such as the American Public Health Association (APHA) and the National Safety Council (NSC). The American Conference of Governmental Industrial Hygienists (ACGIH) and the American Industrial Hygiene Association (AIHA) were not formed until 1938 and 1939, respectively. Also in 1938, the American Association of Industrial Physicians and Surgeons (AAIPS) established a permanent conference dedicated to occupational disease that was composed largely of industrial hygienists. In these early years, it was estimated that there were only approximately 300 industrial hygienists in the United States, by 1950, this number increased to approximately 900 (Clayton & Clayton, 1994).

By the early 1940s, ACGIH had formed a subcommittee to recommend exposure limits for chemicals and substances commonly found in the workplace (Beaetjer, 1984). The need for such a committee was recognized as important for bringing order and uniformity to the various state and local industrial hygiene units with their numerous, and often conflicting, recommendations for the protection of workers (Stokinger, 1981). The first list of recommended values was issued by ACGIH in 1946. Values were compiled from a list reported during ACGIH's 1942 annual meeting, a list published by Warren Cook in 1945, and the published values of the Z-27 Committee of the American Standards Association (ACGIH, 1968; Paustenbach, 2000).

The ACGIH guidelines regarding the purpose of occupational exposure limits for airborne chemicals were intended to "represent conditions under which it [was] believed that nearly all workers would be repeatedly exposed day after day without adverse effect" (Beaetjer, 1984) and "should not be regarded as fine lines between safe and dangerous concentrations" (LaNier, 1984). This philosophy is reflected in the terminology that the ACGIH subcommittee used to represent its recommended exposure limits. Initially, the term "maximum allowable concentration" (MAC) was used to describe the recommended exposure limit. However, this term erroneously implied that the concentrations above the MAC posed a genuine potential health hazard; therefore, the subcommittee changed the term to "threshold limit value" (TLV) in 1948 (LaNier, 1984). After 1953, a prefacing statement was applied to the TLVs, in which the term was defined as the "maximum average atmospheric concentrations to which workers may be exposed for an eight-hour working day without injury to health" (LaNier, 1984). In later years, modifications of the definition of the TLV were developed and discussed within the preface of the annual TLV booklet.

As discussed earlier, Dreessen et al. (1938) recommended an occupational guideline of 5 mppcf for exposure to airborne asbestos. Prior to 1946, several states had adopted this recommended guideline (Air Hygiene Foundation [Illinois], 1941; Oregon State Board of Health, 1945; State of California Department of Industrial Relations, 1945), and, not surprisingly, ACGIH adopted 5 mppcf as its recommended exposure limit for all types of asbestos in 1946. The report by Dreessen et al. (1938) appears to have served as the primary basis for ACGIH's first TLV for asbestos (ACGIH, 1962).

THE MIDDLE YEARS (1960–1974)

From 1960 to 1974, additional developments occurred in the manufacturing and design of brakes and brake friction materials. Disc brakes, which offered cooling far superior to internal drum brakes, were introduced in the mid-1960s and later adopted for use in the front wheels of most automobiles. A new friction product formulation, called semimetallic, was developed and incorporated for use with disc brakes. In addition, the National Motor Vehicle Safety Act was passed, which led to the first brake system performance requirements by the federal government. Further, concerns were expressed during this time period with regard to potential asbestos exposures and related health effects for a wider variety of worker populations. In particular, studies conducted and published during this period suggested that asbestos exposures could result in chronic diseases other than asbestosis and lung cancer, such as mesothelioma, a rare cancer (Wagner et al., 1960), and that exposure to even relatively low concentrations of asbestos fibers could pose a significant health hazard. The question arose whether the type of asbestos fiber exposure (i.e., chrysotile versus amphibole) was an important predictor of disease. The importance of fiber length continued to be discussed.

The focus of asbestos health effects studies also expanded to include manufacturing environments and end users of asbestos-containing products, including brake linings and pads. To investigate these issues further, additional studies were conducted during this period, including efforts to (1) measure the amount of chrysotile fibers released from brake linings and pads during braking, and (2) quantify the exposure of brake mechanics to asbestos and incidence of observed asbestos-related health effects. In 1970, the first national health regulations pertaining to asbestos exposures in the workplace were established (OSHA, 1971a). The following sections describe these issues in more detail.

Developments in Brakes and Brake Linings and Pads

Introduction of Disc Brakes Although the internal drum brake dominated the automobile market from the 1930s until the 1960s, changes in automobile design (e.g., reduced brake pedal effort, higher horsepower engines, and increased car weight) revealed that these brakes had an important limitation (Rodger, 1950). Specifically, under continuous downhill braking (or quick repeated hard braking from high speeds), the internal drum brake could overheat and lose its ability to stop a vehicle with a reasonable brake pedal effort (Disc, 1969). This problem stemmed from the fact that most of the heat generated during braking had to be transferred through the relatively thick wall of the drum before it could be dissipated to the surrounding air, which was its only coolant. The brake drum was also nested within the wheel, which restricted access to airflow that promoted cooling. These design constraints resulted in heat building up within the drum, which led to unacceptably high temperatures in the brake linings (Disc, 1969). The effect of such continued heat was that brake linings could wear out rapidly and some drivers were unable to apply sufficient brake pressure to stop the car.

To address this issue, disc brakes were introduced for the front wheels of passenger vehicles in the 1960s. This type of brake consisted of a caliper containing two flat small friction pads (i.e., brake pads), which were clamped onto a revolving disc when the brake was applied. The disc brake was attached to and rotated with the hub, which carried the road wheel. The caliper, which retained the brake pads, was the means for forcing the pads into contact with the disc. Because of its unique design, the disc brake offered cooling that was far superior to that of the internal drum brake. Heat was dissipated directly from the hottest part of the front disc by a greater surface area and cooling airflow. Likewise, when the brake was released, the working faces of the brake pads were directly exposed to airflow and were cooled between brake applications. Because both faces of the disc were working surfaces, the total area exposed to cooling air was appreciably greater than in an internal drum brake of comparable braking power. The open-to-air arrangement of the disc brake meant that the brake was self-cleaning, and accumulations of dust (which occurred in the internal drum brakes) were avoided. The ultimate effect was reduced brake wear and a diminished likelihood of scoring the metal working surfaces (Disc, 1969).

Phase-In of Front-Wheel Disc Brakes The effectiveness of the disc brake at high speeds as well as other functional considerations (e.g., fade resistance, cooling rates, and consistency in performance), led to its widespread development for passenger vehicles during the mid-1950s and early 1960s (Anderson, 1995). Disc brakes were first introduced in U.S. production cars in 1965 (Rinek & Cowan, 1995). The new Federal Motor Vehicle Safety Standards (FMVSS) braking requirements resulted in front disc brakes being installed on virtually all cars by 1974 (Jacko et al., 1984). Internal drum brakes, however, remained on the rear of most U.S. cars during this period, because rear disc brakes were readily contaminated by water and particles coming off the front wheels. They were also difficult to design with an integral and dependable parking brake (Anderson, personal communication, 2002).

Initially, chrysotile-based pads were used with the disc brake (Disc, 1969; Harper, 1997), but in the 1960s, a new friction material was developed called "semimetallic" (or "resin-bonded metallic"). This formulation provided better performance in disc brakes than the traditional chrysotile formulations with respect to stable friction, improved fade resistance and durability, rotor compatibility, and quieter operations (Jacko & Rhee, 1992). The semimetallic pads had little strength, however, so a chrysotile-based backing material was added to the semimetallics during the molding process (Anderson, personal communication, 2002). With the second generation of better performance semimetallic formulations, semimetallic pads gained general acceptance by the vehicle manufacturers in the mid-1970s, despite their relatively higher costs, which were due to more expensive ingredients, higher specific gravity, and more costly processing requirements (Jacko et al., 1980). Semimetallic pads were used primarily in automobiles that were driven aggressively, such as highway patrol cars and taxis, but for other vehicles driven under more normal conditions, these pads were found not generally to work well.

Brake Safety and Performance Standards

First Federal Standard for Brake Systems By the mid-1960s, there were over 61 million registered vehicles on U.S. roadways (McGeveran, 2001) and a growing number of annual fatalities associated with automobile use (National Motor Vehicle Safety Act, 1966). In fact, it was estimated that about 1.6 million persons had died on the roads since the introduction of the automobile (National Motor Vehicle Safety Act, 1966). Alarmed by this fact, the U.S. Congress sought to involve the federal government in the area of vehicle safety (Yanik, 1997b). Prior to this time, automobiles were subject to only a small number of state regulations, and the federal seat belt and brake fluid laws. Consequently, the National Motor Vehicle Safety Act was passed in 1966, which mandated federal regulations for the design and manufacture of all automobiles in the U.S. (Yanik, 1997b). In the legislative preamble to the National Motor Vehicle Safety Act, it was noted that the federal government had the responsibility to ensure the safe performance of private passenger cars (which it had yet to fulfill), and it was quoted that "for too many years, the public's proper concern over the safe driving habits and capacity of the driver (the 'nut behind the wheel') was permitted to overshadow the role of the car itself" (National Motor Vehicle Safety Act, 1966, p. 2710). From this legislation, the National Highway Safety Bureau was formed, which was later renamed the National Highway Traffic Safety Administration (NHTSA) (National Motor Vehicle Safety Act, 1966). Authority was granted to NHTSA to perform a number of functions, including (1) establishing federal motor vehicle safety standards; (2) conducting automotive research, testing, development, and training; and (3) providing a mechanism for the recall of vehicles that were manufactured with safety defects or were not in compliance with the federal safety standards (National Motor Vehicle Safety Act, 1966). According to NHTSA, the braking system was one of the most important factors in vehicle performance: "Braking system performance has consistently rated high on the safety criticality list. The dominance of the role of braking systems in accident avoidance maneuvers has long been recognized and undisputed. The importance of braking in motor vehicle safety is evidenced by the fact that of all vehicle defects which cause or contribute to accidents, brake failures leads the list" (National Highway Traffic Safety Administration, 1973)

Health Effects Studies

In the early 1960s, a significant finding was made within the scientific community in regard to health effects associated with asbestos exposures. Specifically, a number of researchers pointed out the casual relationship between asbestos exposure and risk of lung cancer and mesothelioma even in the absence of asbestosis. The paper by Wagner et al. (1960) represented the first publication to highlight this observation, wherein they reported on 33 cases of mesothelioma identified in three South African groups: (1) crocidolite asbestos miners, (2) residents with no apparent occupational exposure to asbestos but who lived in the vicinity of the crocidolite mine, and (3) workers who were exposed in other asbestos-related industries. This case series study is credited with linking exposure to crocidolite with mesothelioma and highlighted the potential for asbestos-related disease among individuals with relatively low exposure levels.

In a later study by Thomson et al. (1963), 500 consecutive autopsies of the general population in Cape Town, South Africa, were reviewed. Based on the presence of so-called "asbestos bodies" in the lungs of the decedents, these researchers concluded that asbestos fibers had been inhaled by the urban dwellers. Interestingly, these researchers also speculated that brake wear debris (i.e., brake dust) could have accounted for a significant source of asbestos in urban air, although they noted that the concentrations of asbestos inhaled were "not in amounts sufficient to produce pulmonary lesions or disability" (Thomson et al., 1963, p. 31). Based on this finding, several studies were initiated in an attempt to estimate (1) the amount of chrysotile in brake wear debris, and (2) the concentrations of chrysotile fibers in the ambient air.

Soon after the publication of Thomson et al. (1963), Dr. Irving Selikoff, who was a researcher at the Mt. Sinai Hospital in New York City, and his colleagues reported on a cohort mortality study of 632 workers who installed asbestos-containing insulation materials (Selikoff et al., 1964). Specifically, Selikoff et al. reported a much higher than expected incidence of lung, pleural, and other cancers in

these workers. For example, 45 of the 632 workers died of lung or pleural cancer, which was 6.8 times higher than expected (Selikoff et al., 1964). Prior to this study, the only other large-scale study of insulation workers as end users of asbestos products in the United States was that of Fleischer et al. (1946), who observed only three cases of asbestosis among shipyard insulators (a very "dusty" occupation). However, unlike this previous study, the majority of participants in the Selikoff et al. study had worked in the same industry for more than 20 yr (the majority of workers in the Fleischer et al. study had worked for 5 yr or less in the pipe-covering industry). By this time, it was becoming apparent that exposure duration was not the only important predictor of disease, but that time since first exposure (i.e., latency) needed to be considered as well. Based on these and subsequent data the latency period between first exposure and the development of disease is believed to be about 30 yr or more for mesothelioma, 20 yr or more for lung cancer, and 15 to 40 yr for asbestosis (Lanphear & Buncher, 1992; Murphy et al., 1996; ATSDR, 2001). Therefore, it is now clear that studies that attempt to evaluate the health of workers need a sufficient latency period to be able to detect an increased incidence of asbestos-related disease.

In a later publication, Selikoff et al. (1968) also reported a synergistic effect between exposure to asbestos and smoking. Selikoff's publications of insulation workers eventually (in the period after 1974) led to additional worker population studies largely focusing on end users of other asbestos products such as asbestos sprayers, railroad maintenance workers, bus garage workers, locomotive drivers, construction workers, and electrochemical plant workers (Ohlson et al., 1984; Gustavsson et al., 1990; Hilt et al., 1991; Sanden & Jarvholm, 1992; Fletcher et al., 1993; Nokso-Koivisto & Pukkala, 1994; Oksa et al., 1997). These and other subsequent studies served as the foundation for justifying lower occupational exposure limits for asbestos in workplace air. The fact that these worker populations were not studied earlier is not surprising. As noted by Selikoff in 1970, "[While] the risk of heavy exposure to occupational dusts [in the asbestos mining and manufacturing industry] had been recognized for some years,...the extrapolation of that experience to another classification of workers...was a more sophisticated task for clinical medicine and epidemiology" (Selikoff, 1970, p. 163).

Concern About Chrysotile Emissions to Ambient Air Due to Brake Wear The concerns that brake wear debris might significantly contribute to asbestos concentrations in urban air (which were initially raised by Thomson et al., 1963) motivated the U.S. Public Health Service (U.S. PHS), the U.S. EPA, automobile manufacturers, and friction product manufacturers to conduct a series of studies to evaluate potential chrysotile emissions from brake wear (Lynch, 1968; Anderson et al., 1973; Jacko et al., 1973). Other researchers also collected data on chrysotile content in brake wear debris, although these data were not the primary focus of their investigations (Hickish & Knight, 1970; Luxon, 1970; Davis & Coniam, 1973). Table 3 summarizes the amounts of chrysotile measured in these studies, as well as those measured in subsequent studies, which are discussed later.*

These studies found that during brake use, some chrysotile fibers released from the brake lining during braking are either trapped in the brake housing, fall to the road, or are emitted to the atmosphere but that the percent asbestos in brake wear debris (i.e., brake dust) is quite small. In the first study, which was conducted by Lynch (1968) of the U.S. PHS, wear debris from brake lining test machines was collected and analyzed for chrysotile fibers using electron microscopy. In this study, generally less than 1% of the wear debris particles emitted from the brakes was found to be chrysotile fibers, even though the chrysotile fiber concentrations in original (unused) brake linings ranged from 30% to 50% by weight (Lynch, 1968). In the few cases where the percentage of wear debris found to be chrysotile fibers was greater than 1%, the author noted that those tests were conducted at extremely high temperatures for the type of lining tested, and had these linings been subjected to such conditions on a vehicle, the brakes would have failed. Lynch also noted that the wear debris was largely a nonfibrous mineral resulting from the thermal decomposition of chrysotile fibers. A follow-up study co-sponsored by the U.S. EPA and Bendix (a friction product manufacturer) measured an average of 0.23% by weight chrysotile content in all size fractions of the brake wear debris from the automobiles

* Care needs to be taken when comparing the results of the various studies because the methods employed to estimate the percentage of chrysotile fibers in brake dust varied among the researchers.

tested (Jacko et al., 1973). Only 1% of the debris was classified as airborne. The results of this study were considered to be more accurate, because an automobile was used rather than a laboratory dynamometer for testing, and sophisticated sampling techniques separated trapped debris in the drum from that fraction normally dropped on the road from the airborne fraction and analytical techniques included both optical phase-contrast microscopy and transmission electron microscopy (TEM).

Another study, which was conducted by researchers at Ford Motor Company using a dynamometer, collecting and analyzing the airborne wear debris (with TEM), confirmed the results of Lynch (1968) and Jacko et al. (1973) and concluded that less than 0.05% by weight of airborne brake dust consisted of chrysotile fibers (Anderson et al., 1973). Anderson and colleagues observed no chrysotile fibers longer than 5 μm in wear debris samples. The observations that only small amounts of chrysotile fiber were emitted from brakes were not surprising. The intense local heating and severe local mechanical action resulted in the decomposition of most of the chrysotile fibers in brake linings or pads during usage to nonfibrous magnesium silicate in both crystalline (forsterite) and amorphous phases (Gatrell & Schreiber, 1967). Because the decomposition products lacked the fibrous characteristics of asbestos, the magnesium silicates, including forsterite, were not thought to pose a health hazard similar to asbestos.

Exposure Studies Focusing on Brake Mechanics The first studies to measure the amount of chrysotile fibers released during the replacement of brakes in passenger vehicles were published by researchers from the U.S. PHS and the automobile and friction product industries in 1970 and 1972 (Hatch, 1970; Hickish & Knight, 1970; Dement, 1972) (Figure 3). These studies reported measurements of airborne concentrations from personal samples on mechanics collected during brake repair activities that, prior to 1970, typically involved using compressed air or brushing to remove the brake wear debris from the drum prior to installing the replacement linings.

The publication by Hickish and Knight (1970) was the only study during this time period that reported a daily long-term time-weighted average (TWA) airborne asbestos concentration during passenger car brake repair work, which was 0.68 fibers per cubic centimeter (f/cc).* Based on later surveys, it turns out that the mechanic sampled by Hickish and Knight serviced far more cars during the day he was sampled (11) than mechanics in other studies (generally 3 or fewer per day) (Johnson et al., 1979; Roberts & Zumwalde, 1982). Hickish and Knight also reported a daily long-term TWA asbestos concentration of 1.75 f/cc during brake repair on heavy trucks. Based on these results, Hickish and Knight wrote, "Our investigations show that exposure to asbestos during brake maintenance is not as severe as was anticipated, and in the situations we examined, the personal exposure of the operators was below the limit corresponding to 50-year exposure"[†] (p. 20). Both of the reported long-term TWA concentrations were also below the proposed ACGIH TLV-TWA of 12 f/cc that was in effect at the time and the soon to be adopted OSHA permissible exposure limit (PEL)-TWA of 12 f/cc. It should be noted that these researchers also evaluated airborne asbestos concentrations generated during different brake cleaning techniques (Knight & Hickish, 1970), as did another researcher in Great Britain (Lee, 1970). However, the data from these studies were collected over very short time periods (on the order of minutes) and are not considered relevant to evaluating long-term exposure to brake mechanics.

Following the initial paper by Hickish and Knight, industrial hygienists within the auto industry in the U.S. became involved in evaluating potential exposure to mechanics during auto brake repair. For example, between 1972 and 1974, Ford Motor Company (Ford) collected a number of

* By the mid 1960s, asbestos analyses were shifting from the impinger dust counting method, which provided total dust measurements in mmpcf, to a fiber counting method using phase-contrast microscopy (PCM), which provided asbestos measurements in fibers per ml (f/ml) or fibers per cubic centimeter (f/cc), which are equivalent units (i.e., 1 f/ml is the same as 1 f/cc). This change in analytical technique was in recognition of the fact that the number and size of the individual asbestos fibers versus the total number of particles were more relevant for assessing potential health risk. The membrane filter method also allowed for long-term (e.g., 8-h) personal sampling. A total dust measurement of 1 mppcf is roughly equivalent to 6 f/cc (ACGIH, 1971).

† In 1970, Great Britain's occupational exposure limit for asbestos was 100 fibers per cubic centimeter-year (f/cc-yr), which represents a cumulative dose rather than an airborne concentration (Lane et al., 1968). Cumulative dose is equal to the concentration of asbestos in air (f/cc) multiplied by the duration of exposure to that concentration (years). Therefore, if the exposure duration was 50 yr, the airborne asbestos concentration would have to be greater than 2 f/cc to exceed 100 f/cc-yr.

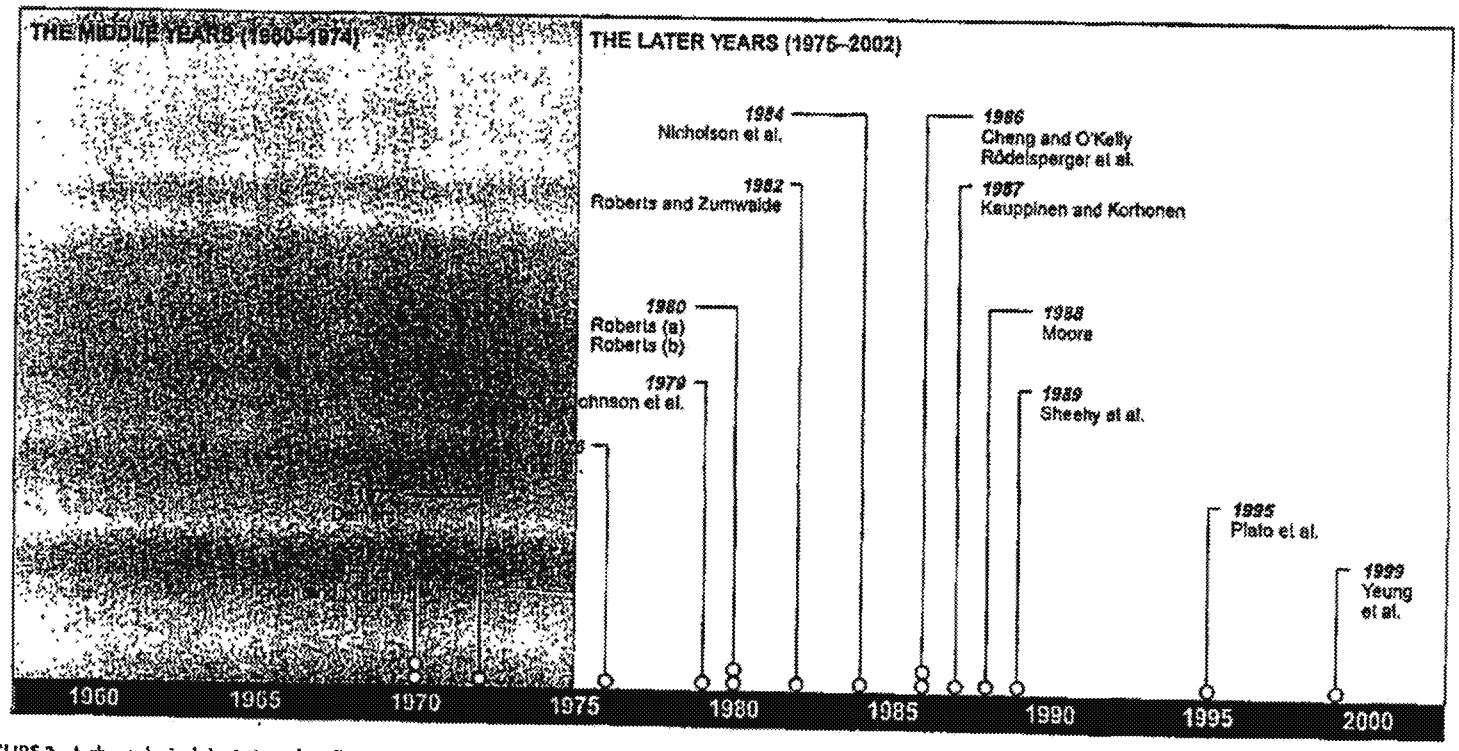

FIGURE 3. A chronological depiction of studies measuring asbestos exposure of mechanics involved in brake repair activities (1960–2002).

brake personal airborne asbestos samples of mechanics conducting various brake repair operations on automobiles (Lick, 1973; Ford, 1974). The measured brake job TWA concentrations were considerably below the prevailing occupational exposure limits.

First Health Effect Studies of Garage Mechanics Several studies and case reports were published in the 1960s and 1970s that evaluated the relationship between occupational exposure to asbestos and asbestos-related diseases. Of these, a few included a reference to occupations such as garage mechanics or service station operators (Hueper, 1965; Newhouse & Thompson, 1965; Bentley, 1970; McDonald et al., 1970; Oels et al., 1971; Moertel, 1972; Greenberg & Davies, 1974). However, the health effects studies of primary interest during this and subsequent eras are those epidemiological studies that quantitatively evaluated the association of work as a garage mechanic and asbestos-related diseases. Enterline and McKiever (1963) published results from a surveillance study of mortality from cancer of the trachea, bronchus, and lung by occupation in the United States in 1950. The authors reported an elevated death rate for "automobile mechanics and repairmen," but suggested it could be due to exposure to automobile exhaust. This study did not control for smoking, which would have been necessary to properly evaluate an association between occupational exposure and lung cancer. Boillat and Lob (1973), however, were the first researchers to specifically evaluate the prevalence of asbestosis among garage mechanics (Figure 4). In this study, lung function and chest radiography data from 39 brake lining repair workers in Switzerland were examined, and no cases of asbestosis were observed. No information was provided regarding the airborne concentration of chrysotile fibers in the workplace (Boillat & Lob, 1973).

No New Information on Brake Lining Manufacturing Workers Few studies were conducted between 1960 and the mid-1970s that provided additional information on airborne concentrations of chrysotile fibers in the U.S. friction product manufacturing environment or on asbestos-related health effects to U.S. friction product manufacturing workers (Figure 5). Enterline (1965) and Enterline and Kendrick (1967) conducted a mortality study of white males between the ages of 15 to 64 employed at some time between 1948 and 1951 in asbestos building, textile, and friction product plants in the United States. Enterline and Kendrick (1967) provided results explicitly for those 7510 men employed at 11 friction product plants included in the study and reported 29 cases of asbestosis, of which 21 cases were reported with asbestosis as the cause of death, in these workers. The authors also reported a standardized mortality ratio (SMR) of 123.7 for cancer of the respiratory system (which could include respiratory cancers other than lung cancer, for example, laryngeal cancer) for this group of workers. Enterline and Kendrick (1967) did consider mesothelioma, noting that "on only one of the 1853 death certificates examined did the term 'mesothelioma' appear, and this was for a worker in the asbestos building products industry." Overall, the authors considered the results for the friction product plant workers an indication of a "modest" response to asbestos exposure and concluded: "these workers had slightly increased death rates for cancer of the respiratory system and a high death rate for abestosis" (Enterline & Kendrick, 1967). In regard to exposure information available for these workers, the authors stated that "historical data regarding dust levels proved to be inadequate and this part of the project was abandoned" (Enterline & Kendrick, 1967, p. 182).

In an additional study from this time period, McVittie (1965) reported that 247 workers (including four "brake lining workers" who are presumed to be friction product manufacturing workers) were diagnosed by physical exams as having asbestosis between 1955 and 1963, but the diagnostic criteria used to make this determination were inconsistent with the current diagnostic standards, and other sources of asbestos exposure were not considered.

Studies published during this time period that presented chrysotile exposure measurements in friction product manufacturing environments typically did not include complete information (e.g., sampling duration) about the conditions under which sampling occurred. For example, a 1964 U.S. PHS health hazard evaluation collected asbestos exposure data from personal and area air samples at the Raybestos-Manhattan Friction Products plant in Manheim, PA (U.S. PHS 1964).* The air

*A copy of the survey was obtained through the National Technical Information Service. While authorship is assigned to the National Institute of Occupational Safety and Health (NIOSH), NIOSH was not in existence in 1964. The survey was conducted by the U.S. Public Health Service.

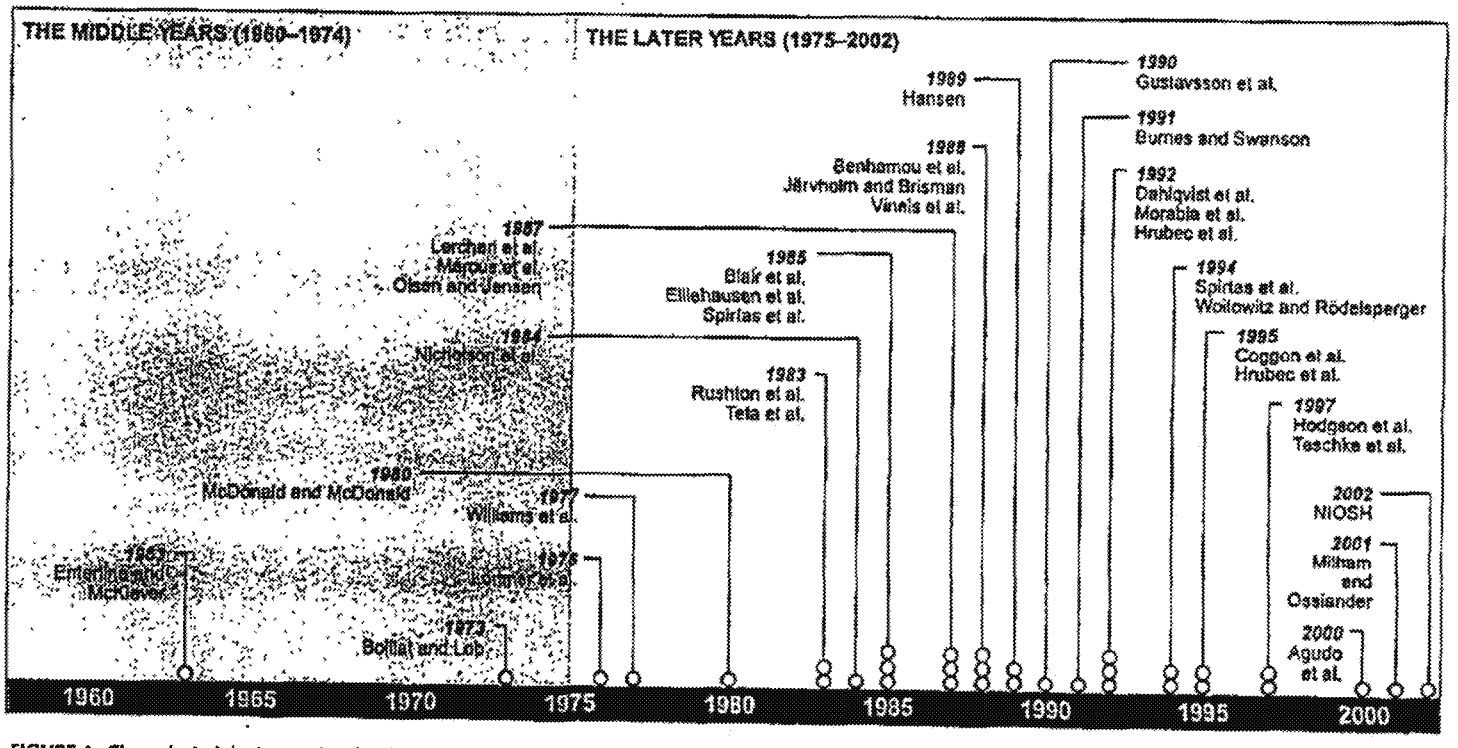

FIGURE 4. Chronological depiction of studies focussed on asbestos-related disease incidence in mechanics involved in brake repair activities (1960–2002).

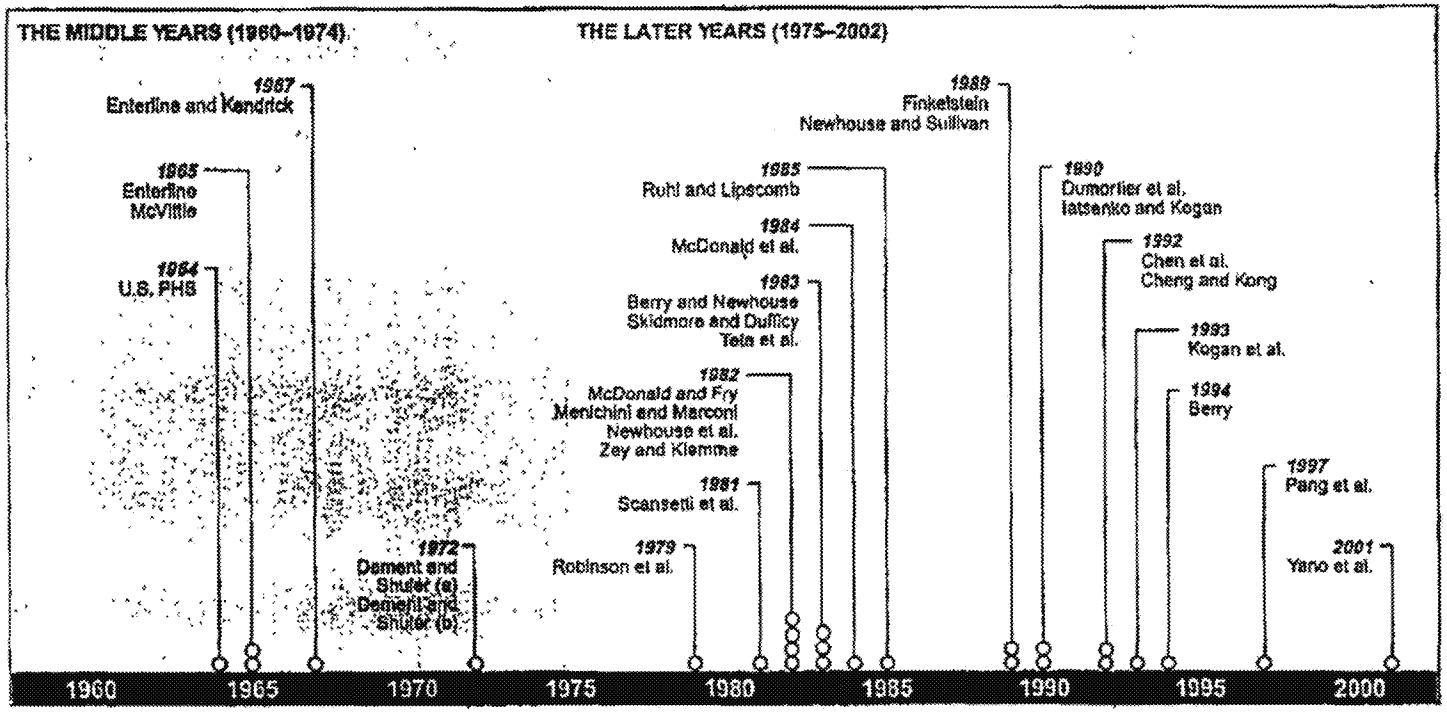

FIGURE 5. Chronological depiction of studies of asbestos-related exposure and health effects associated with friction product manufacturing environments (1960–2002).

sampling data showed asbestos fiber concentrations ranging from less than detection limits to 130.1 f/cc depending on the specific workplace activity. For example, as shown in Figure 6, the asbestos fiber concentration ranged from 1.5 to 75.3 f/cc during grinding. The concentration of total dust ranged from less than detection limits to 3.4 mppcf (U.S. PHS, 1964). Between 1965 and 1972, U.S. PHS collected chrysotile fiber and total dust in personal, breathing zone, and area measurements at the American Brake Shoe facility in Winchester, VA (Dement & Shuler, 1972a). Sampling durations associated with the measurements were not reported. Fiber concentrations ranged from less than detection limits to 17.5 f/cc, whereas total dust measurements ranged from 0.1 to 7 mppcf. Fiber concentrations during grinding ranged from less than the detection limit to 8.1 f/cc (see Figure 6). Later, in 1972, U.S. PHS collected data from personal air samples measured during brake rebuilding operations at the Genuine Parts Company, Rayloc Division plant in Atlanta, GA. These data showed much lower asbestos fiber concentrations ranging from 0.2 to 1.6 f/cc, and from 1 to 1.6 f/cc during grinding (Dement & Shuler, 1972b; see Figure 6). Similar to U.S. PHS (1964), the U.S. PHS surveys in 1972 (Dement & Shuler, 1972a, 1972b) also did not report sampling durations, making it difficult to interpret whether these results represented peak or longer term average air concentrations.

Toxicology of Asbestos

Much of the toxicological research conducted in the 1960s and early 1970s was aimed at developing an animal model that would be predictive of the asbestos-related cancers observed in workers. The failure of animal studies conducted in the 1940s and 1950s to show cancer induction via inhalation of asbestos led to the exploration of other more direct routes of asbestos exposure at higher administered doses. Although the Mellon Institute was successful in inducing lung tumors in rats via inhalation in the 1960s (Gross & deTreville, 1967; Gross et al., 1967), most experiments conducted during this time period consisted of injecting asbestos fibers directly into the animal's pleural and peritoneal cavities or trachea. Even these routes of direct application of asbestos to the target tissue, however, were successful only in inducing tumors in some animal models. For example, lung cancer was induced intrapleurally only in rats (Wagner, 1962; Berry & Wagner, 1969; Wagner & Berry, 1969; Donna, 1970) and hamsters (Smith et al., 1965), the two species identified in the first half of the century as being sensitive to asbestos. Mesotheliomas were induced intrapleurally in rats with chrysotile and crocidolite and in hamsters with amosite (Wagner, 1962; Smith et al., 1965). In general, intratracheal administration was not reliable in inducing lung cancer or mesothelioma in animals (Smith et al., 1965; Gross et al., 1967; Reeves et al., 1971). These studies usually did not evaluate inhalation exposure, which would allow for various biological protection mechanisms to occur; thus, it is not possible to use them to quantitatively predict the human health hazard (because of particle size, deposition, role of macrophages, and other factors).

In the early 1970s, Reeves et al. (1971) suggested that the rat was the superior animal model for predicting asbestos-related malignancies. To date, it is the only species to consistently develop lung tumors following inhalation and mesotheliomas via both intrapleural and intraperitoneal injection. More recent studies show that the Syrian golden hamster is more sensitive to the induction of mesothelioma from amphibole fiber inhalation exposures than the rat (McConnell et al., 1999).

To explain the mechanism of asbestos-related carcinogenesis in animals, several hypotheses were offered in the 1960s and 1970s. Most of them involved investigation into alterations of the fibers and the effects of these alterations on fiber size, route of administration, and physical properties as they related to tumorigenicity. For example, Wagner and Berry (1969) compared carcinogenicity in rats for different asbestos fiber types and composition, and found that oil-extracted and natural crocidolite induced mesothelioma at a similar rate when administered intrapleurally. Smith et al. (1965) found that exposure to soft chrysotile fibers (i.e., less brittle) did not result in animal tumors, regardless of the route of administration, but that exposure to harsh chrysotile fibers (i.e., more brittle) did result in tumors in exposed animals. Some investigators also found modified (milled) asbestos to be less carcinogenic than raw asbestos fibers (Pott et al., 1972; Wagner et al., 1974). This work supported the hypothesis that long fibers (5 to 20 μm) were possibly the carcinogenic fraction or that the shorter fibers (less than 5 μm) were much less carcinogenic.

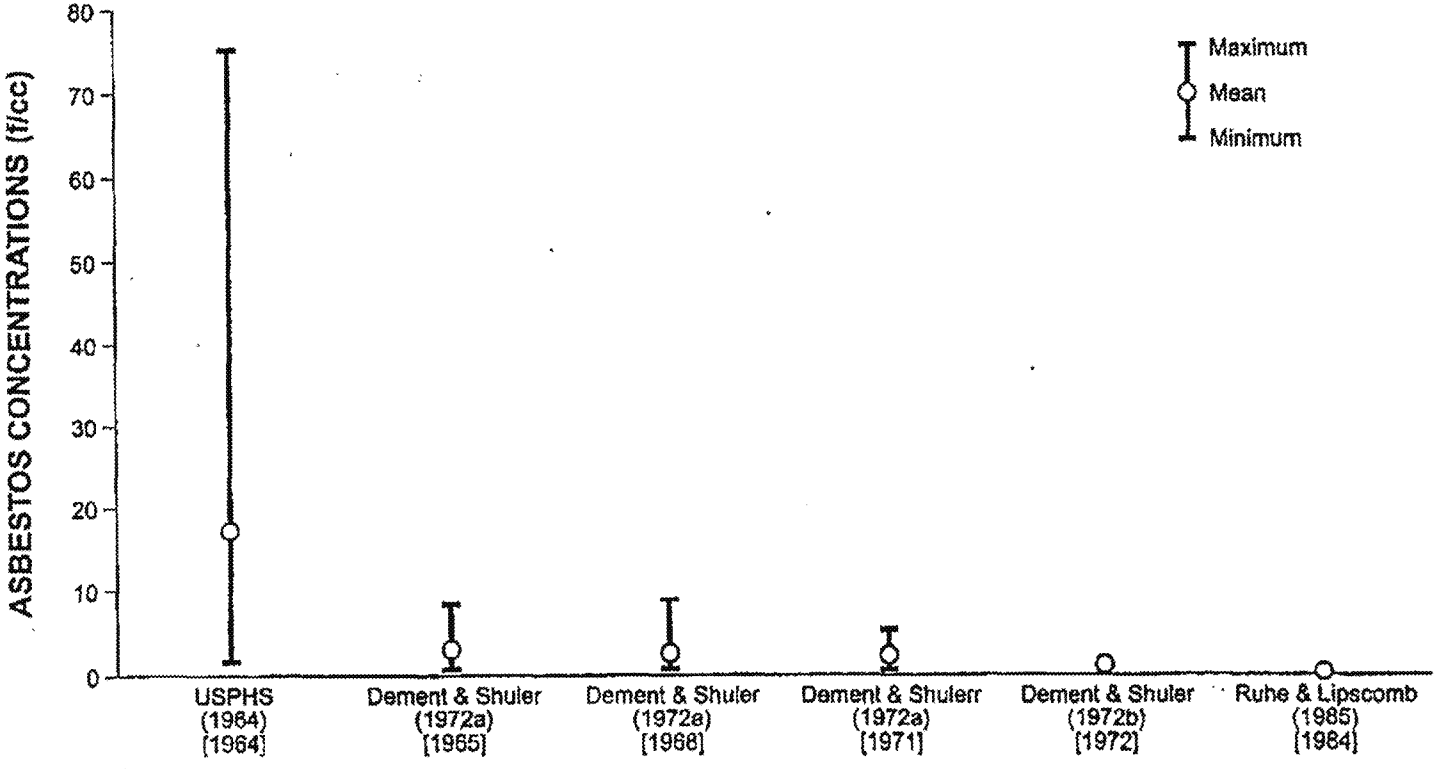

FIGURE 6. U.S. Public Health Service (USPHS)/National Institute for Occupational Safety and Health (NIOSH) surveys of asbestos concentrations during grinding operations at friction product manufacturing facilities. Note: Dates in parentheses are publish dates; dates in square brackets are sampling dates, if different from the publish date.

In the early 1970s, Stanton and Wrench (1972) conducted experiments with asbestos and non-asbestos fibers, as well as nonfibrous materials such as talc, to evaluate the hypothesis that all fibers of a certain length and diameter could induce mesothelioma. These test results indicated that, irrespective of the type of fiber, all fibers of a certain length produced mesotheliomas by implantation, with fibers greater than 8 μm in length and less than 0.25 μm in diameter being the most potent. In later animal implantation studies, chrysotile fibers less than 10 μm in length were found to induce lung tumors in addition to mesothelioma (Pott et al., 1974). These studies prompted further investigation of fiber morphology and its role in the generation of fibrosis (asbestosis) and cancer. Several different mechanisms were hypothesized to have accounted for the observed difference in the cancer potency of asbestos, including those related to fiber type, size, and iron content. These hypotheses continue to be explored (Governa et al., 1999; Ghio et al., 1997).

Asbestos Guidelines and Regulations

From 1960 to 1974, the field of industrial hygiene matured substantially. The federal government began to actively promulgate environmental and occupational health regulations during this period. Asbestos was prominent among the hundreds of chemicals that were regulated. Figure 7 presents the 8-h TWA-PEL for asbestos mandated by OSHA starting in 1971, as well as the changes brought about by subsequent rulemakings.

Stricter Occupational Exposure Guidelines In the early 1960s, various legislation such as the Walsh-Healy Act (Department of Labor, 1960) and the Longshoreman's Act (Office of the Secretary of Labor, 1960) adopted the 5 mppcf value as a binding regulatory limit for airborne asbestos fibers in specific industries. In 1964, at the Conference on the Biological Effects of Asbestos, it was discussed whether the 5 mppcf standard was adequate to provide lifetime protection from exposure to all forms of asbestos (i.e., chrysotile, crocidolite, actinolite, anthophyllite, tremolite, and amosite). This conference called attention to the rising rate of lung cancer among asbestos workers and highlighted the notion that end users may also be vulnerable to asbestos exposures (Schall, 1965; Corn, 1986; Nowinski, 1987). Following this conference, in April 1968, ACGIH recommended, in a Notice of Intended Change, lowering the asbestos TLV from 5 mppcf to 12 fibers per milliliter (f/ml, which is the same as f/cc) as an 8-h TWA (LaNier, 1984).

The federal government soon followed suit in May 1969 by amending the Walsh–Healy regulations to require a threshold limit of 12 f/cc for fibers greater than 5 μm in length (Nowinski, 1987). In 1970, in a second Notice of Intended Change, ACGIH recommended further lowering the TLV to 5 f/cc for fibers greater than 5 μm in length. As part of the proposed TLV in 1970, a ceiling limit of 10 f/cc for a maximal duration of 15 min was included (ACGIH, 2001).

The ACGIH TLV represented a nonenforceable guideline; therefore, no federal health standards governing all workplace exposure to asbestos had been promulgated through 1970. This changed in 1971, however, when OSHA established regulations that promulgated PELs for asbestos, as well as a whole host of other chemicals and substances (more than 400) that were being used in the United States (OSHA, 1971a; Martonik et al., 2001; Stokinger, 1981). On May 29, 1971, OSHA issued its first asbestos standard for general industry and set the PEL at 12 f/cc as an 8-h TWA based on the 1968 ACGIH proposed TLV for asbestos (OSHA, 1971a; Martonik et al., 2001). Just 6 mo later, in response to a request from the AFL-CIO (OSHA, 1971b) OSHA issued an emergency temporary standard (ETS) of 5 f/cc for fibers greater than 5 μm for an 8-h TWA and 10 f/cc for a 15-min ceiling limit. These values were adopted as a final standard in June 1972, with the stipulation that the PEL would be lowered again to 2 f/cc in 1976 (OSHA, 1972).

Other agencies involved with chemical regulations during this period included the U.S. EPA and CPSC. For the first few years after inception, CPSC had little involvement with asbestos; however, starting in the mid to late 1970s, CPSC became involved in regulating asbestos-containing products (CPSC, 1977, 1979). The U.S. EPA, on the other hand, placed asbestos on the first National Emission Standards for Hazardous Air Pollutants (NESHAP) list in March 1971 (U.S. EPA, 1971). In April 1973, when the U.S. EPA promulgated its national emission standard for asbestos under NESHAP, it noted the following: "Asbestos is too important in our technology and economy for its essential use to be stopped. But because of the known serious effects of uncontrolled inhalation of asbestos min-

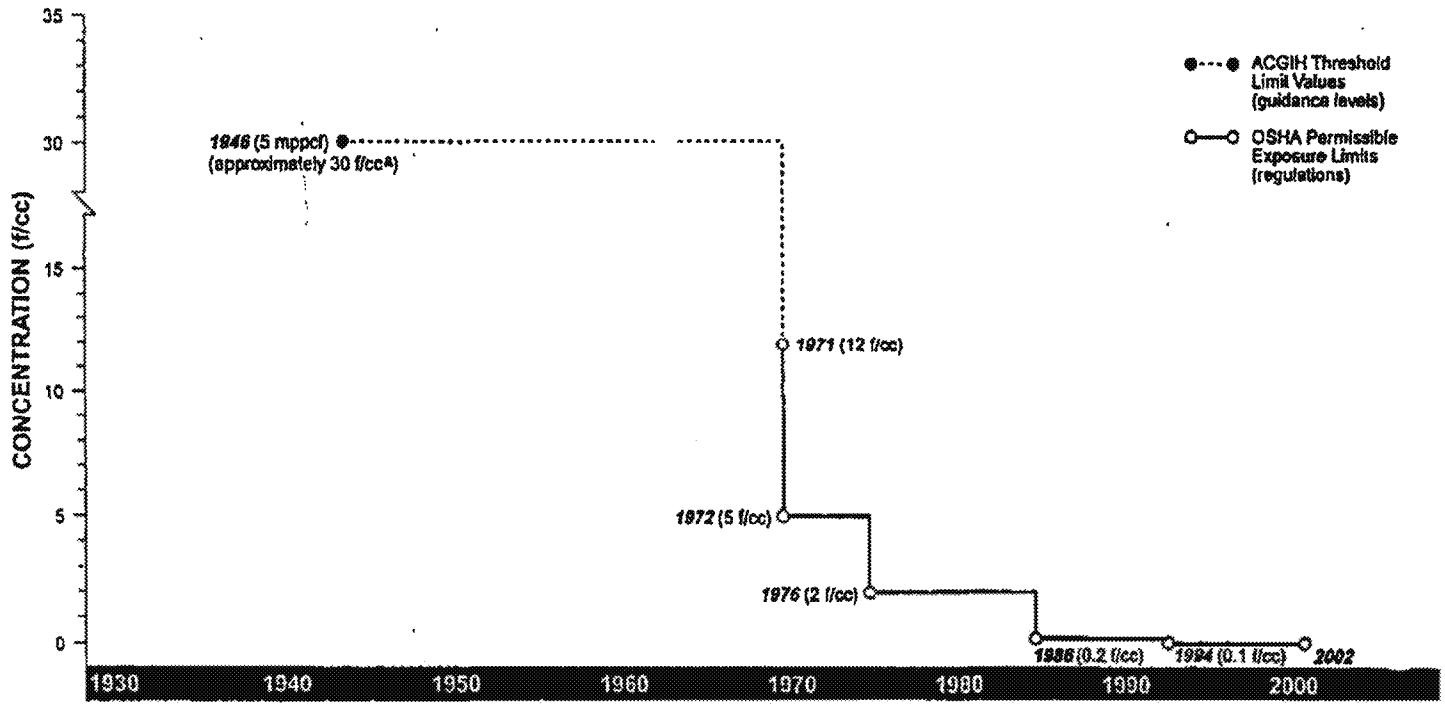

FIGURE 7. Chronological depiction of guidance and regulatory occupational exposure limits for asbestos in the United States (8-hour time weighted average). Note: ACGIH, American Conference of Governmental Hygienists; OSHA, Occupational Safety and Health Administration. a, ACGIH (1971).

erals in industry and uncertainty as to the shape and character of the dose-response curve in man, it would be highly imprudent to permit additional contamination of the public environment with asbestos. Continued use at minimal risk to the public requires that the major sources of man-made emission into the atmosphere be defined and controlled" (U.S. EPA, 1973, p. 8820). This U.S. EPA regulation controlled spray application of products containing more than 1% asbestos.

THE LATER YEARS (1975–2002)

From 1975 to the present day, significant changes occurred in the friction products industry. The first federally mandated brake system performance requirement was implemented in 1975. However, its effect on the friction product industry was minor compared to the increased regulatory efforts to control occupational and public exposure to airborne asbestos. Because of a higher level of concern about asbestos than in the earlier era, which was due to a substantial increase in worker studies in the early 1960s through the 1970s, and the cost of compliance with asbestos standards, asbestos product industries and suppliers began the search for a substitute for asbestos. This effort by the private sector to replace asbestos in consumer products was monumental given the thousands of applications that had been found. For example, researchers estimated that asbestos had been incorporated into as many as 3000 products by the mid-1970s (Levine, 1981). The challenge of finding a substitute to replace chrysotile in brake linings and pads was particularly difficult given the unique qualities of chrysotile fiber. Further, preliminary findings were reported by Mount Sinai researchers, first in 1975 and again in 1976, which suggested that brake mechanics might be at risk of asbestos-related health effects (Lorimer et al., 1976). These preliminary findings, although later shown by Mount Sinai researchers to be unconfirmed (Nicholson et al., 1984), spurred a number of exposure and epidemiology studies of brake mechanics over the next 20 yr. Manufacturers of friction products, brakes, and automobiles spent over two decades developing an adequate substitute for chrysotile fibers in brake linings and pads. By 2000, chrysotile was virtually eliminated in the braking systems of new North American vehicles. The following subsections discuss these issues in more detail.

Developments in Brakes and Brake Linings and Pads

As of the late-1970s, the typical U.S. car had front disc and rear drum brakes. U.S. passenger cars and light trucks with four-wheel disc brakes were rare and, if available, were offered only as an optional feature. Because disc and drum brakes were a standard feature in many vehicles during this period, efforts to develop asbestos-free brake linings and pads posed a real challenge, particularly for after-market (i.e., replacement) parts.

A number of factors led to significant efforts to research and develop replacement fibers for chrysotile in brake linings and pads, including (1) concerns about the toxicity of all forms of asbestos, (2) increasingly stringent air quality standards and regulations, (3) issues related to the disposal of asbestos-containing wastes, and (4) rising insurance costs. When first contemplated in the 1970s, the only viable alternative for chrysotile-based brake pads on disc brakes was a semimetallic formulation, which was already used for some disc brakes. However, the challenge was to find an appropriate material to replace the chrysotile-containing backing material used on semimetallic disc pads (Anderson, personal communication, 2002). In addition, an altogether new friction material needed to be developed for the brake linings in the rear internal drum brakes.

Over the next 20 yr, automobile, brake, and friction product manufacturers expended substantial effort toward developing drum brake linings that did not contain chrysotile fibers (Anderson, personal communication, 2002). Many of these years were spent attempting to develop functional semimetallic drum brake linings. However, manufacturers had difficulty obtaining uniformity with the raw materials mixtures, handling and forming the in-process material, and manufacturing high-quality parts consistently. Modifications to the semimetallic formulation to facilitate processing generally resulted in a friction material that did not achieve the commercially acceptable performance characteristics required for drum brakes (Jacko et al., 1980). The nature of semimetallic friction formulations did not lend itself to molding into the curved segments required for passenger drum brakes, and when cured, they were more brittle and subject to cracking (Jacko et al., 1980). In addition, as

the drums became hotter and expanded during use, the semimetallics did not conform to the increasing drum diameters (Nicholson, 1995). Because of these reasons, efforts to develop semimetallic drum brake linings for passenger cars and light trucks ended in the late 1980s (Anderson, personal communication, 2002).

Although other friction materials were available at the time, these materials were not appropriate for brakes on passenger cars and light trucks designed in the United States. For example, sintered metallic linings were developed, and although these linings were used in race cars, they were too sensitive (to prior usage, temperature, and moisture) to be used on a production passenger car or light truck. Carbon–carbon friction materials, invented in the late 1970s, were too sensitive to water and hydrocarbon vapors to be used on passenger vehicles, and also had light-duty wear problems (Anderson, personal communication, 2002). In addition, the carbon-carbon friction materials were cost-prohibitive for passenger vehicle brakes. These friction materials therefore were used only in military aircraft, race cars, and some commercial aircraft (ASME, 1988).

In the 1970s, research was initiated for nonasbestos organic (NAO) fibers that would serve the same function as chrysotile fibers (ASME, 1988). The transition to NAO-based friction products created many additional challenges, in terms of both manufacturing and performance (Jacko & Rhee, 1992). Specifically, it was impossible to find a single fiber that had the same characteristics as chrysotile (e.g., good tensile strength, low wear, easy processing, flexible, multitude of grades available, good insulator, and thermal stability at temperatures up to 500 °C) (Nicholson, 1995). In addition, chrysotile fibers were a significant component of brake linings and pads, typically varying in composition between 30% and 70% by weight (Jacko & Rhee, 1992). This explains, in part, why it took nearly 20 yr to find acceptable asbestos substitutes for all the passenger cars and light trucks available on the market (Anderson, personal communication, 2002).

Because friction material performance is greatly influenced by composition and the manner in which the components are mixed, fabricated, and cured, thousands of batches of experimental friction materials were made before proper NAO formulations were found. As of the early 1990s, more than 1200 different asbestos fiber substitutes had been investigated (Anderson, 1992). These substitutes included aramid, fiberglass, mineral wool, wollastonite, steel wool, processed mineral fibers, and organic fibers (ASME, 1988). With time, a "fiber cocktail" (blend of several different fibers) was found that provided acceptable performance in an NAO formulation.

Beginning in the early 1980s, light trucks were the first to incorporate NAO-based rear drum linings and semimetallic pads with NAO backing material (Jacko et al., 1984). The in-service use of these first-generation NAO materials demonstrated the challenges that still needed to be overcome. Specifically, the NAO brake linings tended to be hard and brittle; low in permeability and highly anisotropic; and prone to developing hot spots, blistering, and cracking in service (ASME, 1988). However, as these problems were resolved by the mid-1990s, NAOs gradually replaced asbestos-based materials on drum brakes and also replaced some of the semimetallic front disc pads on U.S. vehicles (Jacko & Rhee, 1992). By 2000, vehicle manufacturers had eliminated the use of chrysotile-based brake linings and pads for virtually all passenger vehicles and light trucks sold in the United States.

Brake Safety and Performance Standards

The first federal standard applicable to brake systems was established in 1975 and referred to as FMVSS 105. The purpose of this standard was "to insure safe braking performance under normal and emergency conditions" for hydraulic service brakes and associated parking brake systems, as was found on passenger vehicles (National Highway Traffic Safety Administration, 1978). FMVSS 105 defined service brake and parking brake system performance requirements (e.g., stopping distance) over a broad range of conditions (Gillespie, 1992), and these requirements pertained to the full vehicle, not individual components in the brake system. The establishment of FMVSS 105 did not result in the elimination of internal tests conducted by automobile, brake, and friction product manufacturers, because the federal standards were considered to be minimal, and not necessarily sufficient, requirements by these industries.

The federal government issued a harmonized regulation (i.e., compatible with regulations from other countries) in 1995, referred to as FMVSS 135 (National Highway Traffic Safety Administration,

1995). Like its predecessor, FMVSS 135 required testing of the entire braking system, not of the individual components, such as brake linings or pads. The requirements listed in FMVSS 135 were also a minimum (and not sufficient) standard for performance. Consequently, the internal laboratory and field tests required by the individual automobile manufacturers, in conjunction with brake and friction product manufacturers, remained the primary means of ensuring that automobile brakes were able to perform under a variety of operating conditions. In other words, although NAO-based material formulations may have satisfied the "minimum" requirements of the federal government soon after development, these new friction material formulations were not incorporated into vehicles until the vehicle brake system met the internal laboratory and field tests required by the friction product, brake, and automobile manufacturers.

Exposure and Health Effects Studies

With the exception of the study by Boillat and Lob (1973), no epidemiological studies to characterize asbestos-related health hazards to brake mechanics had been conducted prior to 1975. Although employee exposures to asbestos had been evaluated at some friction products manufacturing facilities as early as the 1930s, it was not possible to correlate these exposures with those of brake mechanics (primarily due to differences in duration of exposure, number of linings or pads handled per day, as well as the composition and particle size of the dust). Between 1975 and 2002, 10 surveys of exposure and 25 studies of health effects of brake mechanics were published along with 11 surveys of exposure and 15 studies of health effects of friction material manufacturing workers. These more recent studies focused on quantifying exposure levels for workers performing specific activities and the relative risk of asbestos-related disease in these workers.

Studies Suggesting That Brake Mechanics Were at Risk to Asbestos-Related Diseases It was not until 1975, when researchers from Mount Sinai presented preliminary results on the risks to brake mechanics at a meeting with NIOSH, automobile company, union and other representatives (later published in Lorimer et al. [1976] and Rohl et al. [1976, 1977]), that significant attention was focused on the question of whether brake mechanics might be at risk of asbestos-related diseases (NIOSH, 1975). The concerns raised were threefold. First, the Mount Sinai researchers reported chrysotile concentrations in brake wear debris that were significantly higher than reported in previous studies (Lynch, 1968; Hickish & Knight, 1970; Anderson et al., 1973; Jacko et al., 1973). Second, the reported short-term (i.e., peak) airborne concentrations of chrysotile fibers in brake repair facilities primarily associated with the compressed air blowout of the brake drum were sometimes higher than the OSHA 15-min ceiling limit of 10 f/cc (Rohl et al., 1976). Third, a preliminary review of x-rays from a select group of mechanics suggested a higher than expected incidence of x-ray and respiratory function abnormalities (Lorimer et al., 1976). Some of these same concerns were also raised by Castleman et al. in 1975. Based primarily on Mount Sinai's preliminary results, NIOSH (Lloyd, 1975) issued an information bulletin for mechanics who might be involved in specific brake servicing operations. In this bulletin, NIOSH acknowledged that brake mechanics, as an occupational group, had "not been studied systematically up to now." One of NIOSH's recommendations was to conduct additional exposure and epidemiology studies specific to brake mechanics (NIOSH, 1975).

Low Asbestos Content in Brake Dust As part of Mount Sinai's study of brake mechanics, the chrysotile content in brake dust was evaluated using an x-ray diffractometry technique. These results, published by Rohl et al. (1976), indicated an average chrysotile concentration in brake wear debris of approximately 4.5%, and up to a maximum of 15% by weight for samples collected in the U.S. (Rohl et al., 1976). In 1977, Rohl et al. re-published these results, along with the results for samples collected in Europe and Australia (Rohl et al. 1977). Based on samples from all countries, the average chrysotile concentration in brake wear debris was approximately 2.4%. These estimates were as much as an order of magnitude higher than those reported by earlier researchers using TEM (Lynch, 1968; Hickish & Knight, 1970; Anderson et al., 1973; Jacko et al., 1973). Perhaps of greater importance, these estimates were not replicated in later studies by automobile manufacturers (Williams & Muhlbaier, 1982; average of 0.03% by weight; maximum of 0.19% by weight) and the U.S. EPA (Cha et al., 1983; average of 0.02% by weight; maximum of 0.14% by weight) (Table 3). Additional

data provided by other researchers also showed the percent chrysotile in brake dust to be less than 1% by weight (Rowson, 1978; Sheehy et al., 1989).

Care needs to be taken in comparing the results of the various studies, however, because they all used slightly different methods to determine the percentage of chrysotile fibers in brake dust. The differences in measurements reported by Luxon (1970) and Rohl et al. (1976, 1977) and those reported in the other studies may be a result of the use of quantitative x-ray diffraction to measure chrysotile in brake dust by the two former groups of researchers, whereas TEM was used in the other studies. One shortcoming of x-ray diffraction is that it does not distinguish between the respirable chrysotile fibers and the nonrespirable fragments nor between encapsulated fiber and free fibers, which is why NIOSH began recommending TEM for identifying asbestos fibers after about 1980 (NIOSH, 1980; Lemen, 1984). This difference in what is being measured likely accounts for the higher estimates of chrysotile content in brake wear debris reported by the Mount Sinai researchers, as compared to the results from other researchers. This conclusion is supported by the fact that researchers estimating the chrysotile content in brake linings and pads observed that most of the brake wear debris samples had a chemical composition similar to chrysotile, but that the form was amorphous and nonfibrous (i.e., forsterite) (Lynch, 1968; Anderson et al., 1973; Davis & Coniam, 1973; Jacko et al., 1973; Rohl et al., 1976). Rohl et al. (1976) did use TEM to evaluate the fiber size distribution in wear debris and found mostly short fibers (80% shorter than 0.4 µm in length), which was consistent with earlier findings.

Estimates of Brake Mechanics' Exposure to Chrysotile Fibers As stated earlier, the 1975 meeting between researchers from Mount Sinai and NIOSH representatives resulted in additional studies to measure the concentrations of chrysotile fibers that brake mechanics were exposed to during brake servicing activities (Figure 3). In the 1975 meeting, the Mount Sinai researchers reported airborne chrysotile concentrations ranging from 1.3 to 29.8 f/cc. However, these were peak exposure concentrations measured during the cleaning of brakes using compressed air and dry brushing, and all breathing-zone air samples were generally collected for periods of 3 to 8 min in duration (Rohl et al., 1976). Although these samples suggested that peak concentrations might exceed the OSHA ceiling level if exposure were to last as long as 15 minutes, they were not particularly helpful in characterizing 8 hr TWA concentrations for mechanics, which were needed to assess the cumulative lifetime dose (i.e., necessary to understand the potential health risk; U.S. EPA, 1986a).

Because the preliminary studies of Mount Sinai addressed only peak exposures, additional studies that characterized brake mechanics' short-term and long-term exposures to chrysotile needed to be conducted. Most subsequent studies of the short-term chrysotile exposure of brake mechanics were conducted during the removal of wear debris from the brake drum using compressed air, a dry brush, a vacuum cleaner, or some other technique (Johnson et al., 1979; Roberts, 1980a, 1980b; Roberts & Zumwalde, 1982; Nicholson et al., 1984; Cheng & O'Kelly, 1986; Rödelsperger et al., 1986; Kauppinen & Korhonen, 1987) (Figure 3). The airborne concentrations of chrysotile measured during compressed air cleaning usually ranged from 0.01 to 15.00 f/cc, and those during the dry brush removal ranged from 0.01 to 2.62 f/cc (Johnson et al., 1979; Roberts, 1980a, 1980b; Roberts & Zumwalde, 1982; Nicholson et al., 1984; Cheng & O'Kelly, 1986; Rödelsperger et al., 1986; Kauppinen & Korhonen, 1987). Airborne concentrations of chrysotile during other methods of removing brake wear debris (i.e., wet brush, vacuum) ranged from nondetected to 2.62 f/cc (Roberts & Zumwalde, 1982). With the exception of a few samples, the sampling durations for the cleaning activities (0.5 to 3 min) were all less than the 15-min sampling period (or a shorter sample corrected for exposure during the remainder of the time period) needed to assess compliance with the OSHA ceiling limit (Martonik et al., 2001). Thus, it is not appropriate to characterize these airborne concentrations as being above or below the ceiling limit that was in place at the time. This is also the case for short-term samples collected on mechanics involved in grinding, sanding, or beveling brake linings, a short-duration task performed relatively infrequently on molded automobile brake linings (Rohl et al., 1976; Johnson et al., 1979; Kauppinen & Korhonen, 1987; Weir et al., 2001a, 2001b).

There were also several surveys conducted that measured longer term (e.g., during br ake work) and day long airborne concentrations (TWAs) of chrysotile fibers for brake repair workers. NIOSH

researchers evaluated 19 garages servicing brakes of passenger cars, generally those that were active at conducting brake jobs. Each garage performed as few as two to as many as 45 brake jobs per week (Johnson et al., 1979; Roberts, 1980a, 1980b; Sheehy et al., 1989). In their investigations, the NIOSH researchers collected more than 200 air samples on more than 50 mechanics as they performed brake cleaning and repair operations. According to the NIOSH findings, the brake job TWA airborne concentrations of chrysotile for automobile brake mechanics ranged from less than 0.004 to 0.28 f/cc for fibers greater than 5 μm in length. Based on these data, the mean brake job TWA concentration was about 0.05 f/cc (Paustenbach et al., 2003). As shown in Figure 8, these measured values were all below OSHA PELs (daily TWAs) in effect at the time of the studies (Johnson et al., 1979; Roberts, 1980a, 1980b; Roberts & Zumwalde, 1982; Sheehy et al., 1989).

Results from other studies conducted in the U.S. and abroad during this period fell within the range of concentrations measured in the NIOSH studies (Rödelsperger et al., 1986; Moore, 1988; Plato et al., 1995; Yeung et al., 1999) (Figure 3). These studies all used phase-contrast microscopy (PCM) to analyze samples for fibers greater than 5 μm in size and reported airborne concentrations that were below the OSHA standards applicable at the time the studies were conducted. Based on the weight of scientific evidence, these studies indicated that brake mechanics were exposed to relatively low airborne concentrations of chrysotile fibers, as defined by OSHA regulations. A recent analysis of the available data indicates that 90% of the 8-h TWA concentrations experienced by mechanics servicing brakes in the 1970s were less than 0.1 f/cc and in the 1980s, with improved dust control measures, less than 0.004 f/cc (Paustenbach et al., 2003). In addition, a recent simulation of brake repair work in the 1960s provided similar estimate of 8 hr TWA concentrations (Blake et al., 2003).

The auto industry in the U.S. continued to evaluate potential exposure to mechanics conducting auto brake repair activities during this time period. Consistent with other studies, brake job TWA concentrations measured by Ford, General Motors Corporation (GM), and Chrysler Corporation (now Daimler Chrylser) between 1976 and 1989 were below the prevailing occupational exposure limits (Krebs, 1976; O'Brien, 1981, Fischer, 1989a, 1989b).

No Increased Asbestosis Risk for Garage Mechanics Epidemiology studies focused on asbestos-related health effects of garage/brake mechanics were initiated during this era, with some likely as a result of NIOSH's recommendation for further study of this worker population. It is also clear that most studies of occupations handling asbestos products at this time, including brake mechanics, were focused on identifying the increase in relative risk associated with exposures. Figure 4 presents a timeline reflecting when studies were published that focused on asbestosis, mesothelioma, and lung cancer incidence in garage/brake mechanics.

Following Boillat and Lob's (1973) observations, only three studies had sufficient data to evaluate the prevalence of asbestosis among populations of brake mechanics (i.e., where both lung function and chest x-rays were evaluated) (Nicholson et al., 1984; Elliehausen et al., 1985; Marcus et al., 1987). The first of these studies, Nicholson et al. (1984), was a follow-up to Mount Sinai's preliminary research on brake mechanics, which had been discussed with NIOSH in July 1975 and later published by Lorimer et al. (1976). At that time, Mt. Sinai had evaluated the lung function and chest radiography data for 90 brake repair maintenance workers in New York City. Five workers were reported to have restrictive lung function and abnormal x-rays consistent with parenchymal fibrosis that was suggestive of asbestosis. The report suffered from a significant number of shortcomings including: a limited number of workers, reliance on volunteers, the lack of a control group, and no correction for smoking or prior exposure to dusts (including asbestos). Later, in an attempt to confirm the Lorimer et al. observation, Nicholson et al. (1984), also with Mount Sinai, performed a more comprehensive study consisting of 450 brake repair workers, 124 mechanics with no brake repair experience, and 205 nonexposed controls. They compared the lung function and chest radiograph results of garage mechanics who performed brake repair work with the results of those who did not and with nonexposed controls. No statistically significant differences were observed for the prevalence of abnormal x-rays among car garage workers with or without brake repair experience. Specifically, the prevalence of x-ray abnormalities among brake repair mechanics (18.5%) was greater than controls (15.3%), but less than garage workers without brake or auto body experience (20.7%). While Nicholson et al. (1984) detected a decrease in lung function among auto preparation and body

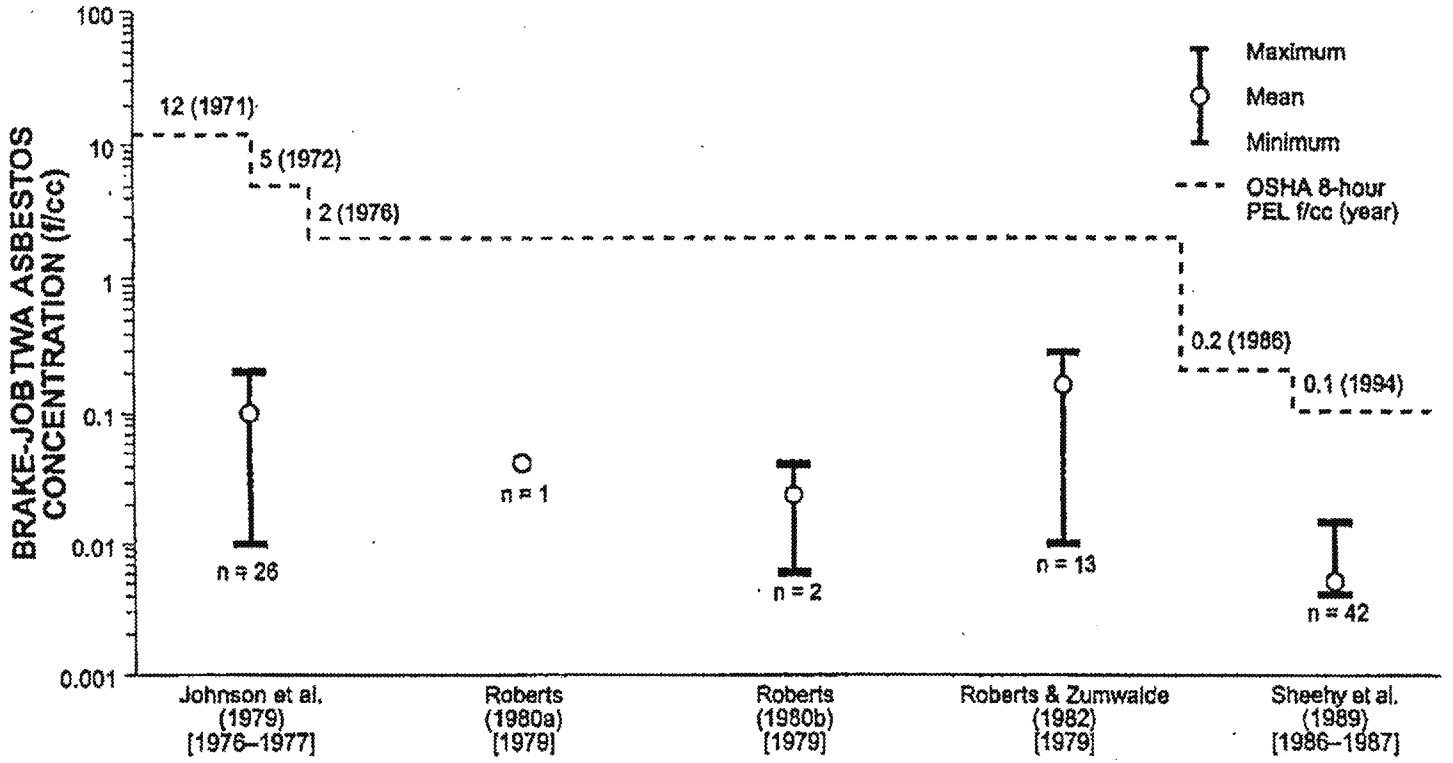

FIGURE 8. National Institute of Occupational Safety and Health (NIOSH) surveys of brake-job time weighted average (TWA) asbestos concentrations for mechanics servicing brakes on automobiles and light trucks. Note: Dates in parentheses are publish dates; dates in square brackets are sampling dates, if different from the publish date.

repair workers without brake experience, no decrease in lung function was observed among brake repair workers as compared to the controls. In short, Nicholson et al.'s follow-up study failed to confirm the initial impressions of Loriner et al. (1976) that exposure of these mechanics had produced an increased risk of adverse health effects.

Other studies have also evaluated the incidence of asbestosis has not been observed among garage mechanics who performed brake repair work. For example, Elliehausen et al. (1985) performed a clinical examination of 205 auto mechanics and concluded that (1) no significant difference could be found in the frequency of suspected radiographic asbestos-related changes in comparison with a reference group, and (2) both the frequency of small irregular opacities in chest x-rays and restrictive changes of lung function were not dependent on the inhaled cumulative fiber-dose. Similarly, Marcus et al. (1987) examined the x-rays and lung function of 925 brake mechanics and concluded that asbestos exposure of mechanics does not impair lung function. Other studies of garage mechanics evaluated either chest radiography or lung function, but not both (Raithel et al., 1989; Dahlqvist et al., 1992; Plato et al., 1995).

No Increased Cancer Risk for Garage Mechanics Due to Asbestos Exposure Between 1975 and 2002, more than 20 epidemiology studies examined the possible risks of mesothelioma and lung cancer in different types of workers, including vehicle and brake mechanics. Six of these studies are case-control studies that evaluated mesothelioma (McDonald & McDonald, 1980; Teta et al., 1983; Spirtas et al., 1985, 1994; Woitowitz & Rödelsperger, 1994; Teschke et al., 1997; Agudo et al., 2000). McDonald and McDonald (1980) evaluated mesothelioma cases in the United States and Canada. This study identified 480 confirmed mesothelioma deaths. Controls were selected from patients at the same hospitals who had pulmonary metastases from non-pulmonary malignancies. Out of a total of 156 cases and 156 controls for workers not employed in occupations with a recognized mesothelioma risk, the occupation "garage" was reported to have 11 cases and there were 12 cases in the controls. The authors did not calculate a relative risk*; however, based on this finding they concluded that "no increase risk was found in garage workers certainly exposed to chrysotile from brake linings" (McDonald & McDonald, 1980, p. 1655). From these data, Wong (2001) reported a relative risk estimate of 0.91, with a 95% confidence interval (CI) of 0.39–2.13.

Teta et al. (1983) identified 220 cases of mesothelioma and other malignant tumors of the pleura in Connecticut. Controls were selected among decedents from Connecticut death certificate files. For subjects employed in the industry "automobile repair and related service," the authors reported a relative risk estimate of 0.65, with a 95% confidence interval (CI) of 0.08 to 5.53 for mesothelioma.

Spirtas et al. (1985, 1994) evaluated 208 cases of mesothelioma identified by the Los Angeles County Surveillance Program, the New York State Cancer Registry (excluding New York City), and 39 large Veterans Administration hospitals. Controls included patients who died of causes other than cancer, respiratory disease, suicide, or violence. Although the authors did not evaluate the risk of mesothelioma in their journal publication (Spirtas et al., 1994), they did report a relative risk estimate of 1.0 (95% CI: 0.6–1.6) for subjects engaged in "brake lining installation or repair" in their earlier analysis of largely the same data (Spirtas et al., 1985).

Woitowitz and Rödelsperger (1994) evaluated 324 cases of mesothelioma in Germany. The control group included 497 persons from two groups: hospital controls selected among patients who underwent lung resection and population controls. Sixteen cases, 16 hospital controls, and 12 population controls were listed as "motor vehicle repair workers." Seven cases and 12 controls were characterized as definitely engaged in brake service. Based on these data, Wong (2001) reported a

* The concept of relative risk is used to measure the strength of an association in an observational study and equals the incidence rate of disease in an exposed group divided by the incidence rate of disease in an unexposed group. The magnitude of the relative risk reflects the strength of the association (i.e., the greater the relative risk, the stronger the association). A relative risk of 3.0 or more indicates a strong association, of 2.0 indicates a moderate association, and between 1.0 and 1.5 indicates a weak association. Relative risks may also be less than 1.0 in value, which would suggest a protective effect from exposure to a factor (Lilienfeld & Stolley, 1994).

relative risk estimate of 0.87 (95% CI: 0.46–1.74) for all motor vehicle mechanics and 0.76 (95% CI: 0.28–2.05) for motor vehicle mechanics definitely engaged in brake service.

Teschke et al. (1997) evaluated 51 incident cases of pleural mesothelioma reported to the British Columbia Cancer Agency. Controls were randomly selected from the provincial list of voters. The authors reported relative risk estimates of 0.8 (95% CI: 0.2–2.3) for "vehicle mechanics" and 0.3 (95% CI: 0.0–1.4) for "brake lining installation or repair" for analyses with and without latency, concluding that "brake installation and repair did not appear to be associated with mesothelioma" (Teschke et al. 1997, pp. 166–167).

Agudo et al. (2000) identified 132 cases of mesothelioma from hospitals in two Spanish provinces. Controls included hospital patients with conditions not related to asbestos. The authors did not report a relative risk estimate for motor vehicle mechanics; however, they did indicate that their study group included 3 cases and 14 controls who were employed as "mechanics, motor vehicles." From these data, Wong (2001) reported a relative risk estimate of 0.62 (95% CI: 0.17–2.25).

Based on the consistent results of these six studies of vehicle mechanics from four countries, there is no evidence that garage mechanics are at an increased risk of mesothelioma (see Figure 9). The results from three cohort mortality studies (Järvholm & Brisman, 1988; Hansen, 1989; Gustavsson et al., 1990) and five surveillance proportionate mortality studies (Olsen & Jensen, 1987; Coggon et al., 1995; Hodgson et al., 1997; Milham & Ossiander, 2001; NIOSH, 2002) also support this conclusion. Figure 10 presents a comparison of the relative risks of mesothelioma across various occupations, including vehicle mechanics (Teschke et al., 1997). The data presented suggest that vehicle mechanics' risk of mesothelioma is similar to that of workers in other occupations not thought to be exposed to airborne asbestos above background concentrations.

Of the several epidemiology studies that have evaluated lung cancer, six studies should be considered most informative because they were able to adequately adjust their results for smoking (Williams et al., 1977; Lerchen et al., 1987; Benhamou et al., 1988; Vineis et al., 1988; Morabia et al., 1992; Hrubec, 1992, 1995). Specifically, Williams et al. (1977) published a summary of the results of the Third National Cancer Survey that examined 7518 incident cancer cases. The report investigated risks associated with specific occupations and industries while controlling for age, sex, race, education, smoking, alcohol use, and geographic location. Cases with various types of cancer were interviewed and case-control analyses were conducted for individual cancer sites using those with other types of cancer as controls ("inter-cancer comparisons"). For the industry category "car repair services," the authors reported a relative risk estimate of 0.85 (confidence interval not reported but relative risk not statistically significant) for lung cancer.

Lerchen et al. (1987) evaluated 333 White and Hispanic male lung cancer patients from New Mexico. Controls were selected either through random-digit dialing or from the Health Care Financing Administration records. For "auto mechanics," the adjusted (for age, ethnicity and smoking relative risk estimate was 0.9 (95% CI: 0.5–1.9) based on 15 cases and 25 controls ever employed for 1 yr or more in this occupation.

Benhamou et al. (1988) evaluated 1260 lung cancer cases from France. Controls were selected from hospital patients with other diseases not related to tobacco exposure. A total of 65 cases had ever been "motor vehicle mechanics," compared to 96 controls. The authors reported adjusted (for smoking) relative risk estimate of 1.06 (95% CI: 0.73–1.54) for this occupational group.

Vineis et al. (1988) evaluated 2973 male lung cancer cases compiled from 5 case-control studies, each conducted in a separate U.S. state. Controls for one study were population based, whereas the other four studies used hospital controls or deceased controls identified from death certificates. Ninety-eight cases and 90 controls were ever employed as "automobile brake workers," yielding an adjusted (for age, birth cohort, and smoking) relative risk estimate of 1.2 (95% CI: 0.9–1.7).

Hrubec et al. (1992, 1995) conducted a cohort study to examine the mortality experience of 248,046 U.S. veterans from 1954 through 1980 by occupation and industry, to evaluate the association between occupational exposures and risk of various cancers. The cohort consisted of veterans who served in the U.S. Armed Forces at some time between 1917 and 1940, held active U.S. government life-insurance policies, and responded to one of two questionnaires sent in 1954 and 1957, providing information on smoking history and occupation and industry of employment. For cancers

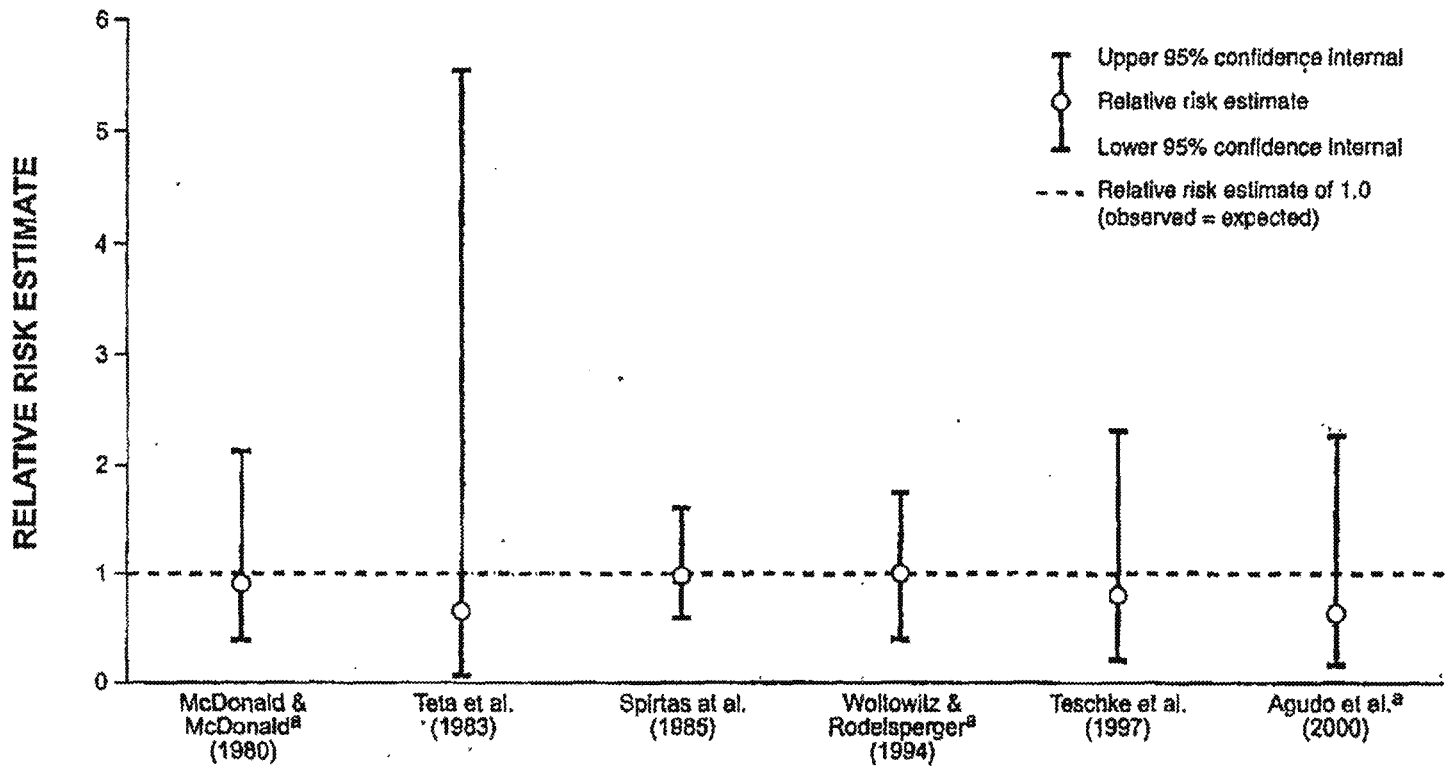

FIGURE 9. Relative risk estimates based on epidemiology case-control studies of mesothelioma in garage mechanics. a, Relative risk estimate and confidence interval reported by Wong (2001).

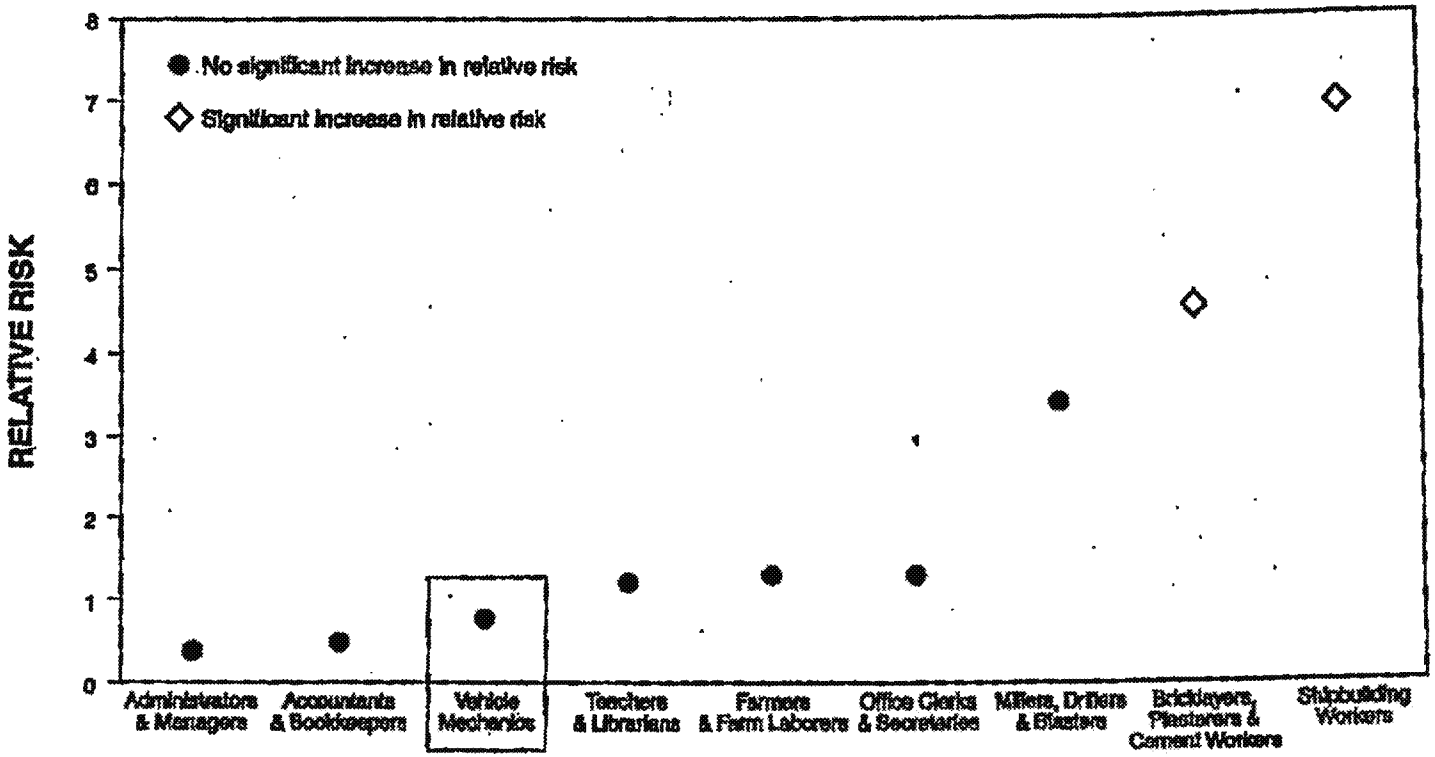

FIGURE 10. Relative risk estimates of mesothelioma for various occupations based on Teschke et al. (1997).

of the respiratory system, the authors reported a smoking-adjusted relative risk estimate of 1.1 (90% CI: 0.89–1.36) for the occupational group "automobile mechanics and repairmen" (Hrubec et al., 1992) and a smoking-adjusted relative risk estimate of 0.9 (90% CI: 0.69–1.17) for the industry type "automobile repair services and garages" (Hrubec et al., 1995).

Finally, Morabia et al. (1992) evaluated 1793 male lung cancer cases identified from hospital records in 9 U.S. metropolitan areas. Controls included cancer or noncancer hospital controls admitted for conditions not related to tobacco. The adjusted (for age and smoking) relative risk estimate for the usual occupation of "mechanics and repairmen—automobile" was 0.7 (CI not reported).

The data from these six studies do not indicate that lung cancer risk in this occupation is related to exposure to asbestos from brake repair work (see Figure 11). Furthermore, the results from four cohort mortality studies (Rushton et al. 1983; Jarvholm and Brisman 1988; Hansen 1989; Gustavsson et al. 1990) found no clear evidence that lung cancer in this occupational group can be attributed to exposure to asbestos during brake repair.

Wong (2001) recently reviewed the key mesothelioma and lung cancer epidemiology studies reporting the relative risk of mesothelioma or lung cancer in garage mechanics, and conducted a meta-analysis* in an attempt to improve the precision of relative risk estimates (i.e., a narrower 95% confidence interval). Based on this analysis, the author concluded that "with respect to strength of association, the meta-analysis of the combined data from all six [case-control] studies [focused on mesothelioma] shows a summary relative risk estimate of 0.90, meaning no increased risk" (p. 174). Further, he noted, "the narrow 95% confidence interval (0.66–1.23) of the summary relative risk is indicative of the large underlying database and the precision of the summary risk estimates" (p. 174). Similarly, Wong's meta-analysis of three cohort studies that focused on lung cancer reported a relative risk estimate of 1.01 with a 95% confidence interval of 0.8 to 1.26 (Wong, 1993, 2001). In short, having looked at the published data using several different techniques, Wong (2001) concluded that the results of the epidemiology studies indicate that auto mechanics were not at an increased risk of mesothelioma or lung cancer as a result of working with asbestos-containing brakes.

The weight of scientific evidence regarding the epidemiology data from more than 25 studies of motor vehicle mechanics using a variety of study methods and evaluating populations from nine countries were consist clearly indicates that brake mechanics are not at increased risk of asbestos-related adverse health effects, including lung cancer and mesothelioma, due to exposure to asbestos from brake repair work. This could be due to one or a number of factors, including that the airborne concentration of chrysotile asbestos and the duration of exposure are too small to be significant, the chrysotile fibers are too short to be biologically important, that chrysotile fibers are substantially less potent than amphibole fibers in inducing lung cancer and mesothelioma, or other yet to be understood factors. The airborne concentrations and duration of exposure during brake repair have already been discussed in detail. The biological importance of short fibers continues to be debated; however, additional support for this hypothesis has recently been offered by Roggli et al. (2002) and Butnor et al. (2003). In the first study, the authors attempted to correlate the type and content of asbestos fiber in lung tissue samples with type of occupation in 1445 cases of mesothelioma. For cases identified as automotive brake repair workers, the lung burden analyses reflected either a normal range of asbestos content or elevated commercial amphiboles attributable to asbestos exposure in other occupations. These findings, in combination with the nature of brake dust and the results of epidemiology studies, led the authors to conclude that brake dust is unlikely to cause mesothelioma (Roggli et al., 2002). Butnor et al. (2003) conducted a more in-depth analysis of these same cases, also concluding that, "friction product exposure, such as that encountered by auto mechanics, is unlikely to contribute to the development of MM [malignant mesothelioma]." (p. 329)

*The completion of many randomized clinical trials of common agents in the past two decades has led to the use of "meta-analysis," in which data from similar studies are pooled in a statistically rigorous manner. The purposes of meta-analysis are fourfold: (1) to improve the statistical power for primary outcomes for subgroups, (2) to resolve uncertainty when reports disagree, (3) to improve estimates of effect size, and (4) to answer questions not posed at the start of the individual trials (Sacks et al., 1987). Underlying these aims is the assumption that one has access to all of the relevant data from all randomized clinical trials involving a given agent. Conversely, meta-analysis obscures differences among trials (Sacks et al., 1987).

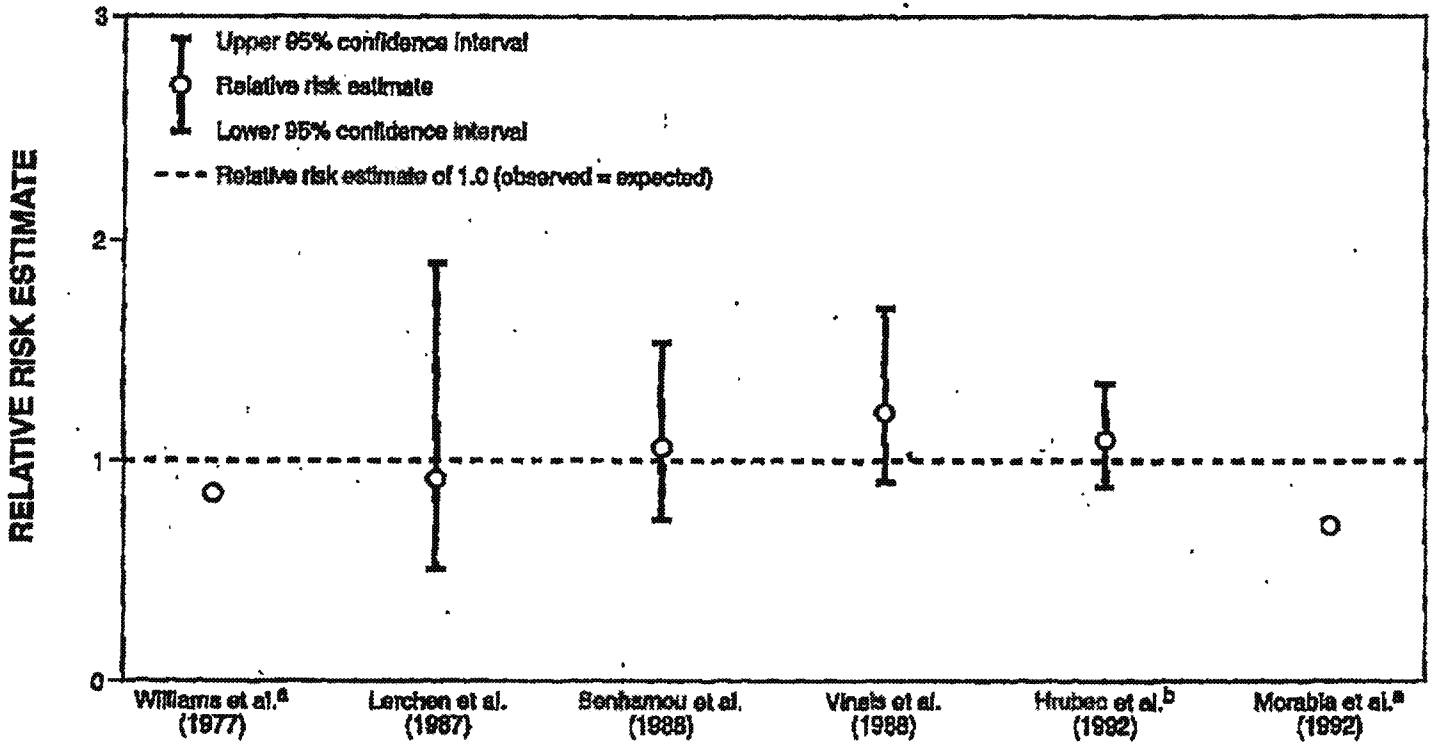

FIGURE 11. Relative risk estimates based on epidemiology studies of lung cancer in garage mechanics that were controlled for smoking. a, No confidence intervals reported by the authors; b, 90% confidence intervals.

Exposure Concentrations for Friction Product Manufacturing Workers Between 1975 and 2002, 11 surveys were published for workers in friction product manufacturing facilities, including two conducted by NIOSH. In 1982, NIOSH collected samples for workers manufacturing brake pads in the Raybestos Friction Materials Company in Crawfordsville, IN (Zey & Klemme, 1982). TWA concentrations for raw material mixers (0.03–0.04 f/cc), machine finishers (0.40–0.45 f/cc), drillers (0.56 f/cc), and slab cutters (0.67 f/cc) were below the OSHA PEL of the time, 2.0 f/cc. The NIOSH survey of workers at the Nuturn Corporation in New Castle, IN, provided similar results (Ruhe & Lipscomb, 1985). For example, the TWA concentrations during grinding ranged from 0.1 to 0.4 f/cc (see Figure 6). Newhouse and colleagues evaluated workers manufacturing friction materials in the UK (Newhouse et al., 1982; Berry & Newhouse, 1983; Skidmore & Dufficy, 1983). They estimated workplace concentrations for four periods, pre-1931, 1932–1950, 1951–1969, and 1970–1979, for several job categories including mixing, forming, and grinding. They reported concentrations of >20 f/cc for all workers pre-1931, 1–2 f/cc to 10–20 f/cc for workers during 1932–1950 with the highest concentration experienced by workers handling raw asbestos during mixing and by workers grinding cured linings, and 1–2 f/cc to 2–5 f/cc for all workers during the period 1951–1969. After 1970, concentrations were estimated to range between 0.5 and 2 f/cc for all workers. Newhouse et al. (1982) also reported that crocidolite was used at this facility but only during two well-defined periods before 1945. This reported use of amphiboles in friction products is rare, and in this case, the extent of crocidolite use was apparently limited to railroad engine brake linings.

McDonald et al. (1984) reported a similar concentration pattern for workers employed been 1930 and 1969 in a friction products plant in Connecticut; however, concentrations are reported in mppcf. Concentrations for all worker categories had ranges of 1–24 mppcf (1930–1939), 1–10 mppcf (1940–1949), 0.2–7.5 mppcf (1950–1959), and 0.1–5 mppcf (1960–1969). The two reports on friction material workers in China report primarily total dust concentrations (Cheng & Kong, 1992; Yano et al., 2001), although Yano et al. provided a concentration range for raw material handlers of 5.8–58 f/cc. Menichini and Marconi (1982) provide short-duration sample concentrations for workers at a brake lining and clutch plate manufacturing facility in Italy, and Kogan et al. (1993) provide similar data for workers at a facility in Russia.

Chrysotile Friction Products Manufacturers Not at High Risk of Asbestos-Related Diseases

Fifteen studies were conducted between 1975 and 2002 that evaluated the risk of developing asbestos-related diseases due to the manufacture of brake linings and pads (see Figure 5). Dumortier et al. (1990) and Chen et al. (1992) both examined the incidence of asbestosis in friction product manufacturers. Neither study reported an increased risk of asbestosis in the study population. Specifically, Dumortier et al. (1990) did not observe any radiological evidence of asbestos-related disease (asbestosis, pleural thickening, or plaques) in 15 friction product manufacturing workers exposed only to chrysotile. Similarly, Chen et al. (1992) did not observe gross or unequivocal changes of asbestosis in chest x-rays of 459 workers exposed to asbestos. However, the specific types of asbestos to which the workers were exposed were not identified.

The major studies evaluating the mortality and cancer incidence of employees working in the manufacture of chrysotile friction products also reported no significant increase in adverse health effects among the exposed workers. Specifically, Newhouse et al. (1982), Berry and Newhouse (1983), and later Newhouse and Sullivan (1989) analyzed the 1941–1986 mortality data for more than 13,000 workers first employed between 1941 and 1979 at a UK factory that produced friction products primarily using chrysotile. The authors observed three cases of asbestosis, all in workers who had long periods of employment at the factory. The study found no detectable excess deaths due to lung cancer. Thirteen deaths were attributed to pleural mesothelioma; however, 11 of the cases had known contact with crocidolite during 2 well-defined periods before 1945 in the manufacture of railroad blocks, one case's diagnosis of mesothelioma was uncertain, and the last case had been employed at the plant for only 2 wk as a fitter mechanic (i.e., occupational history was not well established) (Newhouse & Sullivan, 1989). Overall, the authors stated that "[this study] confirms our previous conclusions that under good environmental conditions chrysotile asbestos products can be manufactured with no detectable excess mortality" (Newhouse & Sullivan, 1989).

In the late 1970s, McDonald and Fry (1982) undertook three parallel cohort studies of asbestos factory workers to investigate the effects of mineral fiber type and industrial process on malignant mesothelioma, respiratory cancer, and asbestosis. One of the studies focused on a cohort of 3641 men employed between 1938 and 1958 in a U.S. friction products and packing plant that, with few exceptions, used chrysotile (McDonald et al., 1984). The authors reported that in no case was asbestosis listed as the cause of death on the death certificate. A significant excess of deaths due to respiratory cancer (which included lung cancer, laryngeal cancer, and "other" respiratory cancers) was observed in the cohort, which was mainly due to high relative risk estimates in men employed for less than one year with minimal accumulated dust exposure. There was no evidence of increasing risk with increasing duration of employment or cumulative exposure, and the authors postulated that "some selective process may have led to the employment of men of relatively poor health or health habits...into low exposure jobs on which they often remained for a fairly short time" (McDonald et al., 1984, p. 155). Based on these findings, the authors concluded: "If we accept that the high mortality from...respiratory cancer...in men employed for less than one year was probably due to some form of selection, our results suggest that the adverse health effects of employment in this chrysotile friction products plant were small" (McDonald et al., 1984, p. 156).

McDonald et al. (1984) also reported that there was no mention of mesothelioma on any death certificates. However, Teta et al. (1983) identified three cases of mesothelioma, using tumor registry data, among individuals who had been employed at the same location. These three cases were missed by McDonald et al. (1984) because the cause of death was not identified on the death certificate or the worker was employed outside the study's observation period, when the facility was used as a textile plant. The discrepancy between mortality and incidence findings is not unexpected. For example, the National Occupational Mortality Surveillance (NOMS) database maintained by NIOSH reports an age-adjusted mesothelioma mortality rate of between 1 and 2 deaths per million per year for U.S. residents (males and females combined) for the years 1987–1996 (NIOSH, 1999). By contrast, the Surveillance, Epidemiology, and End Results (SEER) cancer incidence database reports an annual incidence of mesothelioma of 14 cases per million per year in U.S. males and 3 cases per million per year in U.S. females for the years 1988–1992 (IARC, 1997). The implications of these kinds of discrepancies with respect to the results of epidemiology studies are not always clear; however, it is important to make sure that the comparison of observed and expected rates of disease is based on the same source of data (e.g., mortality or incidence), as was done in both the McDonald et al. (1984) and Teta et al. (1983) studies, to avoid biasing the relative risk estimates.

Finkelstein (1989) investigated mortality rates among 1657 employees at two Ontario factories manufacturing chrysotile friction products. The study population consisted of workers employed for at least 1 yr after January 1, 1950, and were followed until the end of 1985. These factories were unique in that brake shoes and linings were not produced at the plant; they were simply assembled. Thus, exposure to the relatively small number of employees working in the two small brake assembly areas that contained friction materials may have been from drilling, grinding, and riveting brakes. While the authors recognized that only a small portion of the employees worked directly with friction materials, the study included all the employees at the plants because the employees believed that they had been exposed to asbestos from dissemination of fibers throughout the plant.

The Finkelstein (1989) study reported that no cases of asbestosis were diagnosed. He observed a significant increase in mortality from laryngeal cancer and an elevated death rate due to lung cancer. However, an analysis showed "no association between the risk of laryngeal or lung cancer and the total duration of employment (a surrogate for the extent of ambient exposure to asbestos or other workplace toxic substances) or employment in departments where asbestos had been used" (Finkelstein, 1989, p.129). He reported two possible cases of mesothelioma, although the cause of death was recorded as lung cancer and the diagnoses were not confirmed. Overall, he concluded, "An association between risk of death and occupational exposure is uncertain" (Finkelstein, 1989, p. 125). This study also provided little quantitative information about actual worker exposures, but did report, "The first air-sampling survey was performed by government hygienists in 1975; from that time until the factories were closed in 1980 the concentrations of asbestos were less than 2 f/cc of air" (Finkelstein, 1989, p. 126).

Iatsenko and Kogan (1990) published a limited study in Russian on a small cohort of 130 persons involved in brake production in the former USSR. The authors reported one case of asbestosis, but this person had worked elsewhere handling "free asbestos." The authors concluded that despite high levels of dust, there was no significant excess mortality, with no cases of lung cancer or mesothelioma.

Kogan et al. (1993) examined mortality rates of two cohorts of asbestos friction product workers from the former USSR. The first cohort consisted of 156 persons from a plant in Ural and was followed for 20yr. The second cohort consisted of 2834 persons from a plant in Yaroslavl and was followed for 40yr. The authors did not report any cases of asbestosis or mesothelioma in either cohort. In the first cohort, no deaths from lung cancer were recorded, and in the second cohort, two deaths from lung cancer were recorded. The second cohort was subdivided into three subcohorts where the main exposures were to chrysotile, vulcanization and/or polymerization vapors and gases, and dusts consisting mainly of asbestos fibers coated with rubber and resin layers from asbestos bakelite or asbestos rubber, respectively. The only excess in cancer noted was that of stomach cancer deaths in the first subcohort. Thus, Kogan et al. (1993) concluded: "Cancer mortality among asbestos friction product workers was much lower than the expected values with the exception of the increased stomach cancer risk in the subcohort exposed mainly to asbestos dust" (p. 294).

Robinson et al. (1979), Cheng and Kong (1992), Pang et al. (1997), and Yano et al. (2001) also observed mortality patterns of friction product manufacturing workers; however, data for this worker population was combined with those from other occupations exposed to asbestos (e.g., building and textile products). In a review of the risks associated with working in friction material manufacturing plants, Berry (1994) concluded that "if there were any effects on mortality due to working in the manufacture of friction products using chrysotile, these effects were small and much less than the risks due to working in the chrysotile textile industry" (p. 545).

Toxicology of Asbestos

Due to increased knowledge regarding the toxic effects of asbestos, and innovations in science and technology allowing for better analyses, research into the mechanism of action, kinetics of asbestos transport after inhalation, and asbestos-related diseases continued to be conducted during this time period (1975–2002). For example, with the advent of the electron microscope, an increased number of studies were conducted to characterize the effects of asbestos fibers in the lung and to better understand the influence of fiber kinetics on the development of fibrosis and malignant disease (Haque et al., 2001). Also spurring research during this time period was the U.S. EPA 1986 evaluation of the carcinogenic potency of asbestos (U.S. EPA, 1986a). Although the U.S. EPA acknowledged the potential impact of fiber length and type on carcinogenic potency, it ultimately treated all types of asbestos fibers greater than 5 μm equally in its evaluation.

The debate about the potency of long fibers in producing asbestos-related health effects, which began in the late 1960s, developed full-scale by the 1980s (Crapo et al., 1980; Lemaire et al., 1985; Platek et al., 1985; Pinkerton et al., 1986; Bégin et al., 1986; Davis et al., 1986; Adamson & Bowden, 1987a, 1987b; Davis & Jones, 1988). While some early studies evaluating the fibrogenicity of different sized asbestos fibers reported fibrosis in some animals exposed to short fibers (less than 5 μm length), a greater fibrotic response was always observed with longer fibers (greater than 20 μm length). Subsequent studies conducted up to the 1980s showed that these early studies observed fibrosis from exposure to short fibers because the short-fiber formulations were contaminated with long fibers (greater than 20 μm length) (Crapo et al., 1980; Lemaire et al., 1985; Platek et al., 1985; Pinkerton et al., 1986; Bégin et al., 1986; Davis et al., 1986; Adamson & Bowden, 1987a, 1987b; Davis & Jones, 1988). By the 1990s, scientists generally believed that fiber biopersistence in the lungs, which is dependent on efficiency of degradation of macrophages, deposition location; fiber dimension, and chemical composition, was one of the primary determinants of fibrogenesis (Hesterberg et al., 1998a, 1998b; Searl et al., 1999).

The belief that fiber size and/or persistence has a significant impact on comparative carcinogenic potency of various asbestos types was explored in the 1970s and 1980s and continues to this day.

Researchers observed that the shape of asbestos-fibers longer than 2 to 3 μm is the decisive factor for induction of tumors, but that shorter fibers may be a less but not unimportant factor (Pott et al., 1972). Some scientists believed that the cancer-inducing potential of asbestos was attributed to its aspect ratio (i.e., length to diameter ratio) and that any fiber of a certain length and diameter could produce mesothelioma (Stanton et al., 1981). This belief was partially supported in the early 1970s through the work of Stanton and Wrench (1972) and Pott et al. (1974), who indicated that, irrespective of the type of fiber, all fibers of a certain length (greater than 8 or 10 μm) produced mesotheliomas when implanted.

Due to growing concerns about occupational hazards in the late 1970s and 1980s, the specific characteristics of asbestos fibers in asbestos-exposed workers were examined in several studies (Wagner et al., 1982; Davis, 1989). The results of these studies revealed that many of the workers exposed to serpentine fibers had a significant number of amphibole fibers retained in the lungs, while the chrysotile fibers were cleared from the lungs. In addition, chrysotile miners were found to have developed fewer lung cancers and mesotheliomas when compared to miners exposed to other types of asbestos (Churg, 1988). Therefore, it was postulated that amphiboles were a more potent asbestos type than chrysotile (Wagner, 1991, 1997).

Over the next decade, a number of animal studies were conducted in an attempt to explain the differences in potency between chrysotile and amphibole fibers (Davis et al., 1978; Bolton et al., 1982; Monchaux et al., 1982; Suzuki & Kohyama, 1984; Jaurand et al., 1987; Muhle et al., 1987; Minardi & Maltoni, 1988; Davis et al., 1991; Adachi et al., 1992; Carthew et al., 1992). While some investigators reported that chrysotile induced the most lung tumors (Reeves et al., 1971; Wagner et al., 1970, 1974; Wagner, 1972; Davis et al., 1978), other researchers reported that amosite was more tumorigenic than chrysotile (Donna, 1970; Suzuki & Kohyama, 1984; Minardi & Maltoni, 1988; Adachi et al., 1992). Other studies reported that crocidolite was a more potent carcinogen when administered intraperitoneally (Carthew et al., 1992), rather than via inhalation (Muhle et al., 1987). The study by Davis et al. (1991) suggested a dose-response relationship for mesotheliomas and all forms of asbestos, amosite, chrysotile, and crocidolite, whereas the occurrence of lung cancer in animals appeared to be dependent on the route of asbestos fiber administration (Reeves et al., 1971; Wagner, 1972; Muhle et al., 1987), as well as the fiber length (Berman et al., 1995). Specifically, the inhalation of fibers was found to induce lung cancer in rats, while direct intrapleural or intraperitoneal administration of doses was found to result in pleural or peritoneal mesotheliomas, respectively. In contrast, McConnell et al. (1999) reported a dose-related incidence of mesothelioma but no pulmonary neoplasms in hamsters exposed via nose-only inhalation to amosite fibers. Due to conflicting results in animal models, the results of ongoing lung burden studies, and a lack of evidence that only chrysotile contaminated with tremolite can cause cancer, the hypothesis that only amphibole asbestos induces cancer has been questioned (Stayner et al., 1996).

These animal research studies, as well as in vitro studies and epidemiological data, on the influence of fiber type and size on cancer potency are currently being evaluated by the U.S. EPA to better characterize the risks posed by asbestos at lower doses. One of the initial U.S. EPA efforts in this area was the Asbestos Health Effects Conference, held in May 2001 (U.S. EPA, 2001). More recently, new models for assessing potential human health risks have been proposed (Berman & Crump, 2001, 2002) to update the models initially used by the U.S. EPA in their original 1986 cancer evaluation. Their approach clearly recognizes the impact of fiber size and the potential for greater potency of amphiboles compared to chrysotile fibers. In doing so, the authors recommend a protocol where future airborne asbestos samples be collected in a manner that accurately delineates fiber size and type, including use of membrane filters for analysis by TEM. The U.S. EPA subsequently convened a workshop to discuss a proposed protocol to assess asbestos-related risk (U.S. EPA, 2003). The peer consultation panel strongly endorsed the conceptual approach of developing an updated cancer risk assessment methodology that takes into account fiber type and fiber dimension (Eastern Research Group, 2003a). The panelists agreed that there was considerably greater risk for developing cancer with fibers longer than 10 μm and that the risk for fibers less than 5 μm is very low and may be zero. The ATSDR also recently sponsored an expert panel on the influence of fiber length on asbestos health effects (ATSDR, 2002). The expert panel also agreed that fibers less than 5 μm pose a

negligible risk of cancer (Eastern Research Group, 2003b). Langer (2003) recently re-evaluated the available information on the biologic activity of chrysotile fibers subjected to thermal and mechanical shear stresses that approximated conditions experienced during braking (Langer 2003). He concluded that these studies show that chrysotile subjected to these severe conditions does not retain its natural properties due to alterations in its surface and structure, thereby greatly reducing its biologic activity. Langer further concluded that complete transformation to forsterite is not required to result in this loss of activity. Therefore, "(e)xposure to brake wear debris...may be associated with little to no risk of asbestos disease" (Langer 2003). New risk assessments, conducted using more sophisticated methods that account for fiber size and type, biologic activity and better sampling data for mechanics, should help explain why the available epidemiology studies consistently show that there is no increase in relative risk of asbestos disease in mechanics who serviced vehicle brakes with chrysotile linings.

This new work on fiber length, as well as chemical form (serpentine vs. amphibole) and biologic activity, should help explain the apparent discrepancies between the lung cancer and mesothelioma rates predicted by the U.S. EPA risk model and that observed in various populations. For example, in 1994, OSHA estimated that there is a theoretical increased excess cancer risk of between 3 and 4 in 1000 at the current PEL of 0.1 f/cc based on an extrapolation using a linear, no threshold model that is analogous to the model used by the U.S. EPA (U.S. EPA, 1987). However, as reported by Camus et al. (2002) and by others, such model estimates appear to overestimate the actual risks by a factor of 10–100 and, at very low doses, may well be predicting risks that are not present due to the existence of a practical, if not real, threshold.

Asbestos Guidelines and Regulations

In October 1975, OSHA proposed to lower the asbestos PEL from the existing 5 f/cc to 0.5 f/cc for all industries, but the agency never issued a final rule on this proposal (OSHA, 1975). OSHA did, however, lower the 8-h TWA airborne concentration of asbestos dust to 2 f/cc for fibers longer than 5 μm effective July 1, 1976 (OSHA 1972) (Figure 7). The 15-min ceiling limit of 10 f/cc was still in effect at this time. In 1978, the ACGIH adopted separate TLVs for amosite (0.5 f/cc), crocidolite (0.2 f/cc), and tremolite (0.5 f/cc) while maintaining the OSHA 2 f/cc value for chrysotile fibers workplace exposures (ACGIH, 2001).

Seven years later, OSHA (1983) issued a second emergency temporary standard (ETS), which lowered the asbestos PEL to 0.5 f/cc for fibers longer than 5 μm, in response to a petition from the International Association of Machinists and Aerospace Workers. The ETS was overturned by the U.S. Circuit Court of Appeals in 1984, because it was determined that the quantitative risk assessment used by OSHA to justify the ETS required a more thorough review (Martonik et al., 2001). In response to the court, OSHA proposed two alternative values for the 8-h TWA for asbestos—0.2 f/cc or 0.5 f/cc for fibers greater than 5 μm in length—and proposed to revise its ceiling limit to an unspecified value (OSHA, 1984).

On June 20, 1986, OSHA lowered the asbestos PEL to 0.2 f/cc for fibers greater than 5 μm in length as an 8-h TWA for all industries, and removed the ceiling limit requirement. This latter requirement was eliminated for several reasons. First, it was noted that the sizeable reduction in the TWA PEL (from 2 to 0.2 f/cc) effectively reduced the de facto ceiling limit from the 10 f/cc level to 6.4 f/cc. Second, not designating a ceiling level corresponded to OSHA's use of cumulative dose models to derive lung cancer risk and mesothelioma risk values (neither model attributed additional risk to peak ceiling exposures). Third, OSHA believed that there was little biological evidence in the record that supported a dose-response model based on peak or ceiling exposures (OSHA, 1986). In response to the lawsuit filed in 1984 by the Asbestos Information Association (AIA) and AFL-CIO challenging the 1986 standard, Asbestos Information Association/North American, et al. v. Occupational Safety and Health Administration, OSHA added a 1-f/cc 30-min excursion limit to the asbestos standard in 1988 (OSHA, 1988). OSHA lowered the 8-h TWA for asbestos to 0.1 f/cc for fibers greater than 5 μm in length in 1994, but the 30-min excursion limit of 1 f/cc established in 1988 remained unchanged (OSHA, 1994).

Other U.S. agencies were also active in regulating asbestos use during this time period. In the late 1970s, CPSC took regulatory action to ban asbestos in consumer products, focusing on asbestos-containing

patching compounds, artificial emberizing materials for fireplaces, and later, hairdryers (CPSC, 1977, 1979). In 1979, CPSC joined the U.S. EPA in issuing an Advance Notice of Proposed Rulemaking, stating their joint intention to explore the use of the Toxic Substances Control Act (TSCA) to reduce risk to human health from exposure to asbestos (U.S. EPA and CPSC, 1979).

In September 1984, the Natural Resources Defense Council (NRDC) submitted a petition to the U.S. EPA requesting a prohibition on the continued use of chrysotile in automobile brakes (Warren et al., 1984). The U.S. EPA granted the petition by a notice published in the Federal Register of December 18, 1984 (U.S. EPA, 1994), and in 1986, included chrysotile brake linings and pads in its proposal to ban production and importation of asbestos and asbestos-containing products (U.S. EPA, 1986b).

When the U.S. EPA issued this latter proposal, it acknowledged that replacement of chrysotile in friction materials was more difficult than other asbestos product categories because of its unique characteristics. In addition, the agency acknowledged that a ban on chrysotile use in brake friction materials might lead to decreased brake performance, and a lack of effective substitutes for aftermarket friction materials.

Despite these uncertainties, the U.S. EPA included friction products in its 1989 final ruling on the ban (also known as the Ban and Phase Down Rule) (U.S. EPA, 1989). According to the schedule put forth by the U.S. EPA, the phase-out of asbestos use in friction products was to occur by 1993 for original equipment manufacturers of passenger cars and light trucks, and by 1996 for original equipment manufacturers of heavy vehicles and the aftermarket linings and pads for all vehicles. The extension granted with respect to after market brake linings and pads was in response to comments to the U.S. EPA that it was easier to develop replacement asbestos-free brake linings and pads for use in vehicles that were initially designed to use such materials than to develop asbestos-free brake linings and pads as aftermarket replacement products in older vehicles (that had brake systems designed to use asbestos brake linings and pads). Some commentors also believed that a ban on asbestos use in the aftermarket for brake systems designed for asbestos friction materials would compromise the performance of brake systems designed for asbestos brakes (U.S. EPA, 1989).

In 1991, the U.S. Court of Appeals, Fifth Circuit, in Corrosion Proof Fittings et al. v. The Environmental Protection Agency and William K. Reilly, Administrator, annulled most of the U.S. EPA's 1989 ban. In its commentary, the court noted the following:

> Despite the credible record evidence, by a study specifically commissioned by the EPA, that substitute products actually might cause more deaths than those asbestos deaths predicted by the EPA, the agency did not evaluate the dangers posed by the substitutes, including cancer deaths from the other fibers used and highway deaths occasioned by less effective, non-asbestos brakes. This failure to examine the likely consequence of the EPA's regulation renders the ban of asbestos friction products unreasonable. (US Court of Appeals, 5th Circuit, 1991, p. 1224)

The ban remains in effect for those products that were no longer being manufactured, processed, or imported (i.e., pipeline wrap, vinyl/asbestos tile, millboard, asbestos clothing, asbestos-cement corrugated sheet, and asbestos-cement flat sheet) as of the date the Ban and Phase Down Rule came into effect.

Despite this court ruling, friction product manufacturers, in conjunction with brake and automobile manufacturers, continued to proceed with the elimination of chrysotile asbestos from brake linings and pads. This was due, in part, to the belief that the momentum toward integrating chrysotile-free brake linings into the braking systems of new cars had reached the point of no return. For example, a significant investment had already been made to develop chrysotile-free brake linings and pads on the part of the automotive, brake, and friction product industries. Chrysotile-free brake linings and pads were also found to perform satisfactorily in vehicles, and had already been incorporated onto some vehicles. Finally, friction product, brake, and automobile manufacturers were concerned about having to comply with possible bans on asbestos in the future both in the United States and abroad.

SUMMARY

Over the last 100 yr, brake linings have evolved considerably, due to increased public expectations about automobile performance and safety. To meet these challenges, the original woven

materials used on external brakes were replaced with chrysotile-based molded linings attached to internal drum and disc brakes. As a better understanding of asbestos-related disease continued into the early 1970s, and environmental regulations became increasingly more stringent, friction product, brake, and automobile manufacturers began to research and develop chrysotile fiber substitutes. Although nonasbestos organic brake linings and pads may have satisfied the minimum FMVSS requirements soon after development, these new friction material formulations were not incorporated into vehicles until they met all of the internal laboratory and field tests required by friction product, brake, and automobile manufacturers to meet the public's expectation of brake performance. It took several more years to develop the proper formulation for non-asbestos brake linings and pads that were equal in performance to chrysotile-based brake linings and pads that had been in place for more than 70 yr. By the 1980s, most U.S. vehicles had incorporated nonasbestos semimetallic front disc pads, but the technology to replace chrysotile rear drum brakes linings was not fully developed until the mid 1990s.

Early in the last century, questions were raised about the health hazards posed to workers manufacturing asbestos-containing products. In 1930, the first epidemiology study was published showing that exposures to high concentrations of asbestos in dusty manufacturing settings resulted in asbestosis (Merewether & Price; 1930). In this study, initial concerns regarding exposures to asbestos among workers involved in friction product manufacturing were raised. Between 1930 and 1959, seven studies were conducted where friction product manufacturing workers were part of the study population assessed. These studies provided evidence of asbestosis among highly exposed workers, but provided little information on the magnitude of exposure. Findings from early studies of manufacturing facilities eventually served as the basis for the first asbestos exposure limit of 5 mppcf, which was adopted by ACGIH in 1946 and continued to be used as a guideline by ACGIH and others for several decades. It was in 1955 that a causal relationship between asbestos exposure and lung cancer was documented for manufacturing settings (Doll, 1955). During this same time, animal studies were being developed that used high doses of asbestos in an attempt to replicate asbestos-related worker diseases. The data provided during this time period were, however, inadequate to describe an asbestos dose-response relationship for friction product manufacturing workers, and no data were provided on the potential exposures of brake mechanics.

In 1960, mesothelioma was attributed to asbestos exposure in crocidolite miners, as well as individuals living near the mine, leading to an increased focus on low-level exposure to asbestos and concerns about the lung cancer and mesothelioma risks. Simultaneously, several animal models were being developed to better understand these dose-response mechanisms, despite the high doses required to induce cancer in animals. The speculation that brake wear debris could account for a significant source of asbestos in urban air, the creation of several regulatory agencies, including OSHA and the U.S. EPA, and the lowering of recommended asbestos occupational exposure levels resulted in the first series of studies (conducted in the late 1960s and early 1970) to evaluate the contribution of brake dust to the atmosphere. These studies, conducted by the U.S. EPA, NIOSH, and the automobile industry, suggested that brake wear debris was not a significant source of atmospheric asbestos as was originally postulated. In addition, studies conducted on the amount of asbestos released during brake repair operations of passenger vehicles indicated that airborne concentrations of asbestos for brake repair workers were below the occupational standards of the time. Finally, the first preliminary health effects studies of brake mechanics, as well as five additional health effects studies of friction product manufacturing workers, were conducted during the 1960 to 1974 time period.

It was during the post-1974 time period that most of the information on chrysotile exposure of brake mechanics was generated. In 1975, the question about the asbestos-related hazard to brake mechanics came to the forefront with the release of a preliminary study by researchers at Mount Sinai Hospital that, in part, provided conflicting results to previously published studies. Specifically, they reported that chrysotile concentrations in brake dust were higher than previously thought, and that a preliminary review of x-rays from a select group of mechanics suggested a higher than expected incidence of x-ray and respiratory function abnormalities. The results of this report spurred decades of work to evaluate the exposure of garage mechanics and epidemiology studies of brake workers.

More than 25 epidemiology studies were conducted over the next 30 yr after issuance of the Mount Sinai report on vehicle and brake mechanics. In addition, there have been more than 15 studies of either asbestos exposure or asbestos-related health effects in friction product manufacturing workers. This body of information indicates that mechanics have not been exposed to harmful concentrations of chrysotile fibers as a result of their work with brakes. Although the levels of exposure to chrysotile fibers occurring during friction materials manufacturing are substantially higher than those that occur during motor vehicle repair, the studies of friction materials manufacturing workers have shown that an increased risk of asbestos-related disease in this occupational group, if any, is not clearly detectable. Only the friction materials manufacturing workers in the UK who were exposed to crocidolite while making railroad engine brake linings were found to have an increased relative risk of mesothelioma, an example of the differences in the relative potency of amphibole and chrysotile fibers.

Despite these findings, over the years, various regulatory actions have attempted to ban or phase out the use of chrysotile fiber in brake linings and pads. For example, the U.S. EPA banned the manufacturing, importation, and use of asbestos-containing products, including brake linings and pads, in 1989, due to perceived health risk issues. The U.S. Court of Appeals for the Fifth Circuit later annulled the majority of this ban. Although the U.S. EPA ban is no longer in effect for brake linings and pads, friction product, brake, and automobile manufacturers proceeded with the elimination of chrysotile-based brake linings and pads in U.S. passenger cars and light trucks. As of 2000, virtually no new passenger cars or light trucks sold in the United States utilized chrysotile-based brake linings and pads.

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