2 Background and Description of RCFs

2.1 Scope

Information about RCFs was collected and reviewed for this document to assess the health hazards associated with occupational exposure to this airborne fiber. Chapter 2 describes the background for studying the health effects of workplace exposures to RCFs. Information is presented about the physical and chemical properties of RCFs, including the morphology, dimensions, and durability of fibers that make up RCF-containing products. Chapter 3 discusses the production and uses of RCFs as a high-temperature insulation material; the chapter also describes the number of workers with potential for exposure to RCFs. Chapter 4 presents a review of the literature on potential workplace exposures to airborne RCFs during manufacturing and end uses of RCF products. Chapter 5 describes the effects of exposure to RCFs—first with reviews of animal studies and then with a description of epidemiologic studies of RCFs, focusing on U.S. and European workers in the RCF manufacturing industry. Recent quantitative risk assessments of RCFs are also summarized in this chapter. Chapter 6 contains a discussion of fiber characteristics and the parameters (dose, dimensions, and durability) that determine fiber toxicity. Chapter 7 summarizes existing standards and guidelines for occupational exposure to RCFs. Chapter 8 provides the basis and rationale for the NIOSH REL. Chapters 1 and 9 provide recommendations and guidelines for minimizing exposures to airborne fibers of RCFs in the workplace. Finally, Chapter 10 discusses future areas for research relating to fiber toxicity and occupational exposures.

2.2 Background

In 1977, NIOSH reviewed health effects data on occupational exposure to fibrous glass and determined the principal adverse health effects to be skin, eye, and upper respiratory tract irritation as well as the potential for nonmalignant respiratory disease. At that time NIOSH recommended the following:

> Occupational exposure to fibrous glass shall be controlled so that no worker is exposed at an airborne concentration greater than 3,000,000 fibers per cubic meter of air (3 fibers per cubic centimeter of air); . . . airborne concentrations determined as total fibrous glass shall be limited to a TWA of 5 milligrams per cubic meter of air [NIOSH 1977].

NIOSH also stated that until more information became available, this recommendation should be applied to other MMMFs, also called SVFs. Since then, additional data have become available from studies in animals and humans exposed to RCFs. The purpose of this report is to review and evaluate these studies and other information about RCFs.

2.3 Chemical and Physical Properties of RCFs

RCFs (Chemical Abstracts Service No. 142844–00–6) are amorphous fibers that belong to the larger class of SVFs, which also includes fibers of glass wool, mineral wool, slag wool, and specialty glass. SVFs vary according to chemical and physical properties, making them suitable for different uses. Like the naturally occurring mineral fibers defined in Section 1.2, RCFs possess desired qualities of heat resistance, tensile strength, durability, and light weight. The maximum end-use temperature for RCFs ranges from approximately 1,050 to 1,425 °C (1,920 to 2,600 °F), depending on the exact chemistry of the fiber. Unlike naturally occurring mineral fibers, however, SVFs such as RCFs and fibrous glass are noncrystalline in structure and fracture transversely, retaining the same diameter but creating shorter fibers. In contrast, the crystalline structure of mineral fibers such as asbestos causes the fibers to fracture along the longitudinal plane under mechanical stresses, resulting in more fibers with the same length but smaller diameters. These differences in morphology and cleavage patterns suggest that work with SVFs is less likely to generate high concentrations of airborne fibers than work with asbestos for comparable operations, since large-diameter fibers settle out in the air faster than small-diameter fibers [Assuncao and Corn 1975; Cherrie et al. 1986; Lippmann 1990]. During the manufacturing of RCFs, approximately 50% of product (by weight) is generated as fiber, and 50% is a byproduct made up of nonfibrous particulate material called *shot*. Selected physical characteristics of RCFs are presented in Table 2–1.

RCFs are produced by the blowing or spinning of furnace-melted siliceous kaolin ($Al_2Si_2O_5[OH]_4$) clay or blends of kaolin, silica, and zircon. RCFs are also referred to as alumina-based or kaolin-based ceramic fibers because they are produced from a 50:50 mixture of alumina and silica [IARC 1988]. Other oxides (including those of boron, titanium, and zirconium) are added as stabilizers to alter the physical properties of RCFs [RCFC 1996]. The addition of stabilizers and binders alters the properties of durability and heat resistance for RCFs. Generally, three types of RCFs are manufactured, and a fourth *after-service* fiber (often recognized in the literature) is distinguished according to its unique chemistry and morphology. Table 2–2 presents the chemistries of the four fiber types, numbered RCF1 through RCF4. RCF1 is a kaolin fiber; RCF2 is an alumina/silica/zirconia fiber; RCF3 is a high-purity (alumina/silica) fiber; and RCF4 is an *after-service* fiber, characterized by devitrification (i.e., formation of the silica polymorph cristobalite), which occurs during product use over an extended period of time at temperatures exceeding 1,050 to 1,100 °C (>1,900 °F). Another fiber subcategory is RCF1a, prepared from commercial RCFs using a less aggressive method than that used to prepare RCF1 for animal inhalation studies [Brown et al. 2000]. RCF1a is distinguished from RCF1 used in chronic animal inhalation studies, the former having a greater concentration of longer fibers and fewer nonfibrous particles. The lower ratio of respirable nonfibrous particles to fibers in RCF1a compared with RCF1 has been shown to affect lung deposition and clearance in animal inhalation studies [Brown et al. 2000; Bellman et al. 2001]. Chapter 5 presents additional discussion of animal studies and test fiber characteristics.

2.3.1 Fiber Dimensions

Fibers of biological importance are those that become airborne and have dimensions within inhalable, thoracic, and respirable size ranges. Thoracic-sized fibers (<3 to 3.5 μm in diameter) and respirable-sized fibers (<1.3 μm in diameter) with lengths up to 200 μm [Timbrell 1982; Lippmann 1990; Baron 1996] are capable of reaching the portion of the respiratory system below the larynx. Respirable-sized fibers are of biological concern because

Table 2–1. Selected physical characteristics of RCFs

Characteristic	Description
Softening point	1,700 to 1,800 °C
Refractive index	1.55 to 1.57
Specific gravity (density)	2.6 to 2.7 g/cm^3
Shot content (nonfibrous particulate)	20% to 50% by weight
Nominal diameter (bulk)	1.2 to 3 μm
Length (bulk)	2 to 254 μm
Dissolution rate (at pH=7.4)	1 to 10 ng/cm^2/hr

Sources: RCFC [1996], TIMA [1993], and IARC [1988].

Table 2–2. The chemistry of stock RCFs (% oxide)

Oxide component	RCF1	RCF2	RCF3	RCF4
Silicon dioxide (SiO_2)	47.7	50	50.8	47.7
Alumina (Al_2O_3)	48	35	48.5	48
Ferric oxide (Fe_2O_3)	0.97	<0.05	0.16	0.97
Titanium dioxide (TiO_2)	2.05	0.04	0.02	2.05
Zirconium dioxide (ZrO_2)	0.11	15	0.23	0.11
Calcium oxide (CaO)	0.07	0.05	0.04	0.07
Magnesium oxide (MgO)	0.98	0.01	<0.01	0.08
Sodium oxide (Na_2O)	0.54	<0.3	0.19	0.54
Potassium oxide (K_2O)	0.16	<0.01	<0.01	0.16

Adapted from Mast et al. [1995a].

they are capable of reaching the lower airways and gas exchange regions of the lungs when inhaled. Longer or thicker airborne fibers generally settle out of suspension or, if inhaled, are generally filtered out in the nasal passage or deposited in the upper airways. Thoracic-sized fibers that are inhaled and deposited in the upper respiratory tract are generally cleared more readily from the lung, but they have the potential to cause irritation and produce respiratory symptoms. Fiber dimensions are a significant factor in determining their deposition within the lung, biopersistence, and toxicity.

RCFs and other SVFs are manufactured to meet specified nominal diameters according to the fiber type and intended use. RCFs are produced with nominal diameters of 1.2 to 3 μm [Esmen et al. 1979; Vu 1988; TIMA 1993]. Typical diameters for an individual RCF (as measured in

RCF-containing products) range from 0.1 to 20 μm, with lengths ranging from 5 to 200 μm [IARC 1988]. In bulk samples taken from three RCF blanket insulation products, more than 80% of the fibers counted by phase contrast optical microscopy (PCM) were <3 μm in diameter [Brown 1992]. This result is consistent with those from another study of bulk samples of RCF insulation materials [Christensen et al. 1993], which found the fibers to have geometric mean diameters (GM_D) ranging from 1.5 to 2.8 μm (arithmetic mean [AM] diameter range=2.3 to 3.9 μm; median diameter range=1.6 to 3.3 μm).

Studies of airborne fiber size distributions in RCF manufacturing operations indicate that these fibers meet the criteria for thoracic- and respirable-sized fibers. One early study of three domestic RCF production facilities found that approximately 90% of airborne fibers were <3 μm in diameter, and 95% of airborne fibers were <4 μm in diameter and <50 μm long [Esmen et al. 1979]. The study showed that diameter and length distributions of airborne fibers in the facilities were consistent, with a GM_D of 0.7 μm and a geometric mean length (GM_L) of 13 μm. Another study [Lentz et al. 1999] used these data in combination with monitoring data from two additional studies [MacKinnon et al. 2001; Maxim et al. 1997] at RCF manufacturing plants to review characteristics of fibers sized from 118 air samples covering 20 years (1976–1996). Fibers with diameters <1 μm (n=3,711) were measured by transmission electron microscopy (TEM). Of these, 52% had diameters <0.4 μm, 75% had diameters<0.6 μm, and 89% had diameters <0.8 μm. Fiber lengths ranged from <0.6 to >20 μm, with 68% of fibers measuring 2.4 to 20 μm long and 19% of the fibers >20 μm long. On the basis of the results of TEM analysis of 3,357 RCFs observed on 98 air samples collected in RCF manufacturing sites, Allshouse [1995] reported that 99.7% of the fibers had diameters <3 μm and 64% had lengths >10 μm. Measurements of airborne fibers in the European RCF manufacturing industry are comparable: Rood [1988] reported that all fibers observed were in the thoracic and respirable size range (i.e., diameter <3 to 3.5 μm), with median diameters ranging from 0.5 to 1.0 μm and median lengths from 8 to 23 μm.

Cheng et al. [1992] analyzed an air sample for fibers during removal of after-service RCF blanket insulation from a refinery furnace. Fiber diameters ranged from 0.5 to 6 μm, with a median diameter of 1.6 μm. The length of fibers ranged from 5 to 220 μm. Of 100 fibers randomly selected and analyzed from the air sample, 87% were within the thoracic and respirable size range. Another study of exposures to airborne fibers in industrial furnaces during installation and removal of RCF materials found GM_D values of 0.38 and 0.57 μm, respectively [Perrault et al. 1992].

2.3.2 Fiber Durability

Fiber durability can affect the biologic activity of fibers inhaled and deposited in the respiratory system. Durable fibers are more biopersistent, thereby increasing the potential for causing a biological effect. Durability of a fiber is measured by the amount of time it takes for the fiber to fragment mechanically into shorter fibers or dissolve in biological fluids. RCFs tested in vitro with a solution of neutral pH (modified Gamble's solution) had a dissolution rate of 1 to 10 ng/cm^2 per hr [Leineweber 1984]. This test is biologically relevant because of the similarity of the solution to the conditions of the pulmonary interstitial fluid. By comparison, other SVFs (glass and slag wools) are more soluble, with dissolution rates in the 100s of ng/cm^2 per hr [Scholze and Conradt 1987]. Along a continuum of fiber durability determined in tests using simulated lung fluids at pH 7.4, the asbestos fiber crocidolite has a dissolution rate of <1 ng/cm^2 per hr, RCF1 and MMVF32 (E glass) have dissolution rates of 1 to 10 ng/cm^2 per hr, MMVF21 has a dissolution rate of 15 to 25 ng/cm^2 per hr, other fibrous glass and slag wools have dissolution rates in the range of 50 to 400 ng/cm^2 per hr, and the alkaline earth silicate wools have dissolution rates ranging from approximately 60 to 1,000 ng/cm^2 per hr [Christensen et al. 1994; Maxim et al. 1999b; Moore et al. 2001]. Chrysotile, which is considered the most soluble form of asbestos, has a dissolution rate of <1 to 2 ng/cm^2 per hr.

RCFs dissolve more rapidly than chrysotile, even though RCFs have a thicker diameter (by an order of magnitude) than chrysotile. The rate of dissolution is an important fiber characteristic that affects the clearance time and biopersistence of the fiber in the lung. The significance of fiber dimension, clearance, and dissolution (i.e., breakage, solubility) is discussed in Chapter 6.