4 Assessing Occupational Exposure

4.1 Air Sampling and Analytical Methods

The conventional method used to assess the characteristics and concentrations of exposures to airborne fibers is to collect personal and environmental (area) air samples for laboratory analysis.

Personal samples are the preferred method for estimating the exposure characteristics of a worker performing specific tasks. For personal sampling, a worker is equipped with the air sampling equipment, and the collection medium is positioned within the worker's breathing zone. Area sampling is performed to evaluate exposure characteristics associated with an area or process. Sampling equipment for area sampling is stationary, in contrast to personal sampling, which allows for mobility by accompanying the worker throughout the sampling period.

4.2 Sampling for Airborne Fibers

The two NIOSH methods for the sampling and analysis of airborne fibers of asbestos and other fibrous materials are as follows:

- Method 7400 describes air sampling and analysis by PCM
- Method 7402 describes air sampling and analysis by TEM

Both methods (listed in the *NIOSH Manual of Analytical Methods* [NIOSH 1998] and provided in Appendix A) involve using an air sampling pump connected to a cassette. The cassette consists of a conductive cowl equipped with a 25-mm cellulose ester membrane filter (0.45- to 1.2-µm pore size). The pump is used to draw air through the sampling cassette at a constant flow rate between 0.5 and 16 L/min. Airborne fibers and other particulates are trapped on the filter for analysis using microscopic methods. Methods 7400 and 7402 can be used to count the number of fibers (and therefore calculate concentration based on the volume of air sampled) and measure the fiber dimensions. Fiber concentration is reported as the number of fibers per cubic centimeter of air (f/cm^3). Although the two methods differ in preparation of the sampling media for analysis, the major distinction between them is the resolving capabilities of the microscope. With PCM, 0.25 µm is approximately the diameter of the thinnest fibers that can be observed [Dement and Wallingford 1990]. TEM has a lower resolution limit well below the diameter of the smallest RCF (~0.02 to 0.05 µm) [Middleton 1982]. TEM also allows for qualitative analysis of fibers using an energy-dispersive X-ray analyzer (EDXA) to determine elemental composition and selected area electron diffraction (SAED) for comparing diffraction patterns with reference patterns for identification.

4.2.1 NIOSH Fiber-Counting Rules

The appendix to NIOSH Method 7400 specifies two sets of fiber-counting rules that vary according to the parameters used to define a fiber. Under the *A* rules, any particle >5 µm long with an aspect ratio (length to width) >3:1 is considered a fiber. No upper limit exists on the fiber diameter in the *A* counting rules. In the *B* rules, a fiber is defined as being >5 µm long with an aspect ratio ≥5:1 and a diameter <3 µm. The upper-diameter limit in the *B* rules restricts the measurement to thoracic and respirable fibers. It is important to note which set of fiber-counting criteria is used when reporting analytical results. NIOSH recommends using Method 7400 with the *B* rules for evaluating exposures to airborne RCFs. NIOSH Method 7402 specifies use of the *A* rules, with a lower-diameter limit of 0.25 µm to allow comparison with results obtained from NIOSH Method 7400. Method 7402 can also be used to compare fiber counts obtained from Method 7400 (*B* rules). TEM permits the identification and counting of fibers <0.25 µm in diameter; 0.25 µm is the approximate resolution limit for PCM.

4.2.2 European Fiber-Counting Rules

In Europe, a slightly different fiber-counting convention is used. The World Health Organization (WHO) reference method for MMMFs [WHO/EURO Technical Committee for Monitoring and Evaluating Airborne MMMF 1985] recognizes a fiber as >5 µm long with a diameter <3 µm and an aspect ratio ≥3:1. Several studies comparing fiber counts determined with different counting conventions have found good agreement in air sampling for RCF exposures. Buchta et al. [1998] compared fiber counts of air samples for RCF exposures as analyzed using the NIOSH *A* and *B* rules; both methods produced similar results, with no statistically significant difference in fiber density measurements on sample filters. Maxim et al. [1997] found that fiber counts made using NIOSH Method 7400 *B* rules are equal to approximately 95% of the counts determined using the WHO reference method. In studies with other SVFs, Lees et al. [1993] also found that fiber exposure estimates were slightly higher using the *A* rules but were comparable to the values obtained using *B* rules. Breysse et al. [1999] reported a similar finding when comparing RCF fiber counts determined by both *A* and *B* rules: the ratio of *A* to *B* counts was 1.33. These results suggest that for airborne RCF exposures, most fibers with a >3:1 aspect ratio also meet the ≥5:1 aspect ratio criterion and are <3 µm in diameter.

4.3 Sampling for Total or Respirable Airborne Particulates

Airborne exposures generated during work with RCFs may also be estimated by sampling for general dust concentrations. Sampling for particulates not otherwise regulated is described in NIOSH Method 0500 for total dust concentrations and in NIOSH Method 0600 for the respirable fraction [NIOSH 1998]. Both methods (also included in Appendix A) use a sampling pump to pull air through a filter that traps suspended particulates. NIOSH Method 0600 uses a size-selective sampling apparatus (cyclone) to separate the respirable fraction of airborne material from the nonrespirable fraction. The mass of airborne particulates on the filter is measured using gravimetric analysis, and airborne concentration is determined as the ratio of the particulate mass to the volume of air sampled, reported as mg/m^3 (or µg/m^3). This method does not distinguish fibers from nonfibrous airborne particles. No NIOSH REL exists for either total or respirable particulates not otherwise regulated. The OSHA permissible exposure limit (PEL) for particulates not otherwise regulated is 15 mg/m^3 for total particulates and 5 mg/m^3 for respirable particulates as 8-hr TWA concentrations. The American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit value (TLV) for particles (insoluble or poorly soluble) not otherwise specified is 10 mg/m^3 for inhalable particles and 3 mg/m^3 for respirable particles as 8-hr TWA concentrations [ACGIH 2005].

4.4 Sampling for Airborne Silica

Because silica is a major constituent of RCFs, the potential exists for exposure to silica during work with RCFs (e.g., in manufacturing or during removal of after-service RCF furnace insulation). As with sampling for respirable particulates, sampling for respirable silica involves using a pump to draw air through a cyclone before collecting respirable airborne particles on a filter. Qualitative and quantitative analysis of the sample for silica content can be performed using the following analytical methods:

- X-ray powder diffraction (NIOSH Method 7500)
- Visible absorption spectrophotometry (NIOSH Method 7601)
- Infrared absorption spectrophotometry (NIOSH Method 7602)

The NIOSH REL for respirable crystalline silica is 0.05 mg/m^3 as a TWA for up to 10 hr/day during a 40-hr workweek [NIOSH 1974]. The ACGIH TLV for crystalline silica is 0.05 mg/m^3 as an 8-hr TWA [ACGIH 2005].

4.5 Industrial Hygiene Surveys and Exposure Assessments

Assessments of occupational exposures, including quantitative measurement of airborne fiber concentrations associated with manufacturing, handling, and using RCFs, have been performed using industrial hygiene surveys and air sampling techniques at multiple worksites. Sources of monitoring data that characterize occupational exposures to RCFs include the following:

- University of Pittsburgh studies of exposures at RCF manufacturing sites in the 1970s [Corn and Esmen 1979; Esmen et al. 1979]
- An ongoing University of Cincinnati epidemiologic study with exposure assessments that use historical monitoring data and current monitoring strategies [Rice et al. 1994, 1996, 1997]
- A 5-year consent agreement between the RCFC and the U.S. Environmental Protection Agency (EPA) to monitor worker exposures in RCF manufacturing plants and in secondary users of RCFs and RCF products [RCFC 1993; Everest 1998; Maxim et al. 1994, 1997, 2000a]
- Studies of exposure to airborne fibers during the installation and removal of RCF insulation in industrial furnaces [Gantner 1986; Cheng et al. 1992; van den Bergen et al. 1994; Sweeney and Gilgrist 1998; Maxim et al. 1999b]
- International (Canadian, Swedish, Australian) industrial hygiene surveys of occupational exposures to RCFs [Perrault et al. 1992; Krantz et al. 1994; Rogers et al. 1997]
- A study of end-user exposures to RCF insulation products by researchers at Johns Hopkins University [Corn et al. 1992]
- NIOSH Health Hazard Evaluations (HHEs) of occupational exposures to RCFs

4.5.1 University of Pittsburgh Survey of Exposures During RCF Manufacturing

In the mid 1970s, researchers from the University of Pittsburgh conducted environmental monitoring to assess worker exposures to airborne fibers at domestic RCF manufacturing facilities. This research effort was one of the pioneering studies in the use of workplace exposure groupings or *dust zones* for establishing a sampling strategy [Corn and Esmen 1979]. In a series of industrial hygiene surveys, Esmen et al. [1979] collected 215 full-shift air samples at three RCF manufacturing plants. Table 4–1 summarizes the sampling data for the three facilities (A, B, and C) by fiber concentration of total airborne dust. Although a wide range of values for individual samples existed (<0.01 to 16 f/cm^3), average (AM) concentrations ranged from 0.05 to 2.6 f/cm^3. The highest exposure concentrations were measured in manufacturing and finishing operations during which sanding, cutting, sawing, and drilling operations were performed and ventilation was lacking. A large number of these operations were noted in plant A, which is reflected by the elevated fiber and dust concentrations for this plant. When data were compared for similar operations and dust zones, exposure concentrations were consistent across plants. Analyses of air samples also included measurement of fiber dimensions. Approximately 95% of the airborne fibers measured were <4.0 µm in diameter and <50 µm long with a GM_D of 0.7 µm and a GM_L of 13 µm.

4.5.2 University of Cincinnati Study of Exposures During RCF Manufacturing

In 1987, researchers from the University of Cincinnati initiated an industry-wide epidemiologic study of workers who manufacture RCFs. One aim of the study was to characterize current and former exposures to RCFs and silica in U.S. RCF manufacturing facilities. Data from initial surveys conducted at five RCF manufacturing plants indicated airborne RCFs with a GM_D ranging from 0.25 to 0.6 µm and a GM_L ranging from 3.8 to 11.0 µm [Lockey et al. 1990]. The airborne TWA fiber concentrations for these five plants ranged from <0.01 to 1.57 f/cm^3. After the first two rounds of quarterly sampling, Rice et al. [1994] had collected data from 484 fiber count samples (382 samples with values greater than the analytic limit of detection [LOD], 39 overloaded samples, 36 samples with values below the LOD, and 27 samples voided because of tampering or pump failure). They also collected 35 samples from persons working with raw materials that were analyzed quantitatively and qualitatively for respirable mass and for silica polymorphs (quartz, tridymite, and cristobalite). A sampling strategy was developed by identifying more than 100 job

Table 4–1. Industrial hygiene survey data for three RCF* manufacturing plants†

Plant	No. samples	AM total airborne dust		AM fiber concentration	
		mg/m^3	Range	f/cm^3	Range
A	76	6.05	0.37–100.00	2.6	0.02–16.0
B	67	1.6	0.19–9.73	0.63	0.04–6.7
C	72	0.85	0.05–2.34	0.05	<0.01–0.29

Source: Esmen et al. [1997].

*Abbreviations: AM=arithmetic mean; RCF=refractory ceramic fiber.

†Fibers were defined as having an aspect ratio >3:1. Transmission electron microscopy was used to measure fibers ≤1 µm in diameter.

functions across 5 facilities. These job functions were consolidated into industry job titles based on similarities of function, proximity to certain processes, and exposure characteristics within designated dust zones. Table 4–2 presents median TWA exposures to airborne concentrations of RCFs by job title at plants sampled in 1987. TWA fiber concentrations ranged from below the analytical LOD to 1.04 f/cm^3 for workers in 20 different industry job titles. Fiber concentrations obtained by rinsing the walls of the sampling cowl, where a significant number of fibers accumulated during sampling [Cornett et al. 1989; Breysse et al. 1990], ranged from below the analytical LOD to 1.54 f/cm^3. Of the 35 samples analyzed for the silica polymorphs, quantifiable silica was found in 5 samples: 4 of the samples contained cristobalite in concentrations ranging from 20 to 78 µg/m^3, and 1 of the samples contained 70 µg/m^3 quartz. The measurable silica exposures occurred among workers employed as raw material handlers and furnace operators.

As the study progressed, approximately 1,820 work history interviews were conducted and evaluated to refine uniform job titles and to identify dust zones according to the method of Corn and Esmen [1979]. Four years of sampling data (1987–1991) were merged with historic sampling data to construct exposure estimates for 81 job titles in 7 facilities for specified time periods [Rice et al. 1997]. Overall exposures decreased. The maximum exposure estimated was 10 f/cm^3 in the 1950s for carding in a textile operation; subsequent changes in engineering, process, and ventilation reduced exposure estimates for all 20 job titles to near or below 1 f/cm^3 [Rice et al. 1996, 1997]. The study reported that at more recent operations (1987–1991), exposure estimates ranged from below the analytic LOD to 0.66 f/cm^3.

Subsequently, Rice et al. [2005] published the results from an analysis of exposure estimates for 10 years of follow-up sampling (1991–2001) at 5 of 7 facilities (2 facilities had closed before 1991). The researchers found the following estimates for 122 job titles still active in 2001:

Number and % of job titles	*Exposure estimate (f/cm^3)*
97 (79%)	≤0.25
17 (14%)	>0.25 to 0.5
8 (7%)	>0.5

The study shows that exposures decreased for 25% of job titles, remained stable for 53%, and increased for 22%. Of the job titles with increased exposure estimates, 9 estimates were >0.1 f/cm^3 (range = 0.1 to 0.21 f/cm^3), and 19 estimates were <0.1 f/cm^3. The exposure estimates for this study do not include adjustments for respirator use.

4.5.3 RCFC/EPA Consent Agreement Monitoring Data

In 1993, the RCFC and the EPA entered into a negotiated 5-year consent agreement to determine the magnitude of RCF exposures in the primary RCF manufacturing industry and in secondary RCF-use industries [RCFC 1993; Maxim et al. 1994, 1997; Everest 1998]. Another purpose of this consent agreement was to document changes in RCF exposures during the 5 years of the agreement (1993–1998). The Quality Assurance Project Plan in the consent agreement contains the analytical protocols, statistical design, description of the program objectives, and timetables for meeting the objectives [RCFC 1993].

During each year of the consent agreement, a minimum of 720 personal air samples (measured as 8-hr TWAs) were collected according to a stratified random sampling plan. Of these, 320 samples were collected in RCF manufacturing and processing (primary) facilities. The remaining 400 samples were collected in RCF

Table 4–2. Median TWA exposures to airborne concentrations of RCFs* by industry job title at plants sampled in 1987†

Industry job title	Plant 1			Plant 2			Plant 3			Plant 4			Plant 5		
	No. samples	Median TWA f/cm³	SD	No. samples	Median TWA f/cm³	SD	No. samples	Median TWA f/cm³	SD	No. samples	Median TWA f/cm³	SD	No. samples	Median TWA f/cm³	SD
Blanket line	6	0.03	0.01	21	0.15	0.06	2	0.01	0.01	2	0.02	0.01	9	1.04	0.28
Engineer (nonproduction)	—	—	—	—	—	—	1	0.02		—	—	—	—	—	—
Fabrication (dry)	—	—	—	3	0.14	0.05	4	0.51	0.26	3	0.03	0.18	16	0.61	0.07
Fabrication (wet)	—	—	—	—	—	—	8	0.01	0.02	—	—	—	—	—	—
Fabrication (wet/dry)	12	0.05	0.02	—	—	—	3	0.13	0.04	—	—	—	—	—	—
Fore‡ (furnace)	5	0.01	0	—	—	—	1	—	0.05	—	—	—	1	—	0.47
Fore (nonfurnace)	3	0.01	0.01	1	—	0.94	—	—	—	—	—	—	3	0.31	0.12
Furnace	5	0.03	0.06	—	—	—	3	0.04	0.03	—	—	—	4	0.41	0.41
Maintenance	7	0.02	0.01	6	0.11	0.03	5	0.08	0.05	3	0.02	0.01	2	0.62	0
Needler	—	—	—	—	—	—	3	0.04	0.01	3	0.02	0.01	1	—	0.25
Office	—	—	—	1	—	0.03	—	—	—	—	—	—	—	—	—
Office plant	—	—	—	1	—	0.04	—	—	—	—	—	—	—	—	—
Plant cleanup	1	—	0.19	—	—	—	—	—	—	—	—	—	—	—	—
Quality control	—	—	—	—	—	—	2	0.16	0.01	—	—	—	—	—	—
Research and development	—	—	—	4	0.13	0.03	—	—	—	—	—	—	—	—	—
Raw materials	—	—	—	—	—	—	—	—	—	1	—	0.02	—	—	—
Ship	6	0.02	0.03	3	0.06	0.02	2	0.25	0.14	1	—	0.01	—	—	—
Supervisor	—	—	—	1	—	0.04	1	—	0.1	—	—	—	—	—	—
Textiles	—	—	—	3	0.16	0.04	—	—	—	—	—	—	—	—	—
Utility	5	0.02	0.01	—	—	—	1	—	0.06	2	0.03	0.01	2	0.56	0.1

Source: Rice et al. [1994].

*Abbreviations: RCF=refractory ceramic fiber; SD=standard deviation; TWA=time-weighted average.

†Fibers were defined as having an aspect ratio of ≥5:1 and length >0.5 µm if sized using transmission electron micoscopy. For scanning electron microscopy, fibers were defined with the same aspect ratio and length >5 µm.

‡Fore is the area of the plant before the furnace.

customer facilities referred to as end-use (secondary) facilities. The researchers collected a total of 4,576 samples. A number of end-use facilities were randomly selected from a list of known purchasers of RCF products. The remainder consisted of facilities that volunteered for sampling once they learned of the consent agreement. The strata from which the 720 samples were collected consist of eight functional job categories derived so that results could be aggregated for comparison across industries, facilities, and similar job functions [RCFC 1993]. This categorization was based on the approach instituted by Corn and Esmen [1979]. Appendix B lists definitions and major work tasks for each functional job category. TWA and task-length average air sampling data were gathered according to NIOSH Method 7400 (*B* rules) and analyzed using PCM and TEM. Data on respirator use (by type) were also collected [Maxim et al. 1998].

As background for the consent agreement monitoring plan, baseline (now referred to as historical) information about airborne fiber concentrations was obtained through personal sampling of workers at RCF manufacturing facilities from January 1989 to May 1993. Exposure monitoring strategies used during the baseline period (1989–1993) provided the framework for the consent agreement (1993–1998) monitoring protocol. Table 4–3 presents AM and geometric mean (GM) concentrations of RCF exposures determined from historical data (1989–1993) by functional job category. Table 4–4 contains these summary statistics for all 5 years of RCF consent agreement monitoring data. Table 4–5 summarizes data from samples collected during the 5th year of the consent agreement only (June 1997 to May 1998). Table 4–6 presents the average airborne fiber concentrations for the baseline (1989–1993) and consent agreement monitoring (1993–1998) periods by manufacturing and end-use sectors.

A comparison of values from Tables 4–4, 4–5, and 4–6 with those in Table 4–3 indicates that average airborne concentrations for 1993–1998 were lower than those for the preceding baseline sampling period (1989–1993). However, a comparison of values in Tables 4–5 and 4–6 shows that average concentrations for the entire 5-year consent agreement monitoring period (1993–1998) are equal to those of year 5 (i.e., no change).

After the first 3 years (1993–1996) of the consent agreement monitoring period, Maxim et al. [1997] performed interim analyses of these data combined with historical data from the baseline monitoring period (1989–1993). The following conclusions about RCF exposures were based on these analyses of data from 1,600 baseline samples and 3,200 consent agreement samples:

- Airborne concentrations of RCFs are generally decreasing in the workplace.
- Ninety percent of airborne concentrations of RCFs in the workplace are below 1 f/cm^3.
- RCF concentrations have an approximately log-normal distribution.
- Significant differences exist in workplace concentrations by facility.
- Workplace concentrations vary with functional job category.
- Respirator usage varies with the worker's functional job category and the associated average fiber concentration.
- Workplace samples have a lower ratio of respirable nonfibrous particles to fibers than samples used in initial animal inhalation studies [Mast et al. 1995a,b; McConnell et al. 1995].

Functional job categories with the highest average TWA fiber concentrations include removal (AM=1.2 f/cm^3), finishing (AM=0.8 f/cm^3), and

Table 4–3. TWA[*] concentrations of airborne RCFs in personal samples collected during the baseline sampling period (1989–1993),[†] by functional job category

	Manufacturing (primary production)					End use (secondary processing)				
		AM		GM			AM		GM	
Functional job category	No. samples	f/cm^3	SD	f/cm^3	GSD	No. samples	f/cm^3	SD	f/cm^3	SD
Assembly	120	0.5	0.92	0.22	3.94	130	0.29	0.36	0.13	4.08
Auxiliary	119	0.15	0.18	0.07	4.01	26	1.1	2.26	0.2	6.33
Fiber	438	0.52	0.79	0.22	4.17	—	—	—	—	—
Finishing	127	0.76	0.63	0.49	3.11	84	1.57	5.72	0.47	4.18
Installation	—	—	—	—	—	201	0.69	1.09	0.3	4.31
Mixing forming	89	0.27	0.34	0.15	3.23	47	0.41	0.55	0.17	4.71
Other	129	0.33	0.86	0.09	4.25	57	0.38	0.69	0.14	4.88
Removal	—	—	—	—	—	49	1.36	2.97	0.28	6.48
Total	1,022	0.46	0.74	0.19	4.37	594	0.75	2.49	0.23	4.85

[*]Abbreviations: AM=arithmetic mean; GM=geometric mean; GSD=geometric standard deviation; RCF=refractory ceramic fibers; SD=standard deviation; TWA=time-weighted average.

[†]Data collected from August 1989 to May 1993 [RCFC 1993].

Table 4–4. TWA[*] concentrations of airborne RCFs in personal samples collected during the 5-year consent agreement monitoring period, 1993–1998,[†] by functional job category

	Manufacturing (primary production)					End use (secondary processing)				
		AM		GM			AM		GM	
Functional job category	No. samples	f/cm^3	SD	f/cm^3	GSD	No. samples	f/cm^3	SD	f/cm^3	GSD
Assembly	362	0.28	0.27	0.18	2.76	369	0.31	0.4	0.14	4.1
Auxiliary	237	0.12	0.19	0.05	3.87	311	0.19	0.37	0.07	4.68
Fiber	421	0.26	0.47	0.14	3.27	—	—	—	—	—
Finishing	359	0.65	0.56	0.47	2.44	622	0.99	2.09	0.35	4.5
Installation	—	—	—	—	—	456	0.42	0.51	0.2	3.83
Mixing forming	379	0.28	0.27	0.17	2.96	332	0.31	0.47	0.17	3.07
Other	167	0.14	0.21	0.07	3.22	385	0.17	0.46	0.04	4.66
Removal	—	—	—	—	—	176	1.92	2.85	0.82	4.22
Total	1,925	0.31	0.42	0.16	3.65	2,651	0.56	1.39	0.16	5.22

Source: Maxim et al. [1999a].

[*]Abbreviations: AM=arithmetic mean; GM=geometric mean; GSD=geometric standard deviation; RCF=refractory ceramic fibers; SD=standard deviation; TWA=time-weighted average.

[†]Data collected from June 1993 to May 1998.

Table 4–5. TWA* concentrations of airborne RCFs in personal samples collected during year 5 of the consent agreement monitoring period, June 1997 to May 1998

	Manufacturing (primary production)					End use (secondary processing)				
	No.	AM		GM		No.	AM		GM	
Functional job category	samples	f/cm^3	SD	f/cm^3	GSD	samples	f/cm^3	SD	f/cm^3	GSD
Assembly	78	0.28	0.25	0.19	2.48	92	0.28	0.39	0.1	5.32
Auxiliary	44	0.16	0.21	0.08	4.05	89	0.18	0.36	0.06	4.98
Fiber	85	0.29	0.29	0.18	2.85	—	—	—	—	—
Finishing	77	0.6	0.57	0.44	2.11	126	0.93	1.49	0.37	4.43
Installation	—	—	—	—	—	81	0.34	0.49	0.17	3.54
Mixing forming	75	0.23	0.24	0.14	2.78	69	0.28	0.31	0.18	2.65
Other	39	0.22	0.34	0.12	3	70	0.05	0.12	0.02	3.07
Removal	—	—	—	—	—	39	2.3	3.9	0.58	6.15
Total	398	0.31	0.37	0.18	3.12	566	0.54	0.14	0.13	5.83

Source: Maxim et al. [1999a].

*Abbreviations: AM=arithmetic mean; GM=geometric mean; GSD=geometric standard deviation; RCF=refractory ceramic fibers; SD=standard deviation; TWA=time-weighted average.

installation (AM=0.4 f/cm^3). The remainder of the functional job categories had average TWA concentrations near or below 0.3 f/cm^3. Although different jobs and activities are associated with the three higher exposure functional job categories, similarities exist that contribute to exposure concentrations. First, removal and installation activities are performed at remote jobsites where implementing fixed engineering controls may be difficult or impractical for reducing airborne fiber concentrations. Removal requires more mechanical energy and may involve fracturing the structure of the RCF product, resulting in fiber release and higher concentrations of airborne fibers. Finishing activities are performed at fixed locations where it is possible to implement engineering controls, but they also involve mechanical energy to shape RCF products by drilling, sanding, and sawing. These processes also result in the dispersal of airborne fibers.

Regarding particle-to-fiber ratio, Maxim et al. [1997] found average workplace values to be much lower (0.53; n=10; range not reported) than the average ratio (9.1; n=7) in the samples used in a series of animal inhalation toxicity studies with RCFs [Mast et al. 1995a,b, 2000; McConnell et al. 1995].

Monitoring performed during the baseline period (August 1989–May 1993) and the 5-year consent agreement period (June 1993–May 1998) provided data from nearly 6,200 air samples in the domestic RCF industry. Table 4–6 presents the summary statistics of workplace RCF exposure concentrations for the baseline (historical) and consent agreement monitoring data. The data suggest that (1) the AMs and GMs of RCF concentrations were higher for workers during the baseline period than during the more recent (consent monitoring data) period, and (2) AM and GM exposure concentrations were lower for workers in manufacturing facilities than at end-use sites.

Table 4–6. TWA* concentrations RCFs in personal samples collected at manufacturing facilities and end-use site during the baseline (1989–1993) monitoring periods

		Baseline data (1989–1993)†					Consent monitoring data (1993–1998)‡			
		AM		GM			AM		GM	
Type of site	No. samples	f/cm^3	SD	f/cm^3	GSD	No. samples	f/cm^3	SD	f/cm^3	GSD
Manufacturing (primary production)	1,022	0.46	0.74	0.19	4.37	1,527	0.31	0.42	0.16	3.65
End-use (secondary processing)	594	0.75	2.49	0.23	4.85	2,085	0.56	1.39	0.16	5.22
Total	1,616	0.56	1.63	0.2	4.56	4,576	0.46	1.1	0.16	4.53

Sources: RCFC [1993] and Maxim et al. [1999a].

*Abbreviations: AM=arithmetic mean; GM=geometric mean; GSD=geometric standard deviation; RCFs=refractory ceramic fibers; SD=standard deviation; TWA=time-weighted average.

†Data collected from August 1989 to May 1993 [RCFC 1993].

§Data collected from June 1993 to May 1998 [Maxim et al. 1999a].

4.5.4 Exposures During Installation and Removal of RCF Furnace Insulation

To evaluate exposures to airborne dust associated with removing RCF furnace insulation, Gantner [1986] conducted surveys with air sampling at five sites. The surveys were performed at sites where workers removed modules or blanket-type insulation manually using knives or trowels. During removal activities, workers wore disposable, single-use respirators, disposable protective clothing or their own personal clothing, and (in some cases) goggles or other protective eyewear. Personal sampling was performed for total dust concentration as well as respirable dust concentration using a cyclone. Area samples were collected in the center of work zones (industrial furnaces) at 9 ft above the floor, which was at the breathing zone level of the workers, who were on scaffolding. A total of 24 air samples were collected, including 14 personal samples (9 for respirable dust and 5 for total dust concentrations) and 10 area samples (3 for respirable dust and 7 for total dust concentrations). Bulk samples of the insulation materials were analyzed for cristobalite content, which ranged between 0% and 21%. In area air samples, cristobalite content ranged from 4% to 15%. Personal respirable dust concentrations averaged 4.99 mg/m^3 (range=0.12 to 16.9 mg/m^3), and personal total dust samples averaged 13.95 mg/m^3 (range=0.31 to 35.8 mg/m^3). Concentrations in area samples were lower, averaging 1.61 mg/m^3 (range=0.1 to 3.4 mg/m^3) for respirable dust and 8.98 mg/m^3 (range=0.96 to 36.2 mg/m^3) for total dust. As expected, the highest cristobalite concentrations in bulk samples were found on the face of insulation materials closest to high temperatures in furnaces (threshold temperature near 1,700 °F). Results of the surveys indicated that concentrations of respirable cristobalite exceeded the ACGIH TLV (then [10 mg/m^3]/[% SiO_2 + 2]/2) in 75% of the samples, although all sampling times were short because the removal task lasts only 26 to 183 min. The TLV for cristobalite has since been lowered to 0.05 mg/m^3 as an 8-hr TWA [ACGIH 2005].

Cheng et al. [1992] studied exposures to RCFs during the installation and removal of RCF insulation in 13 furnaces at 6 refineries and 2 chemical plants. Air samples were collected and analyzed according to NIOSH Method 7400 (*A* rules); sampling times ranged from 15 to 300 min. Samples collected during minor maintenance and inspection tasks (n=27) showed GM concentrations of 0.08 to 0.39 f/cm^3 (range=0.02 to 17 f/cm^3). Sampling performed during installation of RCF insulation (n=59) revealed GM concentrations of 0.14 to 0.62 f/cm^3 (range=0.02 to 2.6 f/cm^3). The highest exposures were observed in samples collected during removal of RCF insulation (n=32), with GM concentrations of 0.02 to 1.3 f/cm^3 (range=<0.01 to 17 f/cm^3). Workers working outside of enclosed spaces (furnaces) were rarely exposed to more than 0.2 f/cm^3. One sample of after-service RCF insulation was analyzed for fiber diameter and length: median diameter was reported as 1.6 μm (range=0.5 to 6 μm), and length ranged from 5 to 220 μm. Of 100 fibers randomly selected and analyzed from the air sample, 87% were within the respirable size range. Four personal samples were collected during removal of after-service RCF modules and fire bricks and were analyzed for respirable crystalline silica (cristobalite). Samples revealed concentrations ranging from 0.03 mg/m^3 to 0.2 mg/m^3 (GM=0.06 mg/m^3).

At a Dutch oil refinery, van den Bergen et al. [1994] performed personal air monitoring for airborne fibers to assess worker exposures during the removal of RCF insulation from expansion seams in a heat-treating furnace. The 8-hr TWA exposures for 5 workers sampled ranged from 9 to 50 f/cm^3 (GM=16 f/cm^3). Sweeney and Gilgrist [1998] also monitored worker exposures to airborne RCFs and respirable silica during the removal of RCF materials from furnaces. Personal samples from two workers taken during the removal of after-service RCF insulation revealed exposures of 0.15 and 0.16 f/cm^3. Exposures to total particulate (18.3 and 22.4 mg/m^3 as 8-hr TWAs) were above the OSHA PEL of 15 mg/m^3. Exposure concentrations for respirable dust containing crystalline silica (2.4% and 4.3%) were also above the OSHA PEL. The elevated concentrations of respirable and total dust were associated with removal of conventional refractory lining using jackhammers, crowbars, and hammers. A worker performing routing to install new RCF insulation was exposed at 1.29 f/cm^3 (8-hr TWA). Personal samples from another worker using a bandsaw to cut new RCF insulation revealed concentrations of 1.02 f/cm^3 as an 8-hr TWA.

In the RCF industry, worker exposures to respirable crystalline silica (including quartz, cristobalite, and tridymite) may occur during the use of silica in manufacturing, removal of after-service insulation, and waste disposal. Focusing on exposures of workers who install, use, or remove RCF insulation, Maxim et al. [1999a] collected 158 personal air samples analyzed for respirable quartz, cristobalite, and tridymite over the RCFC/EPA 5-year consent agreement monitoring period (1993–1998). A total of 42 removal projects were sampled. For small jobs, all workers engaged in insulation removal were sampled; for larger jobs, workers were selected at random for sampling. Air sampling and analysis were performed according to NIOSH Method 7500 for crystalline silica by X-ray diffraction; sampling times ranged from 37 to 588 min (AM=260 min, standard deviation [SD]=129 min). Short sampling times reflected the short duration of RCF insulation removal tasks (a benefit over time-intensive removal of conventional refractories). Removal of RCF blankets and modules is performed by using knives, pitchforks, rakes, and water lances, or by hand-peeling. The study noted that most (>90%) workers wear respirators (with protection factors from 10 to 50 or more) when removing insulation. Analysis of 158 samples found the following:

- Fourteen samples had task-time respirable quartz concentrations ranging from 0.01 to 0.44 mg/m^3 (equivalent 8-hr TWA range=0.004 to 0.148 mg/m^3); the remainder of samples were below the LOD.
- Three samples had detectable concentrations of cristobalite that were below the NIOSH REL of 0.05 mg/m^3.
- One sample contained tridymite (0.2 mg/m^3) at a concentration exceeding the NIOSH REL of 0.05 mg/m^3.

4.5.5 International (Canadian, Swedish, and Australian) Surveys of RCF Exposure

Perrault et al. [1992] reported on the characteristics of fiber exposures that occurred during the use of synthetic fiber insulation materials on construction sites in Canada. Fiber dimensions were measured from bulk samples of insulation materials used at five construction sites. Area air samples were also collected during the installation of composite RCF and glass wool insulation, glass wool alone, rock wool (both blown and sprayed on), and RCFs alone.

Respirable fiber concentrations were highest during removal and installation of RCFs (0.39 to 3.51 f/cm^3) compared with concentrations measured during installation of rock wool (0.15 to 0.32 f/cm^3), composite RCF and glass wool (0.04 f/cm^3), and glass wool alone (0.01 f/cm^3). Diameters of fibers in bulk samples differed significantly from diameters in airborne fibers. RCFs had the smallest GM_D of fibers in bulk samples (0.38 to 0.55 μm) compared with glass wool (0.93 μm) and rock wool (1.1 to 3.9 μm). For airborne fibers, rock wool (sprayed on) had a GM_D of 2.0 μm, followed by RCFs (1.1 μm), composite RCFs and glass wool (0.71 μm), glass wool (0.5 μm) and blown rock wool (0.5 μm). Elemental analysis and comparison of bulk samples with air samples revealed a greater concentration of fibers with oxides of silicon and aluminum in air samples. For sites with either glass wool or rock wool insulation, airborne samples contained fewer fibers with silicon oxide as the sole constituent than bulk samples. The authors concluded that airborne fiber concentrations were affected by the type of fiber material used and the confinement of worksites. The authors also concluded that characterization of fibers in bulk samples is not a good representation of physical and chemical parameters of the airborne fibers.

A report by the Swedish National Institute for Occupational Health [Krantz et al. 1994] describes exposure to RCFs in smelters and foundries based on industrial hygiene surveys and sampling at 4 facilities: a specialty steel foundry (2,500 workers), a metal smelting plant (1,500 workers), an aluminum foundry (450 workers), and an iron foundry (450 workers). RCF products were used in these plants in ladles, tapping spouts, holding furnaces, heat treatment furnaces, and spill protection mats. Workers and contractors were placed into three exposure categories, depending on their potential for exposure (as determined by distance from a fiber source). The highest exposures to airborne ceramic fibers (category 1) had median concentrations of 0.26 to 1.2 f/cm^3 and involved about 3% (n=160) of the workers at the plants surveyed. Secondary exposures (categories 2 and 3) involved another 33% (n=1,650) of the workers and had median concentrations of 0.03 to 0.24 f/cm^3. During certain operations such as removal or demolition of RCF materials in enclosed spaces, concentrations of up to 210 f/cm^3 were measured. Total dust concentrations increased with fiber concentration and were as high as 600 mg/m^3 during demolition and 60 mg/m^3 during reinsulation. Median fiber diameters from bulk samples analyzed by electron microscopy ranged from 0.6 to 1.5 µm, which was comparable to the diameters of airborne fibers. On the basis of air sampling data, *fiber dose* (assuming a working lifetime of 40 years [fiber concentration × exposure time per year × 40 years]) was estimated for 8 occupations with category 1 exposures. Dose estimates ranged from 0.05 fiber-years/cm^3 for a cleaner to 85 fiber-years/cm^3 for a bricklayer or contractor. Dose estimates for the 6 other occupations ranged from 0.6 fiber-years/cm^3 to 3.1 fiber-years/cm^3.

Researchers at the Australian National Occupational Health and Safety Commission established a technical working group to investigate typical exposures in SVF manufacturing and user industries [Rogers et al. 1997]. The RCF manufacturing industry is relatively small in Australia: 2 plants employing roughly 40 workers have been manufacturing RCFs since 1976 and 1977. Since the plants began manufacturing RCFs, 152 persons have been involved with production. Airborne fiber concentrations in both plants decreased over time as a result of (1) the introduction of a national exposure standard of 0.5 f/cm^3 for synthetic fibers and a secondary standard of 2 mg/m^3 for inspirable dust, (2) the use of various controls and handling technologies, and (3) increased awareness of dust suppression by the workforce. GM concentrations of airborne fibers before implementation of the synthetic fiber exposure standard (1983–1990) measured 0.52 f/cm^3 (geometric standard deviation [GSD]=3.9) and 0.29 f/cm^3 (GSD=2.5) for plants 1 and 2, respectively. GM concentrations for the subsequent period (1991–1996) dropped to 0.11 f/cm^3 (GSD=4.1) at plant 1 and 0.27 f/cm^3 (GSD=3.3) at plant 2.

4.5.6 Johns Hopkins University Industrial Hygiene Surveys

A report of RCF end-user exposure data prepared for the Thermal Insulation Manufacturers Association (TIMA) showed that using blanket, bulk, and vacuum-formed RCFs during certain operations resulted in high fiber concentrations [Corn et al. 1992]. For example, 25 personal air samples collected from workers installing RCF blanket modules had an AM, 8-hr TWA concentration of 1.36 f/cm^3 (SD=1.15). The fibers were collected and analyzed using NIOSH Method 7400 (B rules). Seventeen vacuum formers had AM exposure concentrations of 0.71 f/cm^3 (SD=0.83) while using bulk RCF products. Twenty-eight workers with the job title *vacuum-formed RCF cast finisher* had AM exposures of 1.55 f/cm^3 (SD=1.51). Table 4–7 summarizes exposure data collected for the 17 occupations sampled during the study. Scanning electron microscopy (SEM) was used to measure dimensions of approximately 3,500 fibers from selected air samples of the 17 occupations. GM fiber diameters ranged from 0.9 to 1.5 µm, and GM fiber lengths ranged from 20.4 to 36.1 µm. Fiber aspect ratios based on these data ranged between 16:1 and 30:1.

4.5.7 NIOSH HHEs and Additional Sources of RCF Exposure Data

NIOSH has conducted HHEs involving potential exposures to RCFs at the following work places: an RCF manufacturing facility [Lyman 1992], a steel foundry [O'Brien et al. 1990], a power plant [Cantor and Gorman 1987], a foundry [Gorman 1987], and a railroad car wheel and axle production facility [Hewett 1996]. Table 4–8 summarizes data on airborne fiber concentrations and dimensions from these studies.

Table 4–7. Summary of 8-hr TWA* RCF exposures for workers using RCF insulation products

		PCM (f/cm³)			SEM (f/cm³)			Gravimetric (mg/m³)		
RCF product	**Occupation**	**n**	**AM**	**SD**	**n**	**AM**	**SD**	**n**	**AM**	**SD**
RCF blanket	Module fabricator	5	0.44	0.4	7	0.54	0.8	4	6.26	6.5
	Module installer	25	1.36	1.15	23	1.19	0.8	11	14.2	18.7
	Blanket installer	8	0.37	0.29	9	0.33	0.24	4	1.42	1.2
	Investment caster	20	0.73	0.88	18	0.65	0.57	6	3.59	3.75
	General fabricator	20	0.55	0.55	19	0.46	0.55	7	0.86	0.49
	Fabrication maintenance	—	—	—	—	—	—	—	—	—
RCF bulk	Vacuum former	17	0.71	0.83	13	0.6	0.57	7	1.1	0.7
	Vacuum maintenance	—	—	—	—	—	—	—	—	—
	Vacuum warehouse	—	—	—	—	—	—	—	—	—
	Sprayer	1	1.53	—	1	1.15	—	—	—	—
	Spray feeder	1	0.24	—	1	0.21	—	—	—	—
Vacuum-formed RCFs	General fabricator	2	0.52	0.58	2	0.2	0.05	2	0.57	0.35
	Paper fabricator	—	—	—	—	—	—	—	—	—
	Paper finisher	—	—	—	—	—	—	—	—	—
	Cast finisher	28	1.55	1.51	32	1.17	1.17	8	4.05	5.42
	Finishing maintenance	1	0.12	—	2	0.07	0.01	1	0.75	—
	Board installer	9	0.78	0.84	9	0.66	0.67	1	6.09	—

Source: Corn et al. [1992].

*Abbreviations: AM=arithmetic mean; PCM=phase contrast microscopy; RCF-refractory ceramic fiber; SD=standard deviation; SEM=scanning electron microscopy; TWA=time-weighted average.

Table 4–8. NIOSH Health Hazard Evaluations involving investigation of exposures to RCFs*

Reference	Worksite	Samples: No.	Samples: Type	Concentration: f/cm³	Concentration: SD	Fiber dimension
Lyman [1992]	RCF manufacturing	286	Breathing zone	0.69	—	—
		4	Breathing zone	4.02	1.82	—
		126	Breathing zone	0.81	—	AMD=0.6 µm
				—	—	AML=13.8 µm
		24	Breathing zone	1.65	—	—
O'Brien et al. [1990]	Steel foundry	48	Fibers in an insulating blanket	—	—	D=<1.5 µm (81% of fibers)
				—	—	L= 4-64 µm (77% of fibers)
		54	Fibers in settled dust	—	—	D=<0.5 µm (73% of fibers)
				—	—	L=4-64 µm (62% of fibers)
Cantor and Gorman [1987]	Power plant	4	Breathing zone	0.26	0.08	D=0.5-2.0 µm (73% of fibers)
		2	Area	0.08	0.01	L=>20 µm (60% of fibers)
Gorman [1987]	Foundry	7	Breathing zone	0.1	0.06	D=<2 µm (96% of fibers)
		5	Area	0.4	0.26	L=<20 µm (80% of fibers)
Hewett [1996]	Railroad car wheel and axle manufacturer	6	Breathing zone near heat treatment plant	0.024	0.012	—
		14	Breathing zone during RCF removal	1.44	0.84	—
		1	Breathing zone	3.04†	—	—
				1.7‡	—	Mean D=0.71 (SD=0.44)
				—	—	Mean L=11.9 (SD=11.3)

*Abbreviations: AMD=arithmetic mean diameter; AML=arithmetic mean length; D=diameter; L=length; RCFs=refractory ceramic fibers; SD=standard deviation.
†Measured by phrase control optical microscopy (PCM).
‡Measured by transmission electron microscopy (TEM).

4.5.8 Discussion

Recent and historical environmental monitoring data [Esmen et al. 1979; Cantor and Gorman 1987; Gorman 1987; O'Brien et al. 1990; Cheng et al. 1992; Brown 1992; Corn et al. 1992; Lyman 1992; Allshouse 1995; Hewett 1996] indicate that airborne concentrations of RCFs include fibers in the thoracic and respirable size range (<3.5 µm in diameter and <200 µm long [Timbrell 1982; Lippmann 1990; Baron 1996]). Workers are exposed to these concentrations during primary RCF manufacturing, secondary manufacturing or processing, and end-use activities such as RCF installation and removal. Sampling data from studies of domestic primary RCF manufacturing sites indicate that average airborne fiber concentrations have steadily declined by nearly 2 orders of magnitude over the past 2 decades. Rice et al. [1997] report an estimated maximum airborne concentration of 10 f/cm^3 associated with an RCF manufacturing process in the 1950s. Esmen et al. [1979] recognized average exposure concentrations ranging from 0.05 to 2.6 f/cm^3 in RCF manufacturing facilities in the mid- to late-1970s. During the late 1980s, Rice et al. [1994, 1996, 1997] calculated average airborne concentrations in manufacturing facilities that ranged from <LOD to 0.66 f/cm^3. Maxim et al. [1994, 1997, 2000a] report that from the late 1980s through 1997, concentrations ranged from an AM of <0.3 to 0.6 f/cm^3 (GM≅0.2 f/cm^3).

For many RCF manufacturing processes, reductions in exposure concentrations have been realized through improved ventilation, engineering or process changes, and product stewardship programs [Rice et al. 1996; Maxim et al. 1999b]. Several functional job categories continue to be associated with fiber concentrations that exceed the average; these include finishing operations during manufacturing, removal operations, and installation performed by end users. Activities in these three categories require additional mechanical energy in handling RCF products (e.g., sawing, drilling, cutting, sanding), which increases the generation of airborne fibers. Removal and installation activities are performed at remote sites where conventional engineering strategies and fixed controls are more difficult to implement. For certain operations in which airborne fiber concentrations are greater (such as removal of RCF products from furnaces), jobs are performed for short periods and almost universally with the use of respiratory protection [Maxim et al. 1998].

One additional consideration during work involving RCF exposure is the potential for exposure to respirable silica in the forms of quartz, tridymite, and cristobalite. Although the potential for such exposure exists in primary manufacturing (because silica is a major component of RCFs), monitoring data indicate that these exposures are generally low [Rice et al. 1994]. Maxim et al. [1999a] reported that many airborne silica samples collected to assess exposures during installation and removal of RCF products contain concentrations below the LOD, with average concentrations of respirable silica ranging from 0.01 to 0.44 mg/m^3 (equivalent 8-hr TWA range=0.004 to 0.148 mg/m^3). Other studies indicate a greater potential for exposure to respirable silica (especially in the form of cristobalite) during removal of after-service RCF materials [Gantner 1986; Cheng et al. 1992; Perrault et al. 1992; van den Bergen et al. 1994; Sweeney and Gilgrist 1998]. Processes associated with high concentrations of airborne fibers generally generate high concentrations of total and respirable dust as well [Esmen et al. 1979; Krantz et al. 1994].